

The Role Stainless Steel in Industrial Heat Exchangers

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Many industrial and chemical processes involve heating and cooling. Since heat represents money, heat exchangers are an extremely vital part of the process equipment.

The amount of stainless steel utilized in heat exchange equipment is increasing as industry strives toward greater efficiency and reduced costly shutdowns in its operations and higher product purity. As will be shown, stainless steel is sometimes the only material that can be used; in other situations it is the most economical when costs of installation, maintenance and production stoppages are considered.

Following are ten good reasons for using stainless steels in heat exchange equipment:

1. Resistance to Corrosion in
 - Virtually all cooling waters and
 - Many chemical environments
2. High-Temperature Resistance to Oxidation and Scaling
3. Good Strength Characteristics in Low- and High-Temperature Service
4. Maintains Excellent Heat Transfer Properties in Service
5. Resistance to Fouling Due to Corrosion
6. No Contamination of Product or Process by Corrosion
7. Easy to Clean Mechanical Chemical
8. Fabricability
9. Availability in a Variety of Compositions as
 - Seamless & welded tubing for shell-and-tube exchangers
 - Thin flat-rolled sheet & strip for plate exchangers
 - Plate for tubesheets
 - Bar and wire for mechanical fasteners
10. Economical-in Terms of
 - First cost
 - Long-term service

STAINLESS STEEL

Stainless steels are iron-base alloys containing a minimum of 10.5% chromium. There are 57 separate and distinct commercial compositions designated by American Iron and Steel Institute as standard types. Fifteen of the most widely used types in heat exchange service are listed in Table 1 along with their chemical compositions and properties. A complete listing of all standard AISI types and a description of each are contained in the AISI publication, "Steel Products Manual—Stainless and Heat-Resisting Steels."¹

In addition to the standard AISI types, many special-analysis and proprietary stainless steels are produced in the United States and Canada. Many of these are identified in technical literature, such as in the ASTM Data Series Booklet DS 45.²

AISI stainless steels are identified by a system of numbers that are in either 200, 300, or 400 Series. In addition, all are identified by the new Unified Numbering System (UNS) which has been developed for all commercial metals and rare earths. For example, Type 304 is S30400 in UNS. Special analysis and proprietary alloys may have numbers that resemble AISI type numbers. To avoid confusion, the term "alloy" will be used in this publication in referring to stainless steels other than the AISI compositions.

The terms *austenitic*, *martensitic*, *ferritic* and *precipitation harden-*

ing serve to identify categories of stainless steels on the basis of their metallurgical structure. Engineers should recognize these terms and understand what they mean, because stainless steels so classified tend to have similar characteristics with respect to corrosion resistance, hardenability, and fabricability.

Austenitic

Austenitic stainless steels are chromium-nickel-manganese and chromium-nickel compositions, which can be hardened only by cold working; heat treatment serves only to soften them. They are nonmagnetic in the annealed condition, although some may become slightly magnetic after cold working.

The austenitic group of stainless steels is characterized as having excellent corrosion resistance, unusually good formability, and the ability to develop high strength. In the annealed condition, they possess maximum ductility, good yield and tensile strength, high impact strength, and good notch toughness.

Typical of this group is Type 304, also widely known as 18-8 stainless, a general-purpose stainless steel. There are numerous compositions in this group. In these variations, (1) the chromium/nickel ratio has been changed to improve the forming characteristics (Types 301 and 305), (2) the carbon content has been decreased to prevent carbide precipitation in weldments (Types 304L, 316L, and 317L), (3) titanium or columbium has been added to prevent carbide precipitation resulting from exposure to high temperature (Types 321 and 347), (4) molybdenum has been added or the chromium and nickel contents have been increased to improve corrosion or oxidation resistance (such as Types 316 and 317 with molybdenum, and 309 and 310 with higher alloy content), and (5) sulfur or selenium has been increased or added to improve machining characteristics (Types 303 and 303 Se).

The 200 Series stainless steels (Types 201, 202, and 205) are very similar to the 300 Series types except that manganese replaces some of the nickel, and these alloys have higher yield and tensile strengths.

Ferritic

The ferritic stainless steels are identified by 400 Series numbers. These straight-chromium alloys are not hardenable by heat treatment and only slightly hardenable by cold working. They are magnetic, have good ductility and good resistance to corrosion and oxidation. Typical of this group is Type 430, with nominally 17% chromium. Among the several variations in the ferritic group, two have increased chromium content to improve scaling resistance (Types 442 and 446).

Duplex (Ferritic/Austenitic)

Some stainless steels, such as Type 329, cannot be classified strictly as austenitic, ferritic, or martensitic because of a two-phase structure consisting of a ferritic matrix with pools of austenite. In addition to good general corrosion resistance, comparable to that of Type 316 stainless steel, the ferritic/austenitic alloys have high resistance to stress-corrosion cracking.

Martensitic

The martensitic stainless steels are straight-chromium steels having a carbon/chromium ratio higher than that of the ferritic group. Consequently, they can be hardened by heat treatment.

These stainless steels resist corrosion in mild environments (atmos-

TABLE 1 Stainless Steel Properties

Chemical Analysis % (Max unless noted otherwise)	304 (S30400)	304L (S30403)	309S (S30908)	310S (S31008)	316 (S31600)	316L (S31603)	317 (S31700)	317L (S31703)
Carbon	0.08	0.030	0.08	0.08	0.08	0.030	0.080	0.030
Manganese	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Phosphorus	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
Sulfur	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Silicon	1.00	1.00	1.00	1.50	1.00	1.00	1.00	1.00
Chromium	18.00/20.00	18.00/20.00	22.00/24.00	24.00/26.00	16.00/18.00	16.00/18.00	18.00/ 20.00	18.00/20.0
Nickel	8.00/10.50	8.00/12.00	12.00/15.00	19.00/22.00	10.00/14.00	10.00/14.00	11.00/15.00	11.00/15.010
Molybdenum	—	—	—		2.00/ 3.00	2.001 3.00	3.00/ 4.00	3.00/ 4.0°)
Other								
Physical Constants								
Structure	Austenitic		Austenitic	Austenitic	Austenitic		Austenitic	Austenitic
Magnetic	No		No	No	No		No	No
Density lbs/in ³ (k/m ³)	0.29 (80(x0))		0.29 (8060)	0.29 (8060)	0.29 (8060)		0.29 (8060)	0.29 (8060)
Specific Heat Btu/ lb/F (1/kg-K) 32 to 212 F (0-100 C)	0.12 (503)		0.12 (503)	0.12 (503)	0.12 (503)		0.12 (503)	0.116 (486)
Thermal Conductivity Btu/ hr/ft ² /F (W/ m-K) 212 F (100 C) 932 F (500 C)	9.4(0.113) 12.4 (0.149)		9.0 (0.108) 10.8 (0.130)	8.2 (0.099) 10.8 (0.130)	9.4(0.113) 12.4 (0.149)		9.4 (0.113) 12.4 (0.149)	8.3 (0.100)
Mean Coefficient of Thermal Expansion								
10 ⁻⁶ /F (10 ⁻⁶ /C)								
32 to 212 F (0-100 C)	9.6 (17.3)		8.3 (15.0)	8.8 (15.9)	8.9 (15.9)		8.9 (16.0)	9.2 (16.5)
32 to 600 F (0-315 C)	9.9(17.9)		9.3 (16.6)	9.0 (16.2)	9.0 (16.2)		9.0 (16.2)	10.1 (18.1)
32 to 1000 F (0-538 C)	10.2 (18.4)		9.6 (17.2)	9.4 (17.0)	9.7 (17.5)		9.7 (17.5)	10.3 (18.6)
32 to 1200 F (0-648 C)	10.4 (18.8)		10.0 (18.0)	9.7 (17.5)	10.3 (18.6)		10.3 (18.6)	—
32 to 1800 F (0-982 C)	—		11.5 (20.6)	10.6 (19.1)	11.1 (20.0)		11.1 (20.0)	—
Tensile Modulus of Elasticity psi X 10 ⁶ (GPa)	28.0 (193)		29.0 (200)	29.0 (200)	28.0 (193)		28.0 (193)	29.0 (200)
Torsional Modulus of Elasticity psi X 10 ⁶ (GPa)	12.5 (86.2)							
Melting Point Range F (C)	2550-2650 (1398-1454)		2550-2650 (1398-1454)	2550-2650 (1398-1454)	2500-2550 (1371-1398)		2500-2550 (1371-1398)	2500-2550 (1371-1398)
Typical Mechanical Properties								
(annealed condition)								
Stainless Steel Sheet								
Tensile Strength ksi (MPa)	84(579)	81 (558)	90(621)	95 (655)	84(579)	81 (558)	90 (621)	86 (593)
Yield Strength (offset 0.2%) ksi (MPa)	42(290)	39(269)	45(310)	45(310)	42(290)	42(290)	40(276)	38(262)
Elongation in 2" %	55	55	45	45	50	50	45	55
Reduction of Area %								
Izod Impact Strength ft-lb-force (J)								
Hardness (Rockwell)	B80	B79	B85	B85	B79	B79	B85	B85

321 (532100)	329 (S32900)	347 (S34700)	348 (534800)	410 (S41000)	430 (S43000)	446 (544600)
0.08	0.10	0.08	0.08	0.15	0.12	0.20
2.00	2.00	2.00	2.00	1.00	1.00	1.50
0.045	0.040	0.045	0.045	0.040	0.040	0.040
0.030	0.030	0.030	0.030	0.030	0.030	0.030
1.00	1.00	1.00	1.00	1.00	1.00	1.00
17.00119.00	25.00/30.00	17.00119.00	17.00/19.00	11.50/13.50	16.00/18.00	23.00/27.OC
9.00/12.00	3.00/ 6.00	9.00/13.00	9.00; 13.00	—	—	—
—	1.001 2.00	—	—	—	—	—
Ti (5 X C Min.)	—	Cb + Ta (10 X C Min.)	Cb + Ta (10 X C Min.)	—	—	—
			Ta 0.10 Co 0.20			
Austenitic No	Austenitic-Ferritic No	Austenitic No		Martensitic Yes	Ferritic Yes	Ferritic Yes
0.29 (8060)	0.28 (7780)	0.29 (8060)		0.28 (7780)	0.28 (7780)	0.27 (7550)
0.12 (503)	0.11 (460)	0.12 (503)		0.11 (460)	0.11 (460)	0.12 (502)
9.3 (0.112) 12.8 (0.154)		9.3 (0.112) 12.8 (0.154)		14.4 (0.174) 16.6 (0.201)	15.1 (0.182) 15.2 (0.183)	12.1 (0.146) 14.1 (0.170)
9.3 (16.6) 9.5 (17.2) 10.3 (18.6) 10.7 (19.3) [to 1700] 11.4 (20.6)	[to 1500] 8.0 (14.4)	[to 1500] 11.1 (20.0)	(Similar to Those of Type 347)	5.5 (9.9) 6.3 (11.4) 6.4 (11.6) 6.5 (11.7)	5.8 (10.4) 6.1 (11.0) 6.3 (11.4) 6.6 (11.9)	5.8 (10.4) 6.0 (10.8) 6.2 (11.2) 6.4 (11.6) 6.7 (12.1)
28.0 (193)		28.0 (193)		29.0 (200)	29.0 (200)	29.0 (200)
2550-2600 (1398-1427)		2550-2600 (1398-1427)		2700-2790 (1483-1532)	2600-2750 (1427-1510)	2600-2750 (1427-1510)
90(621)	105 (724)	95(655)	95(655)	70(483)	75(517)	80(552)
35(241)	80(552)	40(276)	40(276)	45 (310)	50(345)	50(345)
45	25 50	45	45	25	25	20
B80	40(54) (Brinell 230)	B85	885	B80	B85	B83

sphere, fresh water, weak acids, etc.). They have fairly good ductility and are always strongly magnetic. There are 12 compositions in this group, with Type 410 being the most common. Type 410 with 12% chromium is used for heat exchange service, but its carbon content is reduced to minimize hardenability.

Precipitation Hardening

Precipitation hardening stainless steels are hardened by a low-temperature aging treatment in combination with cold working. They are rarely used in heat exchange applications.

CHOOSING THE RIGHT STAINLESS STEEL

Selection of the right stainless steel from the many types available requires an evaluation based upon four important criteria. Listed in order of descending importance, they are:

Corrosion Resistance³—the primary reason for specifying stainless steel. The specifier needs to know the nature of the environment and the degree of corrosion resistance required.

Cost Performance—To put everything into proper perspective, a total value analysis is appropriate. How much is it going to cost spread over the entire service life? This considers first cost *plus* savings in maintenance and replacement.

Fabricability—and how the product is to be made is a third-level consideration. This includes ability to be welded, formed, etc.

Mechanical Properties—with particular emphasis on heat transfer characteristics and on strength at ambient, elevated, or low temperature. Generally speaking, the combination of corrosion resistance and strength is the basis for selection.

CORROSION RESISTANCE

Corrosion has always been an important and costly problem facing the process engineer. The decision as to whether a chemical process is practical or not is intimately related to the corrosivity of the process. Not only must equipment damage and repair under corrosive attack and subsequent repair be considered, but the danger of product loss or contamination must be eliminated.

The presence of chromium in all stainless steels is chiefly responsible for their resistance to corrosion. With 10.5% or more chromium (Figure 1) a protective oxide film forms under normal atmospheric conditions. As the chromium content is increased, resistance to corrosion also increases so that stainless containing 17% chromium has improved corrosion resistance, and stainless steel containing 28% chromium is even more corrosion resistant.

Passivity, the mechanism by which the stainless steels derive their corrosion resistance, has been a popular subject for electrochemical research for many years. This phenomenon is difficult to define because of its complex nature and the specific conditions under which it occurs. Essentially, passivity implies a loss of chemical reactivity experienced by certain metals and alloys under particular environmental conditions. For the purpose of this discussion, passivity in stainless steels is generally understood to be related to the thin transparent oxide film that creates a protective barrier between the stainless steel and its environ-

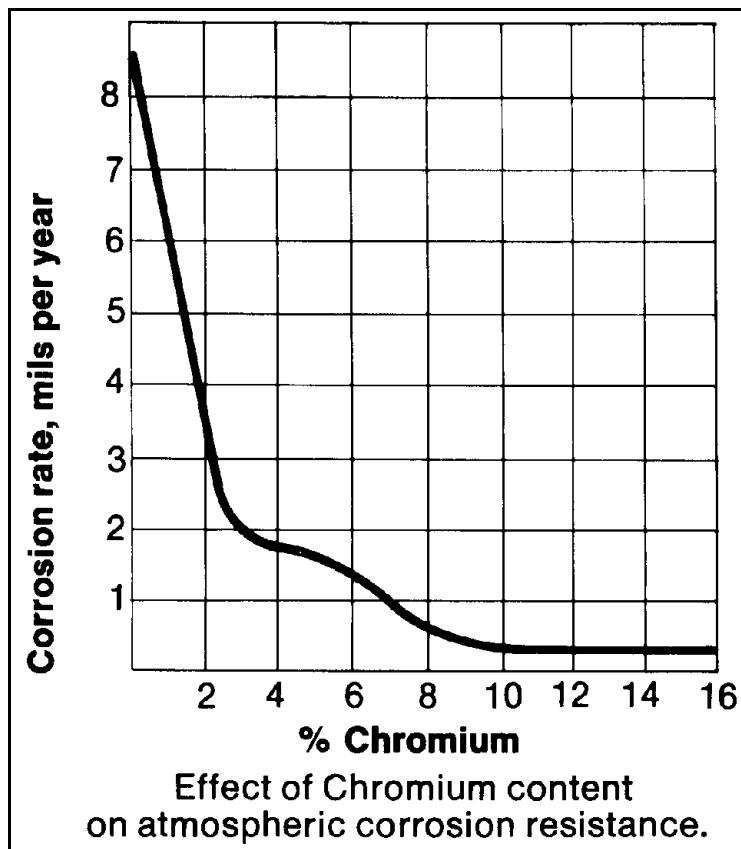


Figure 1

Source: Stainless Steel Industry Data

ment. This film is self-forming and exists on all clean stainless steel alloys. Although this barrier film has been studied for many years, its exact nature is still not known. However, it has been established that chemically oxidizing media are necessary for film formation and repair. Consequently, the fact that stainless steels perform well in oxidizing environments is well founded in corrosion theory.

As oxidizing media are needed to maintain stable passivity, conversely the stainless steels give relatively poor performance in reducing environments. Dilute sulfuric and hydrochloric acids are typical of such environments, and are quite corrosive to stainless steels, particularly at elevated temperatures. The corrosive attack experienced is an instantaneous breakdown of the passive film resulting in general dissolution accompanied by the evolution of hydrogen gas.

Some ions, particularly the halogens, are capable of causing localized breakdown of the passive film. When this occurs under conditions where film repair is impossible or delayed, pitting attack can occur.

When stainless steel contains nickel as well as chromium, ductility, toughness and strength at elevated temperatures are increased. Some improvement in corrosion resistance may also occur.

Stainless steels containing molybdenum (such as Type 316) offer improved resistance over that of Type 304 to chemical agents that cause pitting corrosion, such as chlorides, photographic solutions, sulfite liquors, and hypochlorites.

Table 2 suggests various corrosive environments in which stainless steels are used for heat exchangers and other process equipment.⁴ Also, appearing throughout this publication are more detailed descriptions of specific heat exchanger applications and materials experiences in such industries as pulp and paper, food, LNG, SNG, nitric acid, sulfuric acid, acetic acid, and petroleum refining.

TABLE 2
Where Different Grades Are Used⁴

Environment	Grades	Environment	Grades
Acids Hydrochloric acid	Stainless generally is not recommended except when solutions are very dilute and at room temperature.		used for fractionating equipment, for 30 to 99% concentrations where Type 304 cannot be used, for storage vessels, pumps and process equipment handling glacial acetic acid, which would be discolored by Type 304. Type 316 is likewise applicable for parts having temperatures above 120 F (50 C), for dilute vapours and high pressures. Type 317 has somewhat greater corrosion resistance than Type 316 under severely corrosive conditions. None of the stainless steels has adequate corrosion resistance to glacial acetic acid at the boiling temperature or at superheated vapour temperatures.
"Mixed acids"	There is usually no appreciable attack on Type 304 or 316 as long as sufficient nitric acid is present.		
Nitric acid	Type 304L or 430 is used.		
Phosphoric acid	Type 304 is satisfactory for storing cold phosphoric acid up to 85% and for handling concentrations up to 5% in some unit processes of manufacture. Type 316 is more resistant and is generally used for storing and manufacture if the fluorine content is not too high. Type 317 is somewhat more resistant than Type 316. At concentrations up to 85%, the metal temperature should not exceed 212 F (100 C) with Type 316 and slightly higher with Type 317. Oxidizing ions inhibit attack and other inhibitors such as arsenic may be added.	Aldehydes	Type 304 is generally satisfactory.
Sulfuric acid	Type 304 can be used at room temperature for concentrations over 80%. Type 316 can be used in contact with sulfuric acid up to 10% at temperatures up to 120 F (50 C) if the solutions are aerated; the attack is greater in airfree solutions. Type 317 may be used at temperatures as high as 150 F (65 C) with up to 5% concentration. The presence of other materials may markedly change the corrosion rate. As little as 500 to 2000 ppm of cupric ions make it possible to use Type 304 in hot solutions of moderate concentration. Other additives may have the opposite effect.	Amines	Type 316 is usually preferred to Type 304.
Sulfurous acid	Type 304 may be subject to pitting, particularly if some sulfuric acid is present. Type 316 is usable at moderate concentrations and temperatures.	Cellulose acetate	Type 304 is satisfactory for low temperatures, but Type 316 or Type 317 is needed for high temperatures.
Bases Ammonium hydroxide, sodium hydroxide, caustic solutions	Steels in the 300 series generally have good corrosion resistance at virtually all concentrations and temperatures in weak bases, such as ammonium hydroxide. In stronger bases, such as sodium hydroxide, there may be some attack, cracking or etching in more concentrated solutions and at higher temperatures. Commercial purity caustic solutions may contain chlorides, which will accentuate any attack and may cause pitting of Type 316 as well as Type 304.	Citric, formic and tartaric acids	Type 304 is generally acceptable at moderate temperatures, but Type 316 is resistant to all concentrations at temperatures up to boiling.
Organics Acetic acid	Acetic acid is seldom pure in chemical plants but generally includes numerous and varied minor constituents. Type 304 is used for a wide variety of equipment including stills, base heaters, holding tanks, heat exchangers, pipelines, valves and pumps for concentrations up to 99% at temperatures up to about 120 F (50 C). Type 304 is also satisfactory for contact with 100% acetic acid vapours, and if small amounts of turbidity or color pickup can be tolerated—for room temperature storage of glacial acetic acid. Types 316 and 317 have the broadest range of usefulness, especially if formic acid is also present or if solutions are unheated. Type 316 is	Esters	From the corrosion standpoint, esters are comparable with organic acids.
		Fatty acids	Up to about 300 F (150 C), Type 304 is resistant to fats and fatty acids, but Type 316 is needed at 300 to 500 F (150 to 260 C) and Type 317 at higher temperatures.
		Paint vehicles	Type 316 may be needed if exact color and lack of contamination are important.
		Phthalic anhydride	Type 316 is usually used for reactors, fractionating columns, traps, baffles, caps and piping.
		Soaps	Type 304 is used for parts such as spray towers, but Type 316 may be preferred for spray nozzles and flake-drying belts to minimize offcolor product.
		Synthetic detergents	Type 316 is used for preheat, piping, pumps and reactors in catalytic hydrogenation of fatty acids to give salts of sulfonated high molecular alcohols.
		Tall oil (pulp and paper industry)	Type 304 has only limited usage in tall-oil distillation service. High-rosin-acid streams can be handled by Type 316L with a minimum molybdenum content of 2.75%. Type 316 can also be used in the more corrosive high-fatty-acid streams at temperatures up to 475 (245 C), but Type 317 will probably be required at higher temperatures.
		Tar	Tar distillation equipment is almost all Type 316 because coal tar has a high chloride content; Type 304 does not have adequate resistance to pitting.
		Urea	Type 316L is generally required.
		Pharmaceuticals	Type 316 is usually selected for all parts in contact with the product because of its inherent corrosion resistance and greater assurance of product purity.

These comments on the suitability of stainless steels in various environments are based on successful applications and are intended as starting points for material selection for heat exchangers. In certain media, for example, corrosion rates can be sharply affected by small differences in temperature and chemical content, such as might occur during upsets in the process. The magnitude of the possible effect can be considerable, as indicated in Figures 2 and 3. Figure 2 shows how small quantities of hydrofluoric and sulfuric acids can have a serious effect on Type 316 stainless in an environment of 25% phosphoric acid,⁵ and Figure 3 shows how temperature affects corrosion rates of type 304 and 316 in very concentrated sulfuric acid.⁴

In general, as temperature increases the corrosion rate also increases. A rule of thumb is that the corrosion rate of a material doubles for each 30C rise in temperature. Also, major differences in temperatures of heat exchanger surfaces can cause accelerated attack, as suggested by the data in Table 3. Heat exchange through a tube or vessel wall usually results in greater attack to a metal than by simply immersing the metal in a hot solution.⁴

Each material selection problem must be solved on its own merits. Selection must be based on knowledge of the problem, the properties of the materials under consideration, and common sense.

Service tests are the most reliable way to determine the optimum material of construction, especially under conditions of heat transfer. ASTM G-4-68 (1974) is a recommended practice for carrying out such tests.

The tests should cover corrosive conditions during shutdowns as well as during operation. For instance, sulfuric, sulfurous and polythionic acid condensates formed during shutdowns may be more cor-

Small quantities of hydrofluoric and sulfuric acids can have a serious effect on Type 316 stainless in 25% P₂O₅ phosphoric acid with 1.5% F as H₂SIF₆ at 190 F (90 C).

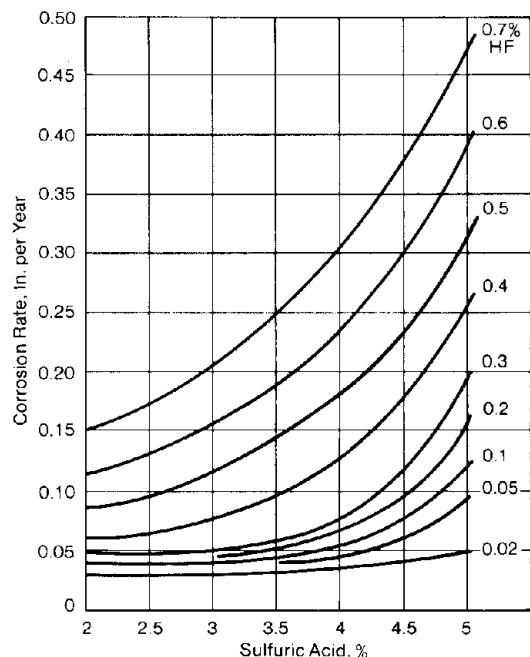


Figure 2
Source: Parker & Briggs⁵

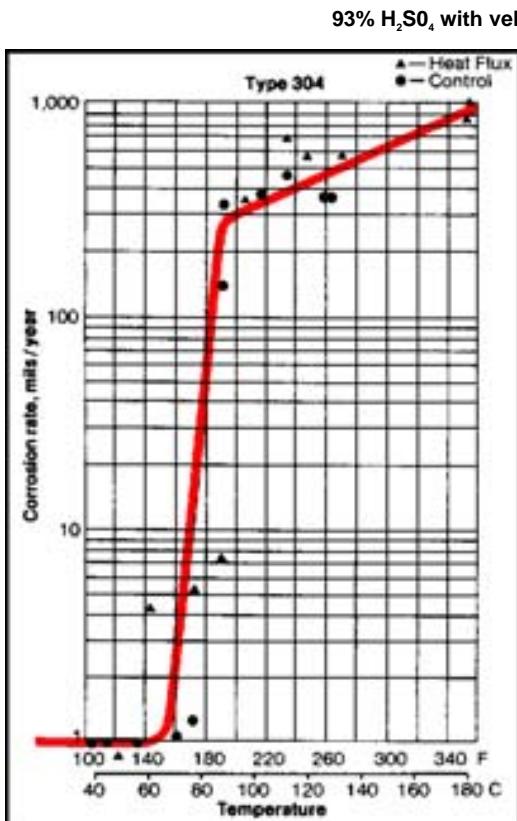


Figure 3
Source: Climax Molybdenum Company

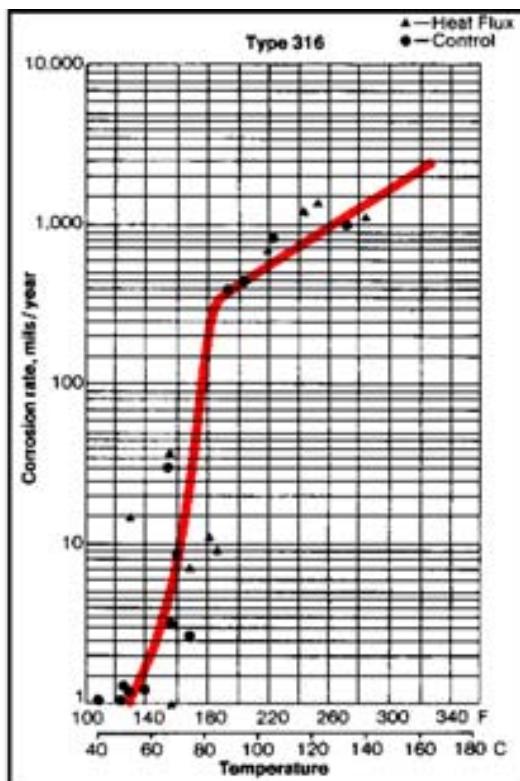


TABLE 3
Effect of Heat-Transfer Conditions on Corrosion of Stainless Steel⁴

Acid	% Concentration*	Type	Control Tests Without Heat Transfer			Corrosion Rate in mils/year With Heat Transfer and Specimen at Indicated Temperature		
			Specimen Temperature F	Specimen Temperature C	Corrosion Rate mils/year	230 110	257 125	284 F 140 C
Acetic	10	304L	214	101	<1	<1	<1	<1
		316	214	101	<1	<1	<1	<1
	50	304L	216	102	130	210	220	250
		316	216	102	<1	<1	<1	<1
	99.6	304L	244	118	69	260	340	20
		316	244	118	<1	<1	13	10
Formic	10	304L	214	101	742	>1000	570	570
		316	214	101	10	16	62	73
	50	304L	217	103	>1000	>1000	>1000	>1000
		316	217	103	39	58	60	84
	88/90	304L	217	103	716	540	500	520
		316	217	103	10	48	40	48
Phosphoric	10	304L	214	101	<1	<1	2	4
		316	214	101	<1	10	13	9
	50	304L	230	110	8	13	3	>1000
		316	230	110	6	39	4	22
	86	304L	208	97	>1000	22	>1000	>1000
		316	230	110	9	110	215	35

* By weight

rosive than is the process stream during operation. Tests should also be conducted under the worst operating conditions anticipated. Even after a plant is on stream, it is helpful to have a continuous corrosion monitoring program to determine the proper selection of the materials and to evaluate equipment modifications and inhibitors. While inhibitors are not commonly required in stainless steel systems, there are conditions where they can perform a useful service. For example, the general attack on stainless steel caused by contaminants in acetic acid can, under some conditions, be controlled by the addition of oxidizing agents, such as permanganate, dichromate, cupric and ferric salts, or by air injection.⁵

Cooling Water Conditions

While it is difficult to classify the chemical environments to which a heat exchanger may be exposed, evaluation of cooling water (if the exchanger is used for cooling or condensing) is relatively simple. Although water varies widely from location to location, tests can be conducted to determine its quality and corrosiveness, and materials can be selected accordingly. Some general observations on different cooling water types are worthy of comment.

Cooling towers. The use of spray ponds and cooling towers, which is becoming increasingly popular because of water shortages and thermal pollution problems, complicates the cooling water problem because the tendency of these devices is to concentrate impurities such as sulfides and chlorides. Cooling tower applications have been highly successful for both Types 304 and 316 stainless steel, especially in the Southwest where ground water supplies are scarce, and in some cases with the use of sewage effluent for makeup water.

Fresh water. In fresh water as found in virtually all inland locations in the United States, it can be said that *clean* stainless steel heat exchange surfaces resist all forms of corrosive attack by fresh waters. Exceptions have been reported, but investigation revealed that problems were related to dirty surfaces and could have been prevented. Spotty conditions of fouling and scale can result in localized corrosion of the lower alloyed stainless steels. It has been observed in power plant condensers that fouling occurs in two ways: as a solid continuous coating on the surface, or as small isolated or localized spots. Conditions underneath continuous fouling are generally uniform and not considered serious to stainless steel in fresh water, whereas spotting or localized fouling can create concentration cells that are potential sites for localized corrosion.

Polluted fresh water. Stainless steels offer special advantages in handling so-called fresh water contaminated by acid, such as resulting from acid mine drainage in the Monongahela River near Pittsburgh, Pennsylvania. Tests conducted by utilities in these waters, which have a pH as low as 3 and contain ferric ions, show that Type 304 stainless steel is completely satisfactory.

Clean salt water. Type 316 stainless steel has been used successfully in sea water for heat exchange service, but only when great care has been taken to keep the metal surfaces clean and free of fouling deposits. It would be better to consider the higher alloyed stainless steels, many of which have proven performance.

Polluted salt water. Here too, Type 316 and especially the higher alloyed stainless steels, have been used. Metal surfaces should be cleaned regularly to eliminate spotty deposits and to improve heat transfer performance.

Contamination

Corrosion rate is not always the key factor in material selection. The presence of minute amounts of metal in solution may be deleterious to product quality in certain instances, even when the corrosion rate is low. A common example is in the production of pharmaceuticals, where Type 316 is generally chosen because of its excellent corrosion resistance. Even small amounts of metallic ions might affect product quality, effectiveness or color. Another example is the selection of a special grade of Type 304—rather than Type 316—for the production of hydrazine by an improved Raschig process with chloramine as an intermediate. Even tiny amounts of molybdenum catalyze the decomposition of hydrazine. Freedom from contamination is one of the chief reasons why stainless steels are preferred for heat exchangers in nuclear power plants, such as the feedwater heater bundle shown in Figure 4.

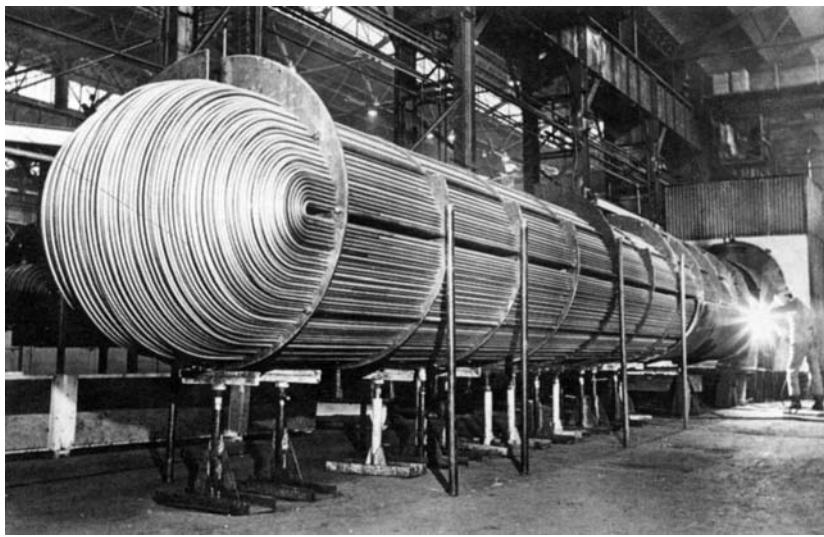


Figure 4

Versatility of Stainless Steels for Corrosive Environments

The versatility of stainless steels for heat exchangers is exemplified by the wide range of alloys available to solve various corrosion problems. For instance, Type 304 is the most widely used stainless steel, but in some aggressive heat exchange environments it may suffer crevice attack, pitting, or stress-corrosion cracking, such as in condensers and coolers using brackish or sea water, or in processes having fairly high chloride contents. When these problems occur, there are other stainless steels more suitable for such environments, and which will eliminate the specific corrosion problem. Consider the following:

Pitting or Crevice Corrosion If pitting or crevice corrosion are due to chlorides, a stainless steel, such as Type 316 or 317 containing 2-3% and 3-4% molybdenum, respectively, is often suitable. For more severe salt water conditions, it may be necessary to consider even higher alloyed candidates from among the following proprietary austenitic stainless steels:

Alloy 6X (20Cr-23Ni-6Mo)⁶

Alloy 216 (19.75Cr-6Ni-8.25Mn-2.5Mo-0.37N)⁷

Nitronic 50 (22Cr-13Ni-5Mn-2.25Mo)⁸

Alloy 20Cb-3 (20Cr-33Ni-2.5Mo-3.5Cu)⁹

Alloy 6X, which is undergoing commercial development, has exhibited excellent resistance to pitting and crevice corrosion in salt water environments, such as in power plant condensers.

All four proprietary alloys mentioned above plus Type 317 performed well in heat exchangers in desalination tests that were conducted over a three-year period in Freeport, Texas.¹⁰ In these tests, deaerated sea water heated to 250F (121C) in a 3000-gallon-per-day desalination test plant was evaporated to produce fresh water.

Stress-Corrosion Cracking The austenitic stainless steels may be subject to stress-corrosion cracking in chloride environments at high temperature—above approximately 130-140F (54-60C)—if tensile stresses are present.

The mechanism of stress-corrosion cracking is not fully understood, but there are methods to minimize the hazard—particularly through material selection. For instance, AISI Type 329 is an austenitic/ferritic stainless steel (25-30% chromium, 3-6% nickel, 1-2% molybdenum) that exhibits superior resistance to chloride stress-corrosion cracking; plus it has a general corrosion and pitting resistance similar to Type 316. Recent studies by Climax Molybdenum Company indicate that Type 317 with 3.5% (minimum) molybdenum has excellent resistance to stress-corrosion cracking. Such an alloy has been shown to have excellent performance in a flue-gas desulfurization environment. Proprietary Alloy 18-18-2 (18Cr-18Ni-2Si)¹¹ is another austenitic stainless steel that has been shown to be highly resistant to stress-corrosion cracking in hot chloride environments, and it exhibits a general corrosion resistance at least equal to Type 304.

The ferritic stainless steels should also be considered when a stress-corrosion cracking potential exists. The immunity of straight-chromium, ferritic stainless steels to chloride stress-corrosion cracking, such as Types 405, 410, and 430, has been known for many years.^{12,13} It has been demonstrated that the corrosion resistance of ferritic stainless steels can be improved by increased chromium and molybdenum contents,^{14,15} and that their ductility, toughness and weldability can be improved by reducing the carbon and nitrogen contents.¹⁶ The recent commercialization of new stainless steel melting and refining processes has made the purer ferritic stainless steels economically attractive.

The specially melted and/or alloyed ferritic stainless steels of particular interest for heat exchanger service can be classified as follows: those with about 18% chromium, which have corrosion resistance qualities similar to that of Type 304, and those with more than 18% chromium, which have resistance to corrosion comparable or superior to that of Type 316. The ferritic stainless steels referred to are not standard AISI grades; they are proprietary alloys.

Three of the proprietary ferritic stainless steels commercially available are:

18Cr+titanium (Alloy 439)¹⁷

18Cr-2Mo¹⁸

26Cr-1Mo¹⁹ (electron beam refined)

In various stages of commercial development are:

26Cr-1 Mo+titanium²⁰

29Cr-4Mo²¹

29Cr-4Mo-2Ni

Commercial development means that—at this writing—the stainless steels mentioned are limited in availability and can be obtained on special order. They are mentioned and should be considered as candidate materials for high-chloride applications, because they show up

TABLE 4

Mechanical Properties at Elevated Temperature	304 & 304L	309 & 309S	310 & 310S	316 & 316L
Creep Strength ksi (MPa) (Load for 1% Elongation in 10,000 hr)				
1000 F (538 C)	20 (137)	16.5 (114)	33 (228)	25 (172)
1100 F (593 C)	12 (83)	12.5 (86)	23 (159)	17.4 (120)
1200 F (649 C)	7.5 (52)	10 (69)	15 (103)	11.6 (80)
1300 F (104 C)	4 (28)	6 (41)	10 (69)	7.5 (52)
1500 F (816 C)	1.5 (10)	3 (21)	3 (21)	2.4 (17)
Scaling Temperature F (C)				
Max. Continuous Service	1650 (899)	1950 (1666)	2050 (1121)	1650 (899)
Max. Intermittent Service	1550 (843)	1850 (1010)	1900 (1038)	1550 (843)

well in service and in standard laboratory tests for pitting and stress-corrosion cracking. The high-chromium ferritic stainless steels have resistance to chlorides previously obtainable only in the high-nickel and titanium alloys.

Intergranular Corrosion Carbide precipitation occurs in some stainless steels when heated and cooled, such as in welding. If this occurs and the stainless steels are subsequently exposed to aggressive environments, intergranular corrosion may occur in the zone affected by the heat. Although this problem can be solved by heat treating the final part, it is generally better to avoid the problem entirely simply by selecting the right stainless steel.

When stainless steels are heated above 1000F (538C) and cooled slowly, the chromium along grain boundaries tends to combine with carbon to form chromium carbides. The resulting chromium-depleted areas adjacent to the carbides have less resistance to corrosion, which paves the way for intergranular attack. The less the carbon content of the steel, or if an alloying element is present that preferentially combines with the carbon (such as columbium, titanium, etc.), chromium carbides do not form, and the grain boundary areas do not become chromium depleted.

The low-carbon grades—Types 304L, 316L, and 317L—are recommended if weldments will be made and exposed to environments in which intergranular attack is likely to be encountered. Likewise for Types 309 or 310, which are selected for high-temperature heat exchange service, there are low-carbon variations, Types 309S and 310S, respectively.

Type 321 stainless (17-19Cr, 9-12Ni) is stabilized against sensitization to intergranular attack by the addition of titanium in proportion to the carbon content, while Types 347 and 348 are stabilized with columbium.

Among the above proprietary stainless steels, Nitronic 50 and Alloy 20Cb-3 are stabilized while Alloy 216 is available with a low carbon content. The electron beam refined Alloy E-Brite 26-1 has an extremely low carbon content while titanium is used as a stabilizer for Alloys 26Cr-1 Mo+titanium and 18Cr+titanium (Alloy 439). Alloy 18Cr-2Mo is stabilized with either titanium or columbium, or with a combination of both alloying elements.

HIGH-TEMPERATURE RESISTANCE

Selecting a stainless steel for high-temperature service is complex because of the many factors involved. Mechanical and physical prop-

.317	321	347 & 346	410	430	446
23 (159) 16.8 (116) 11.2 (77) 6.9 (48) 2.0 (14)	18 (124) 17 (117) 9 (62) 5 (34) 1.5 (10)	32 (221) 23 (159) 16 (110) 10 (69) 2 (14)	11.5 (79) 4.3 (30) 2 (14) 1.5 (10) —	8.5 (59) 4.7 (32) 2.6 (18) 1.4 (10) —	6.4 (44) 2.9 (20) 1.4 (10) 0.6 (4) 0.4 (3)
1700 (927) 1600 (871)	1650 (899) 1550 (843)	1650 (899) 1550 (843)	1300 (704) 1450 (788)	1550 (843) 1650 (899)	1950 (1666) 2050 (1121)

erties as well as corrosion resistance must be considered.

For instance, specific interest in gas-metal reactions at elevated temperatures has been generated by use of higher temperatures and more corrosive fuels and by conditions associated with some of the newer chemical processes. Most of the activity in this field has centred around oxidation by air.

Of the three major components in stainless steels, chromium is the most important in determining the degree of oxidation resistance under constant temperature conditions (Figure 5). Table 4 gives both scaling resistance and strength properties of those stainless steels used for heat exchange service at elevated temperature.

As the high-temperature environment becomes contaminated by the presence of various compounds of sulfur, carbon, hydrogen, and the halogens, the problem of materials selection becomes even more complex. Therefore, special care should be taken to assure selection of the correct type of stainless steel. A fairly comprehensive discussion of the application of the austenitic chromium-nickel stainless steels in high-temperature environments is found in reference 22.

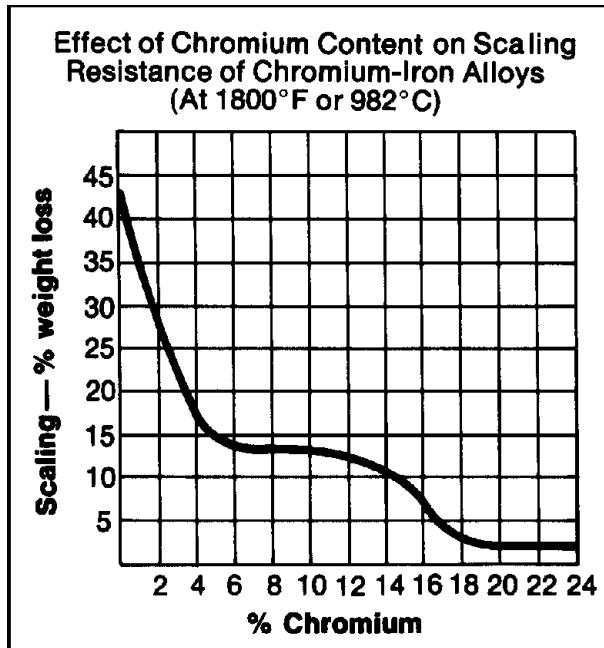


Figure 5

Source: Stainless Steel Industry Data

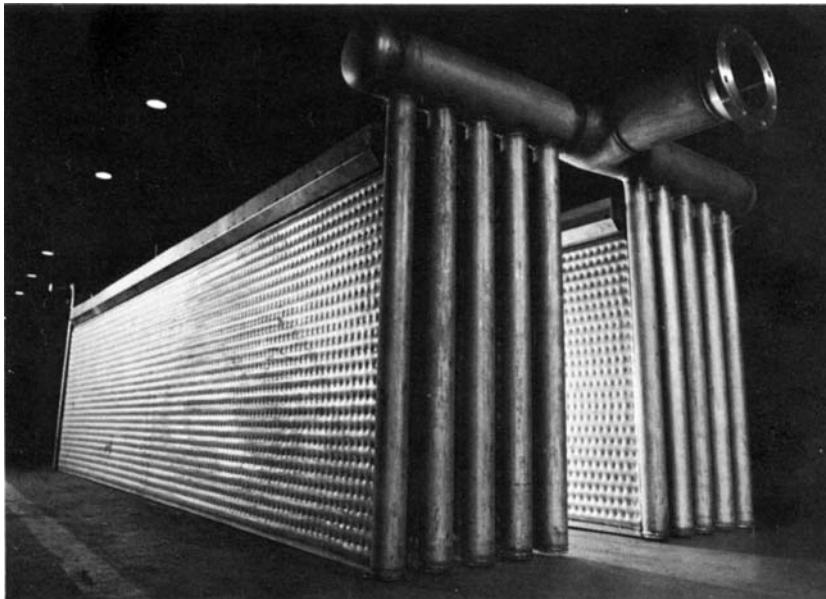


Figure 6
Paul Mueller Company

LOW-TEMPERATURE RESISTANCE

Of primary importance to the development of the world's natural gas supplies is the storage and handling of liquid natural gas (LNG). Heat exchangers have a role in LNG processing, such as the unit shown in Figure 6, and in other cryogenic applications.

Austenitic stainless steels are the most widely used materials in cryogenic applications, especially Type 304, because of their excellent toughness and ductility. Not only does Type 304 remain tough at LNG temperatures-minus 260F (-162C), but it retains these properties for use with liquid hydrogen (-423F or -253C) and liquid helium at -452F (-268C). Its thermal conductivity is also suitable for low-temperature use. Table 5 shows low-temperature mechanical properties of several stainless steels used in cryogenic service.

TABLE 5
Cryogenic Properties of Stainless Steel

AISI TYPE	Test Temperature		Yield 0.2%	Strength Offset	Tensile Strength	% Elongation in 2" (5.08 cm)	% Reduction of Area	Izod ft-lb	Impact kg-m	
	°F	°C	ksi	kg/mm ²	ksi kg/mm ²					
304	-40	-40	34.0	24.0	155.0	109.0	47.0	64.0	110	15.2
	-80	-62	34.0	24.0	170.0	120.0	39.0	63.0	110	15.2
	-320	-196	39.0	27.0	221.0	155.0	40.0	55.0	110	15.2
	-423	-252	50.0	35.0	243.0	171.0	40.0	50.0	110	15.2
316	-40	-40	41.0	29.0	104.0	73.0	59.0	75.0	110	15.2
	-80	-62	44.0	31.0	118.0	83.0	57.0	73.0	110	15.2
	-320	-196	75.0	53.0	185.0	130.0	59.0	76.0	Not Available	
	-423	-252	84.0	59.0	210.0	148.0	52.0	60.0	Not Available	
430	-40	-40	41.0	29.0	76.0	53.0	36.0	72.0	10	1.4
	-80	-62	44.0	31.0	81.0	57.0	36.0	70.0	8	1.1
	-320	-196	88.0	62.0	92.0	65.0	2.0	4.0	2	0.3
410	-40	-40	90.0	63.0	122.0	86.0	23.0	64.0	25	3.5
	-80	-62	94.0	66.0	128.0	90.0	22.0	60.0	25	3.5
	-320	-196	148.0	104.0	158.0	111.0	10.0	11.0	5	0.7

Source: Stainless Steel Industry Data

HEAT TRANSFER PROPERTIES OF STAINLESS STEELS

The heat transfer properties of materials used in the construction of heat exchangers cannot be based exclusively on the thermal conductivity of the metal itself. If this were the case, stainless steels would lose out in most applications because published "text book" figures place stainless steels in an unfavorable position in comparison with other metals.

The power generation industry, however, after very carefully analyzing the heat transfer characteristics of heat exchanger materials, has conclusively demonstrated that stainless steels are superior to other metals when it comes to performance in actual service.

For instance, the curves in Figure 7 show the results of a two-year test of overall heat transfer coefficient of two materials in identical heat exchanger service. In the early stages, the relative performance of both materials corresponded to values established by the Heat Exchange Institute. However, in only 240 days, the overall heat transfer rate of the stainless steel was found to surpass that of the Admiralty brass. The heat transfer rate for both materials deteriorated with time, but that of the Admiralty brass deteriorated more rapidly because of the action of both fouling and corrosion, while the stainless steel was affected only by fouling.²³

Overall Heat Transfer vs. Exposure Time

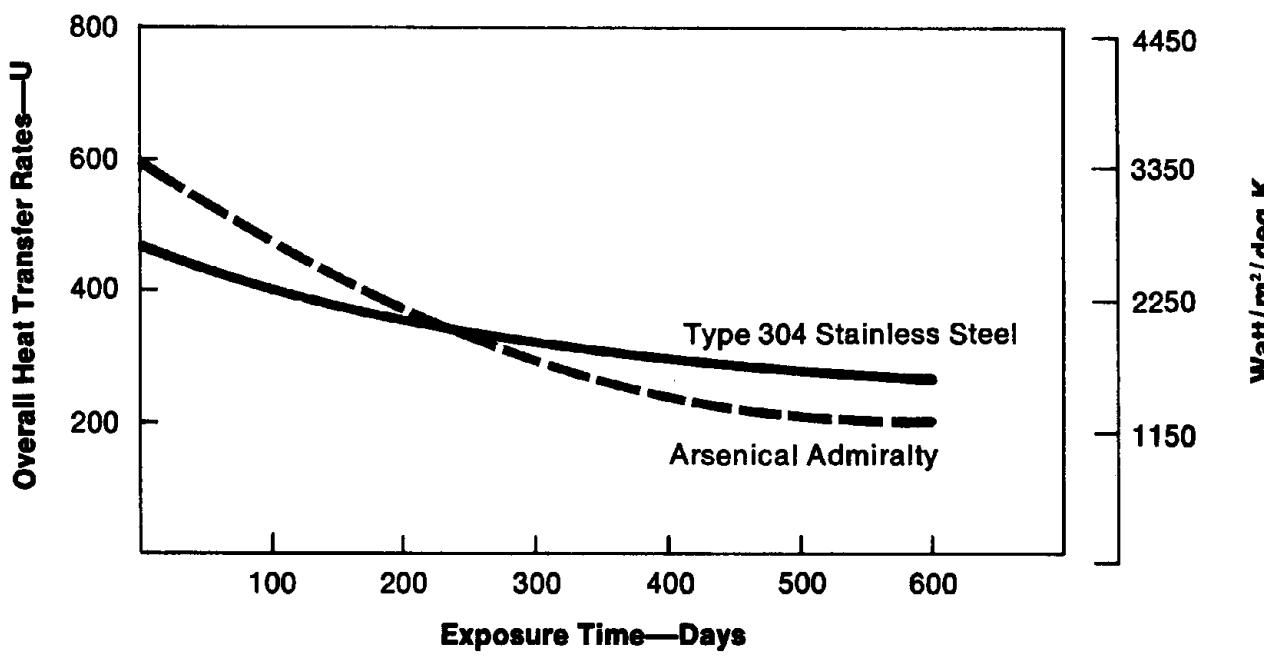


Figure 7

Source: McAllister²³

Similar results are suggested by Schrieber et al, as shown in Figures 8 and 9. Heat transfer rates of four tubing materials were compared over a 70-day period at a desalination test facility in Texas. In each case, the heat exchange performance of stainless steel showed less degradation than the other three metals exposed to identical conditions.

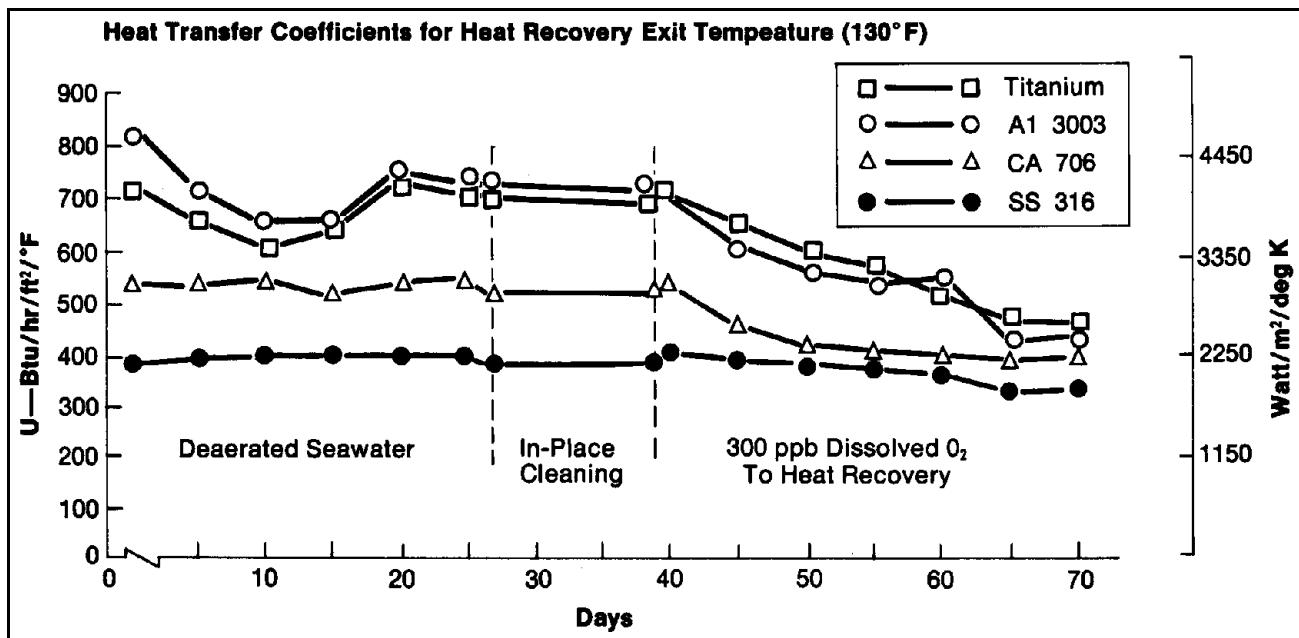


Figure 8

Source: Schrieber²⁴

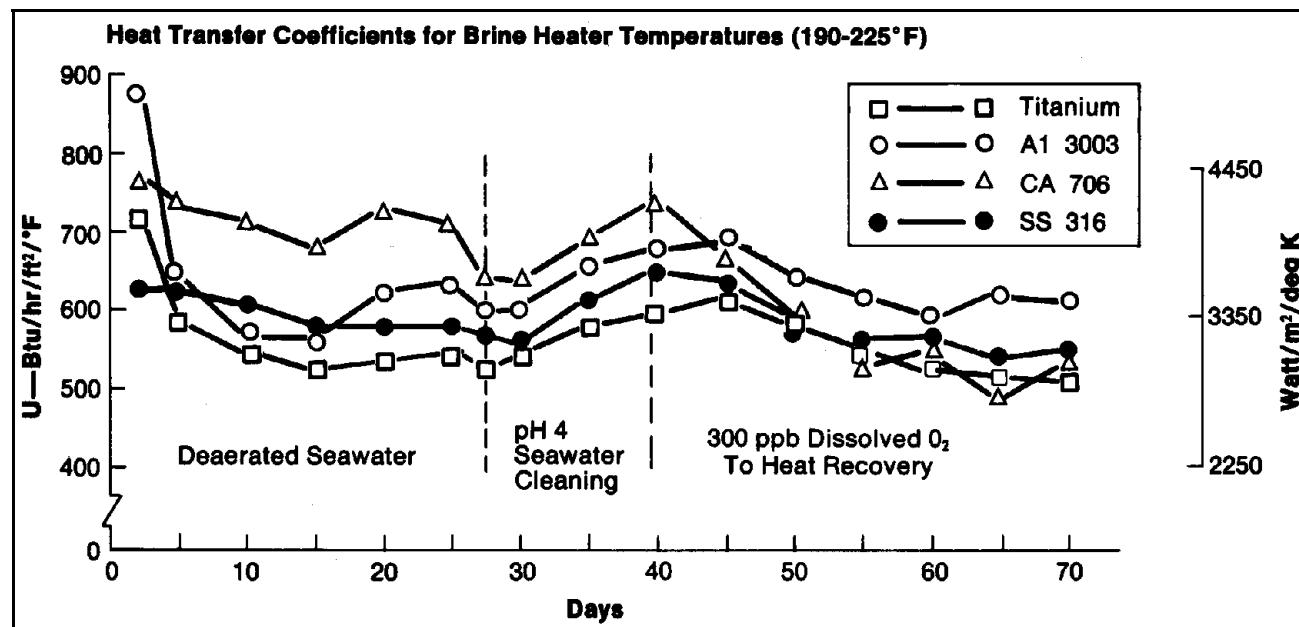


Figure 9

Source: Schrieber²⁴

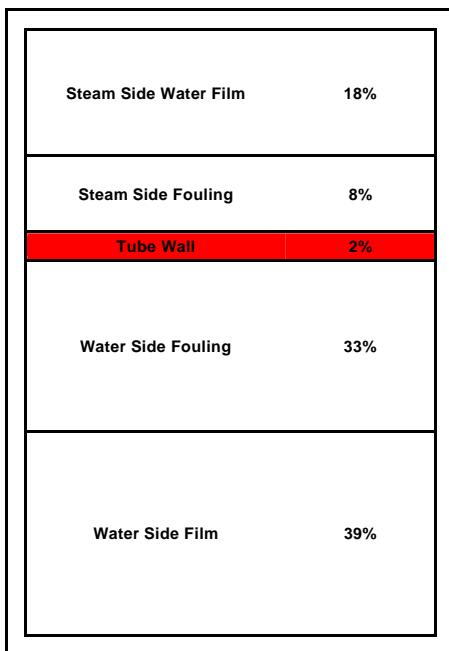


Figure 10

Figure 10 is a graphic representation illustrating the various factors affecting resistance to heat transfer in actual service. It is obvious that the films and scale that form on either side of the heat transfer surface affect overall performance to a far greater degree than the metal wall, which accounts for only 2% of the total resistance to heat flow.

Film resistance is dependent on the type of fluid involved as well as its velocity (Table 6). Scale resistance is related to corrosion of the metal and the buildup of fouling deposits. Since corrosion is at a minimum with stainless steel and it requires less cleaning, in practice there would be less difference among the four metals than indicated. Moreover, the values in the table are based on equal thickness. On the basis of equal strength, the stainless steel could be used in a thinner wall, which in turn increases its overall heat transfer efficiency.

TABLE 6
Effect of Metal Conductivity on "U" Values

Application	Material	Film Coefficients Btu/hr sq ft F h_o h_i	Thermal Conductivity of Metal Btu/hr sq ft F/in.	Metal Thickness Inch	U Value Btu/hr sq ft F
Heating Water with Saturated Steam	Copper	300 1000	2680	0.0747	229
	Aluminum	300 1000	1570	0.0747	228
	Carbon Steel	300 1000	460	0.0747	223
	Stainless Steel	300 1000	105	0.0747	198
Heating Air with Saturated Steam	Copper	5 1000	2680	0.0747	4.98
	Aluminum	5 1000	1570	0.0747	4.97
	Carbon Steel	5 1000	460	0.0747	4.97
	Stainless Steel	5 1000	105	0.0747	4.96

where h_o = outside fluid film heat-transfer coefficient
 h_i = inside fluid film heat-transfer coefficient
stainless steel is any grade in 300 series

Source: Tranter Mfg., Inc.

$$U = \frac{1}{\frac{1}{h_0} + \frac{\text{thickness of metal wall}}{\text{thermal conductivity}} + \frac{1}{h_i}}$$

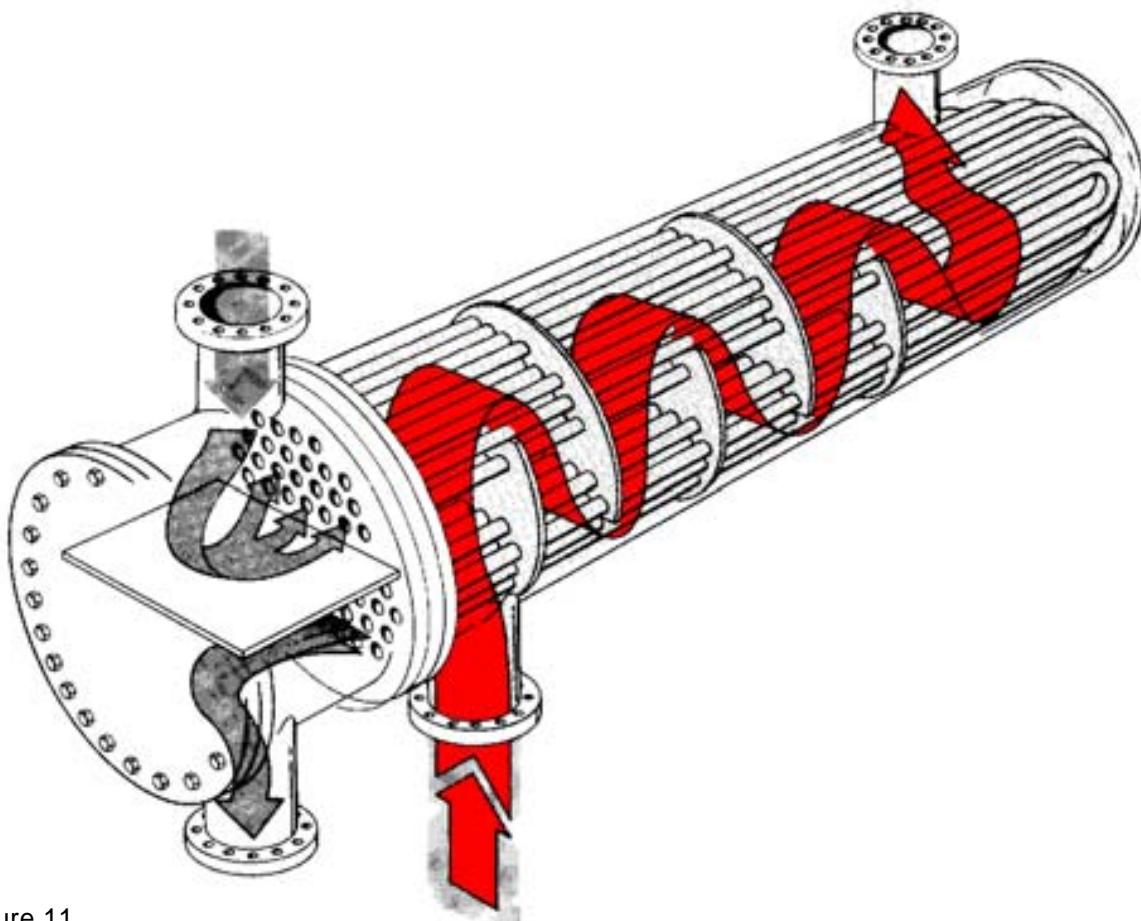


Figure 11

CLEANLINESS OF STAINLESS STEELS

Two additional qualities of stainless steels that are important to heat exchanger service are cleanability and freedom from fouling.

Most stainless steels in heat exchanger service resist chemical and biological fouling. Because the metal often does not suffer general corrosive attack, surfaces remain smooth and bright offering little opportunity for accumulation of fouling or deposits. If fouling should occur, cleaning can be performed either chemically or mechanically.

For chemical cleaning, the best acids to use are citric, formic, or sulfamic. These should be used under the supervision of qualified personnel. **WARNING:** Hydrochloric or inhibited hydrochloric acids should not be used with stainless steels since this acid can be extremely corrosive to all stainless steels.

A variety of mechanical means are also available for cleaning tubular heat exchangers, including one or two continuous, in-service processes. Extreme high-pressure water is also effective for cleaning both inside and outside tubular surfaces and exterior surfaces of flat-plate type exchangers.

DESIGN VERSATILITY

Stainless steels are available as sheet, strip, plate, bar, wire, tubing, and pipe. This variety of product forms, the wide range of sizes

in which these forms are available, and the fabrication versatility of stainless steels provide manufacturers with unlimited flexibility. Heat exchanger manufacturers-specialists or job-shop fabricators-can produce equipment to meet most process requirements.

Shell-and-tube heat exchangers, for instance, shown by the examples in Figures 11, 12, and 13 have long been the standard design for most applications. These units use practically all of the mill forms mentioned above. Tubing is the heat exchange surface. Plate is used for tubesheets, heads, shells, and flanges. Bar is forged into fittings, such as valve stems, while wire is formed into fasteners. Pipe is used for connections, and sheet is used for baffles and tube supports. The unit in Figure 13, for example, is Type 316L stainless steel throughout.

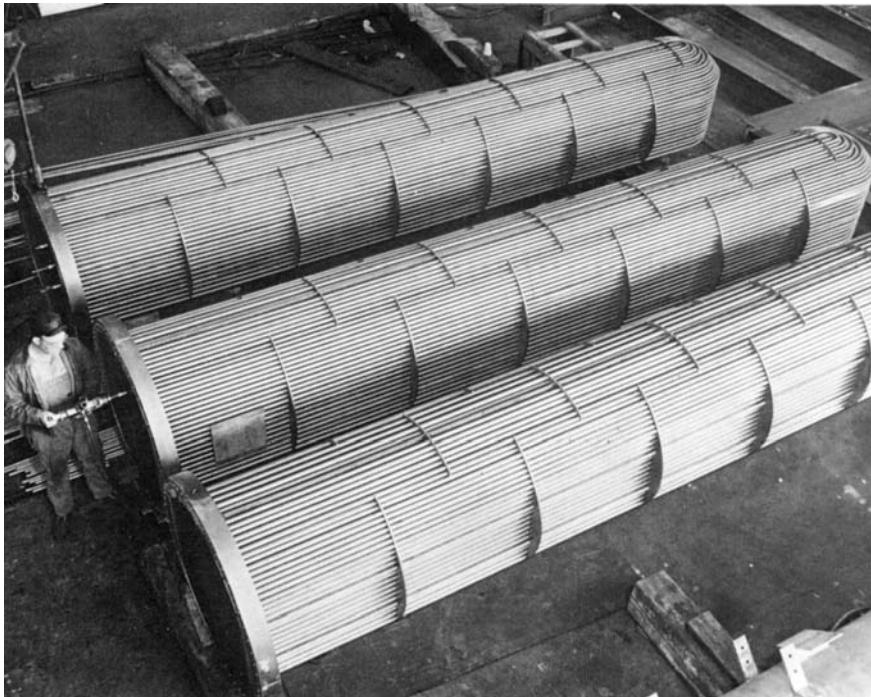


Figure 12

Fluor Corporation

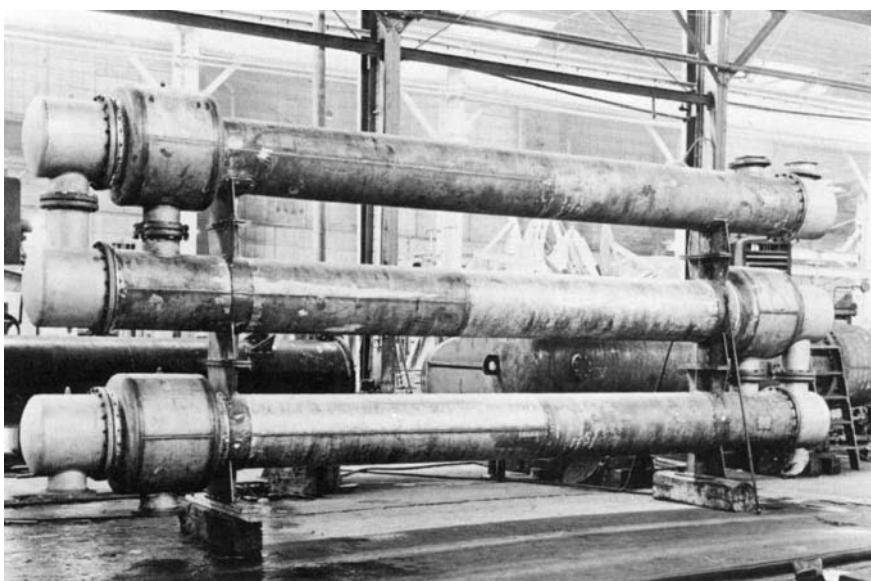


Figure 13

Struthers Wells Corporation

While most designers are acquainted with the conventional type of shell-and-tube heat exchanger, there are lesser-known types that offer advantages in some applications, with respect to versatility, efficiency, or compactness. For instance, many heat exchange surfaces are fabricated from two sheets welded to form a series of passes through which a heating or cooling medium flows. "Platecoil" and "Temp-Plate" are two trade names for these plate-type exchangers. The plates can either be embossed prior to fabrication as shown in Figure 14, or the assembled plate exchanger can be expanded by pressure after fabrication, such as the design in Figure 15.

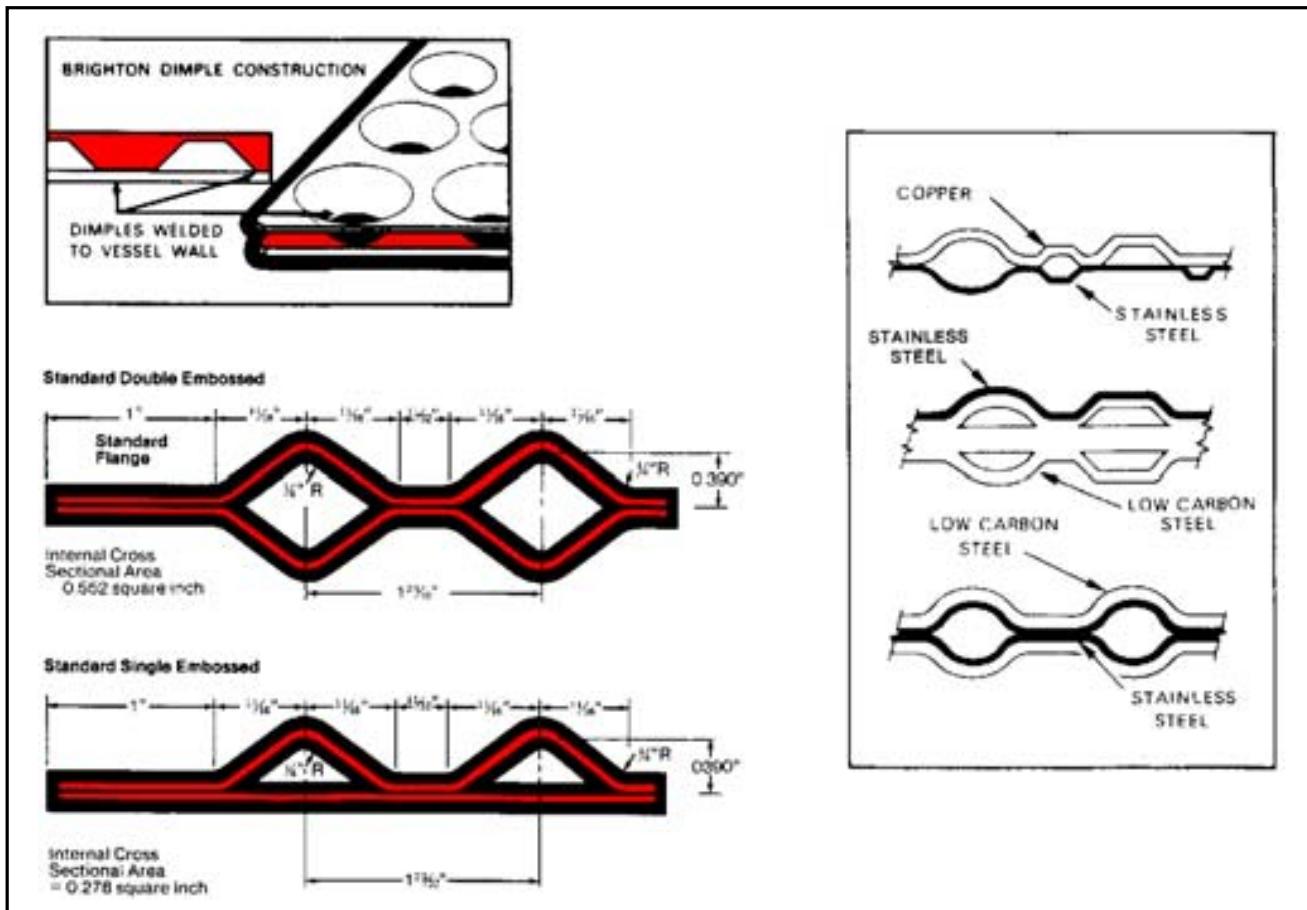


Figure 14
Brighton Corporation, Tranter Mfg. Inc., Texas Instruments

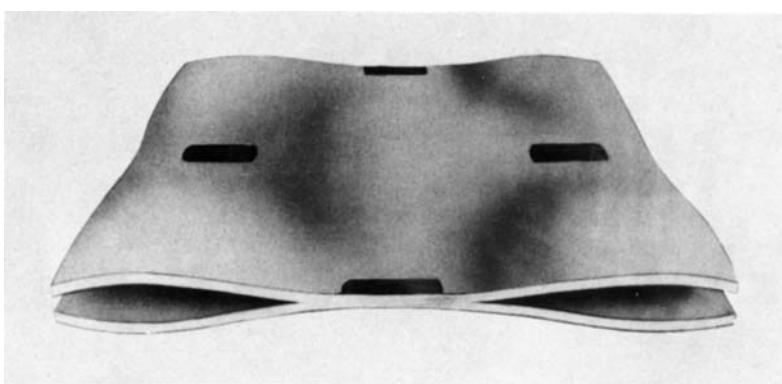


Figure 15
Paul Mueller Company

The most frequent use of the flat heat transfer surfaces is for immersion in tanks for the heating or cooling of solutions, such as in Figures 16 and 17, or as evaporator surfaces where liquids cascade down the outside.

In many applications, however, the transfer surface is integral with the vessel itself, actually being the vessel wall, such as the jacketed vessels shown in Figures 18 and 19.

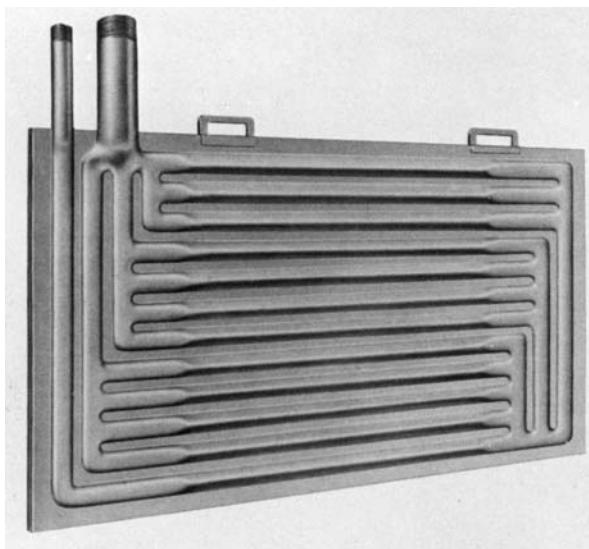


Figure 16
Tranter Mfg. Inc.

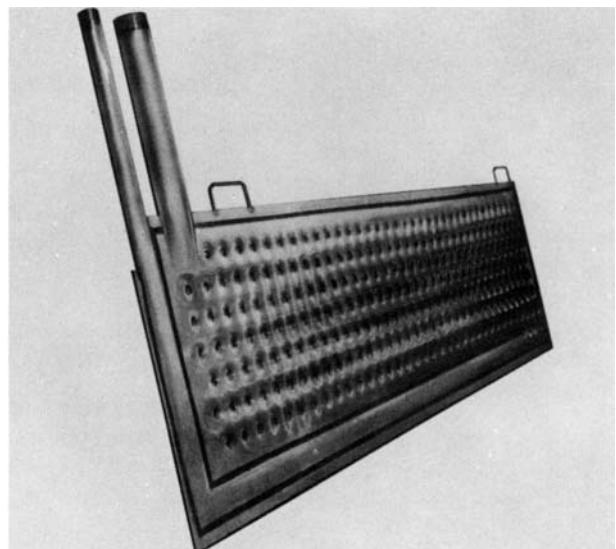


Figure 17
Paul Mueller Company



Figure 18
Paul Mueller Company

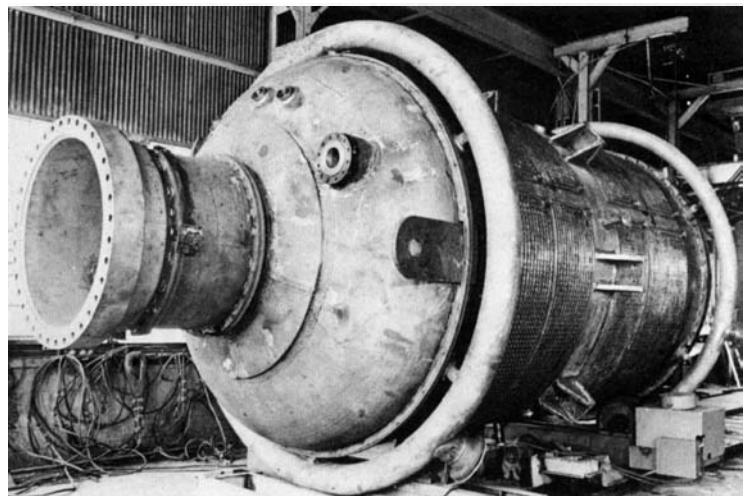


Figure 19
Panhandle Manufacturing, Inc.
Subsidiary of Tranter Mfg. Inc.

Plate-type exchangers are also constructed of alternating layers of thin plates and corrugated sections, such as the one shown in Figure 20. They are similar in appearance to plate-and-frame filters. Integral channel and manifold sections enclose the open ends. The process material flows into the corrugated openings.

Plate exchangers give better heat-transfer efficiencies than shell-and-tube units; also the plate type has a lower pressure drop at the same heat transfer coefficient. In Figure 21, a plate heat exchanger does double duty, cooling condensate from a pulp mill digester and heating incoming process water. The digester blow-down is collected and condensed to eliminate one source of malodorous compounds in a pulp mill while the heat is reclaimed for energy conservation. Figure 22 shows a plate heat exchanger used in steel mill operations.

Spiral heat exchangers in essence consist of one spiral wrapped around another, as illustrated in Figure 23, so the same flow characteristics are obtained for each medium. Its advantages include compact design, ability to handle sludges and slurries with low fouling incidence, and adaptability for liquid-to-liquid or liquid-to-vapour service. Figure 24 shows two spiral exchangers, one vertical and the other horizontal. The vertical unit cools phenol while the horizontal unit cools condensate for two gas atmosphere generators. Both are constructed of Type 316 stainless steel.

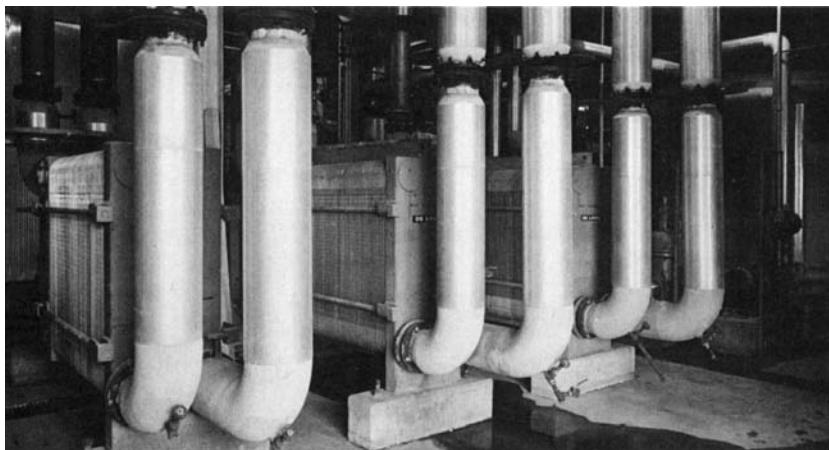


Figure 21
American Heat Reclaiming Corporation

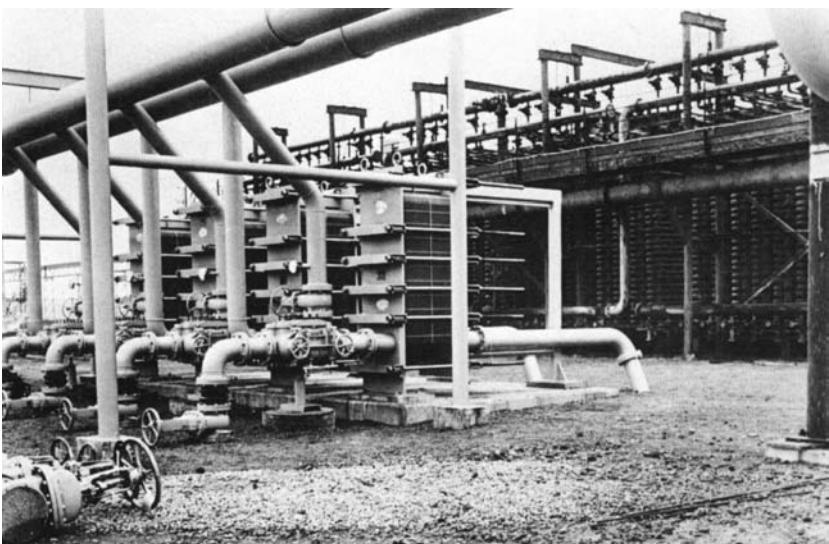
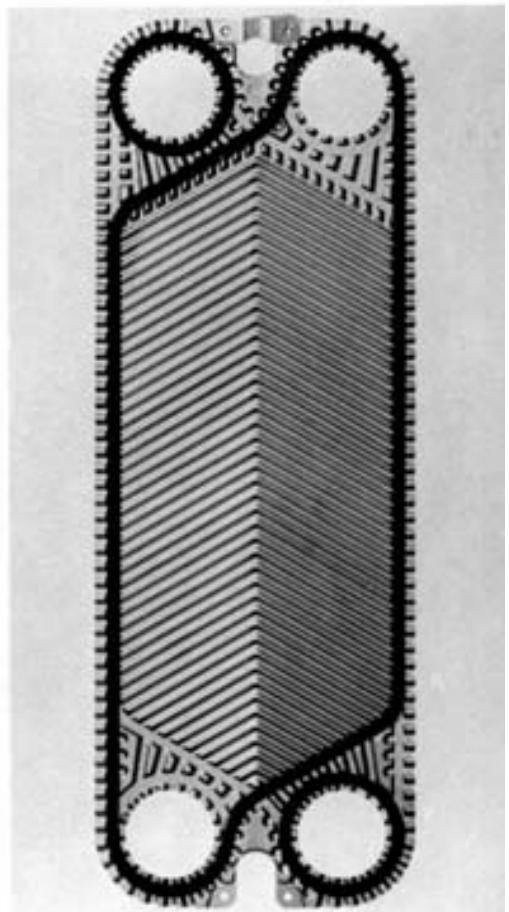
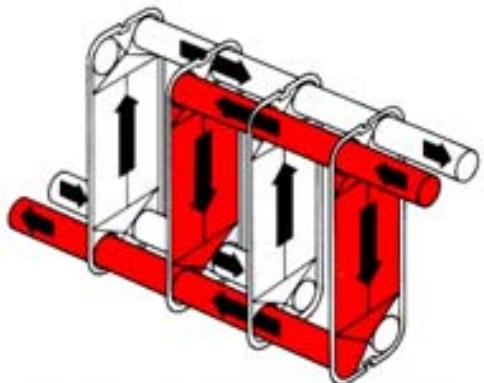
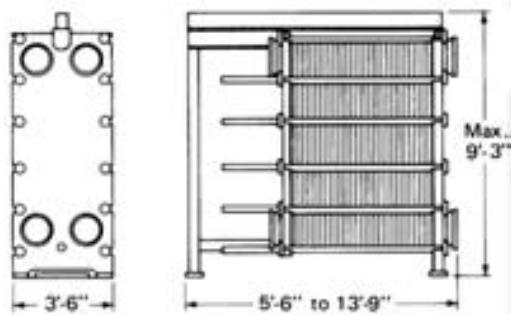


Figure 22
American Heat Reclaiming Corporation

Figure 20
American Heat Reclaiming Corporation



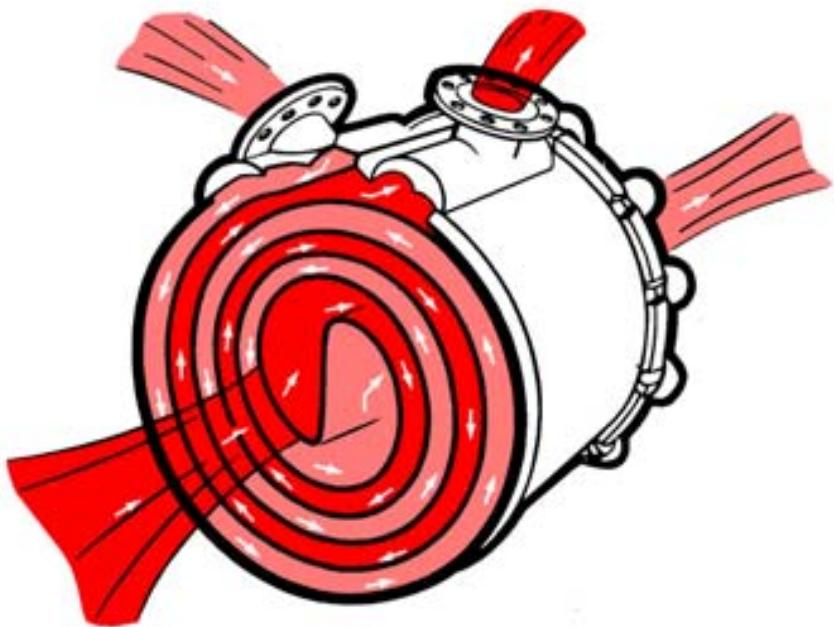


Figure 23

American Heat Reclaiming Corporation

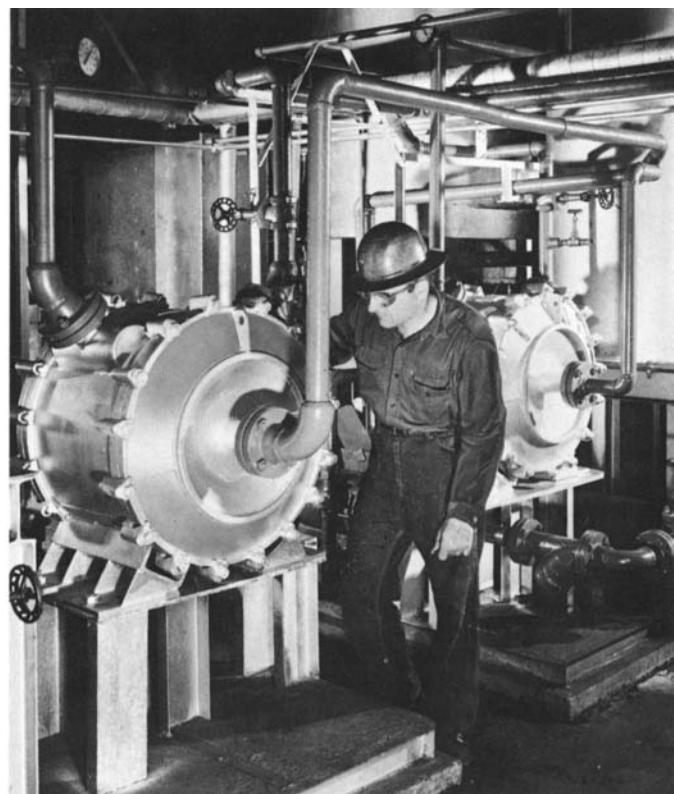
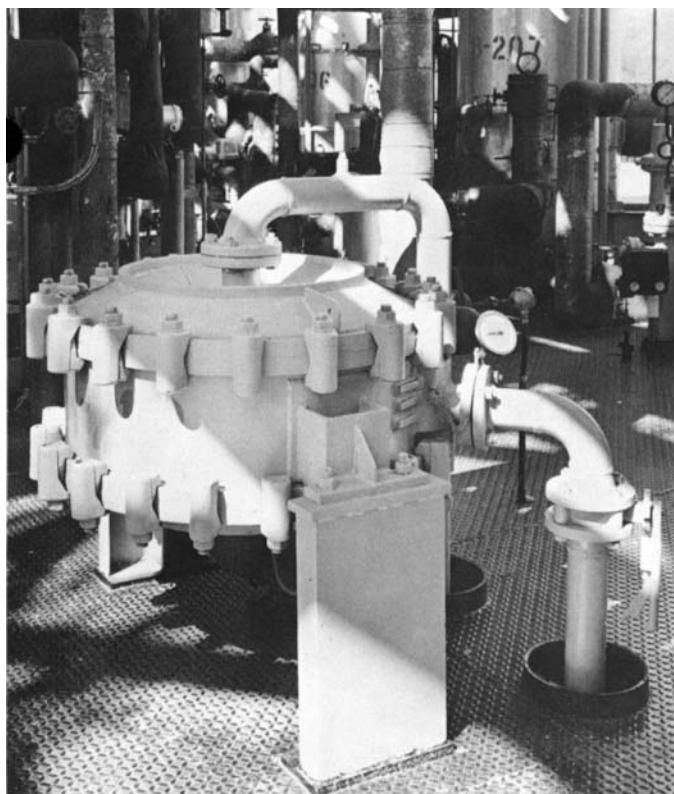


Figure 24

American Heat Reclaiming Corporation

To increase the heat transfer performance of an exchanger using tubing, the surfaces of stainless steel tubing can be "enhanced." Tubing can be spirally indented or double fluted, which tends to alter the flow characteristics around the tube surface both inside and out (Figure 25). Integral-finned tubing is available in which fins are formed circumferentially on the outside surface (Figure 26), increasing the external surface area about 2.5 times. Fins can also be attached to stainless tubing to increase surface area, especially useful for air coolers. Bi-metallic tubing is also available to provide answers to dual corrosion or erosion problems that cannot be solved by one material alone (Figure 27).

Tube-in-tube exchangers are also used, such as in food processing and sewage treatment. One such unit is shown in Figure 28.

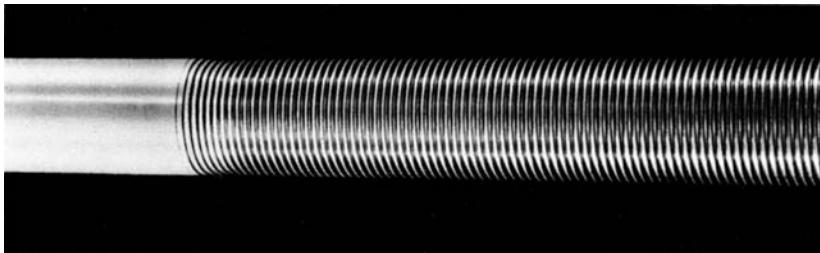


Figure 25

Integral-Finned tubing offers 2.5 times the external surface area of equivalent-diameter, bare-surface tubing. It is manufactured to ASTM A-498 from 0.500" OD to 1.000" OD, in wall thicknesses ranging from 0.049" (18 BWG) to 0.083" (14 BWG), and in lengths up to 50 feet.

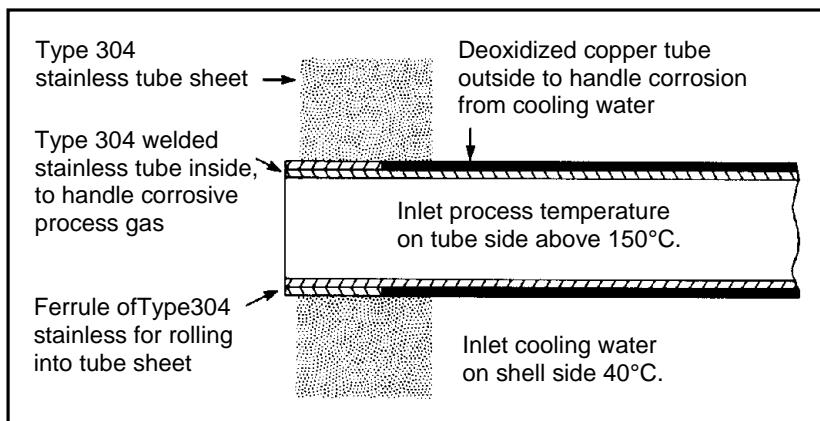


Figure 26

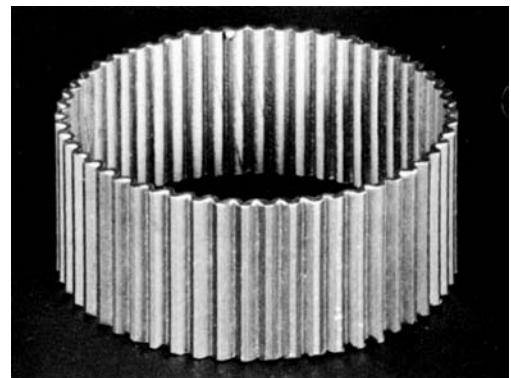
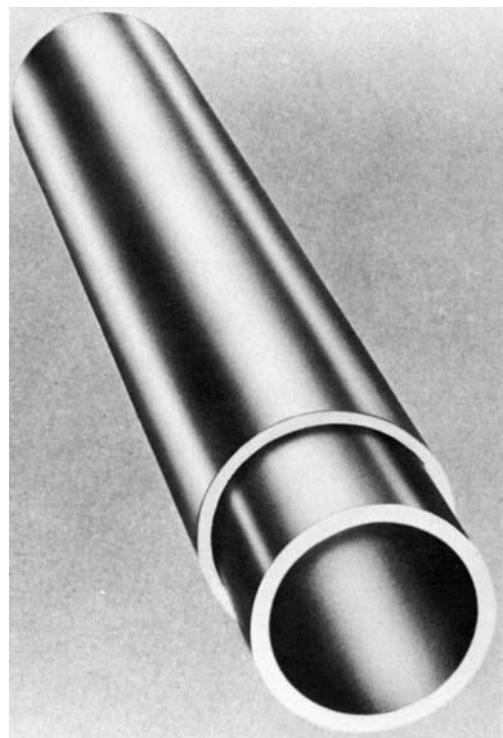


Figure 25

For improved heat transfer, stainless steel tubing can be enhanced by commercially available techniques—such as spiral indentation or double fluting. In one falling-film evaporator test comparing fluted- and nonfluted stainless steel tubes, the heat transfer of the fluted tube was about 45 percent better. A small section of double-fluted stainless is shown.



Bi-Metallic tubing is the single answer to dual corrosion and erosion problems in condensers. It is available as fully finished stainless tubing mechanically bonded to the entire ID or OD surface of either carbon, brass, copper, stainless, or other alloy tubing.

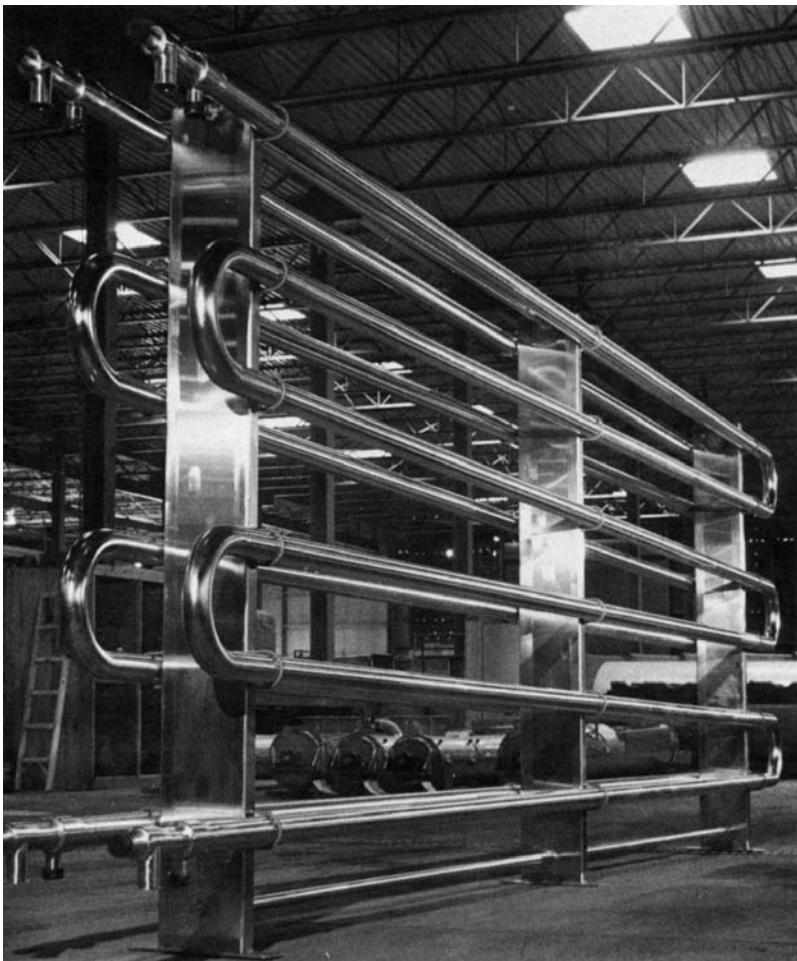
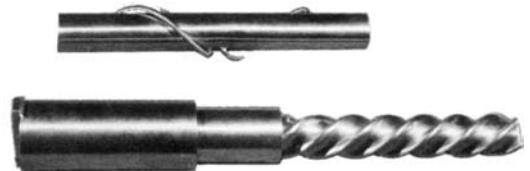


Figure 28
Paul Mueller Company



STAINLESS STEELS ARE ECONOMICAL

The following outline can help in evaluating the economics of candidate materials for heat exchange service. A cardinal rule is that no material should be eliminated from consideration on the basis of its initial purchase price alone.

1. List all materials suitable for the process.
2. For each material, list sizes and quantities based on corrosion resistance, oxidation resistance, strength, and heat transfer.
3. Estimate total cost for each material, including fabrication costs, capitalized costs, etc.
4. Is intended unit life a factor; will the process be phased out after a given number of years? If so, a material that corresponds to this unit life should be given strong consideration.
5. Calculate replacement and maintenance costs for each material, including costly production losses due to shutdowns.
6. Compile and compare costs.
7. Eliminate all but the most economical materials.
8. Work the remaining materials through the process unit design with a complete economic evaluation.
10. Pick the material that yields the best return on investment.

At the design level, consult a stainless steel supplier. A list of the companies represented on the Committee of Stainless Steel Producers appears on the back cover of this publication.

COMMENTS ON INSTALLATION AND MAINTENANCE

Tube-rolling practices and tolerances recommended by the Tubular Exchanger Manufacturers Association (TEMA) should be followed, to avoid problems of over-rolling, such as described in the example on food processing (Page 32). In that application, the tubesheet hole sizes were as much as .035" (0.889mm) above the nominal tube size. For a 2"-diameter (50.8mm) tube, TEMA recommends a hole diameter of 2.018" (+ .003" or - .007") (51.26mm). In the food processing example, the tubesheet hole oversize was twice what it should have been.

When any shell-and-tube heat exchanger is to be retubed, the holes in the tubesheets should be carefully measured and the sizes transmitted to potential tube suppliers in order to obtain tubes of optimum size, remembering, of course, that tubing is manufactured to ASTM specifications.

Protrusion of tubes above the top tubesheet of a vertical exchanger should be avoided. If tubes are too long and a protrusion results, it should be applied to the bottom tubesheet. This measure will help eliminate areas where chlorides or other aggressive elements can be trapped and concentrated, and it will facilitate draining when the unit is shut down.

The area beneath the top tubesheet of vertical heat exchangers is another potential trouble spot, as illustrated by the two drawings in Figure 29. If a process liquid or cooling water is on the shell side and the heat source on the tube side, this area has potential for higher temperatures or alternate wetting and drying-both of which can increase the potential for corrosion. (Stress-corrosion cracking of austenitic stainless steels is common under these conditions.) The lower drawing shows how to properly port this area to prevent such problems.

The time during which a heat exchanger is down, in many instances, may be more critical in terms of corrosion than when the unit is in operation. If the process stream is allowed to remain without motion in contact with heater tubes, temperatures can increase, aggressive solutions can concentrate, and corrosive conditions can become more severe. Prompt draining and flushing followed by thorough drying should be standard operating procedure for shutting down any heat exchanger.

There are, of course, situations in which the above practices cannot be applied. One example is in reheater exchangers following wet scrubbers in coal-fired power plants. During an outage, it may be desirable to keep steam flowing through reheater tubes in order to keep temperatures on tube surfaces above the dewpoint of various constituents in the flue gas. In SO₂ scrubbers, condensing sulfuric or sulfuric acids can lead to early failure of reheater tubes (Figure 30).

Removing scale from heat exchanger surfaces often necessitates the use of acids. As previously stated, hydrochloric acid (inhibited or not) should not be used. With any acid, care should be exercised and it's always advisable to consult with the metallurgist or corrosion engineer. For example, Type 304 stainless steel tubing may be ideal for a certain process. However, if acid cleaning is used, tubing that has been welded to the tube sheet may suffer localized attack in the weld area.

Since the corrosive effect of any acid is dependent on the temperature, be sure both acid and tubes are cool. If it is necessary to use hot acid cleaning, heat the acid prior to pumping into the heat exchanger so the metal surface will be the same temperature. If steam is used to heat the acid in the exchanger, the metal temperature is approximately that of the high temperature steam and the corrosion rate can be very high.



Figure 30a
Kansas City Power & Light Company

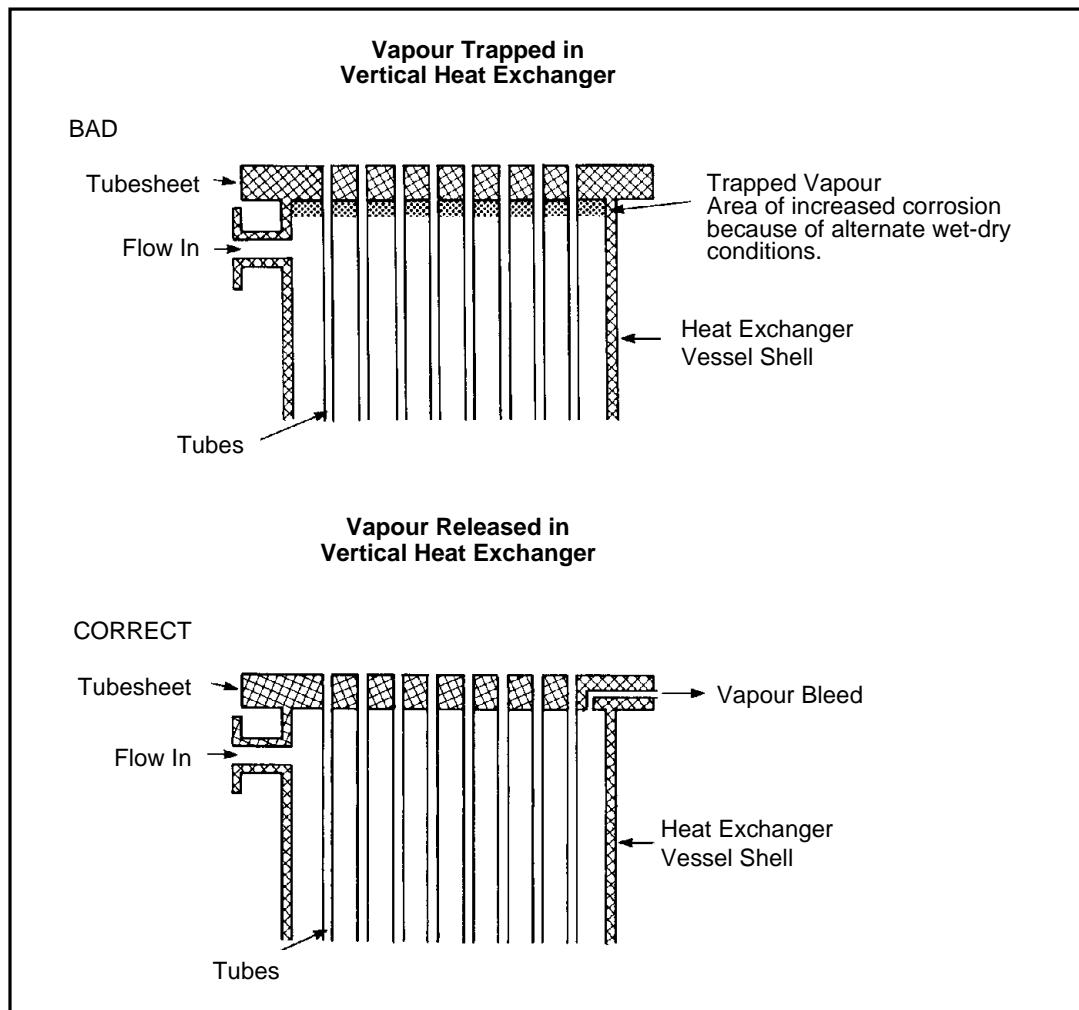


Figure 29

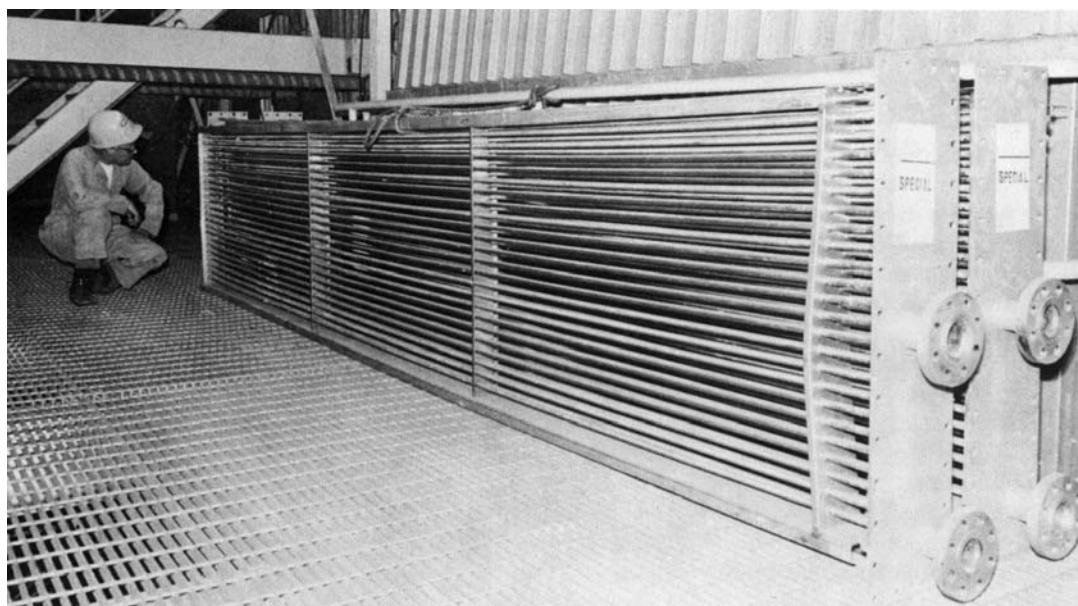


Figure 30b
Kansas City Power & Light Company

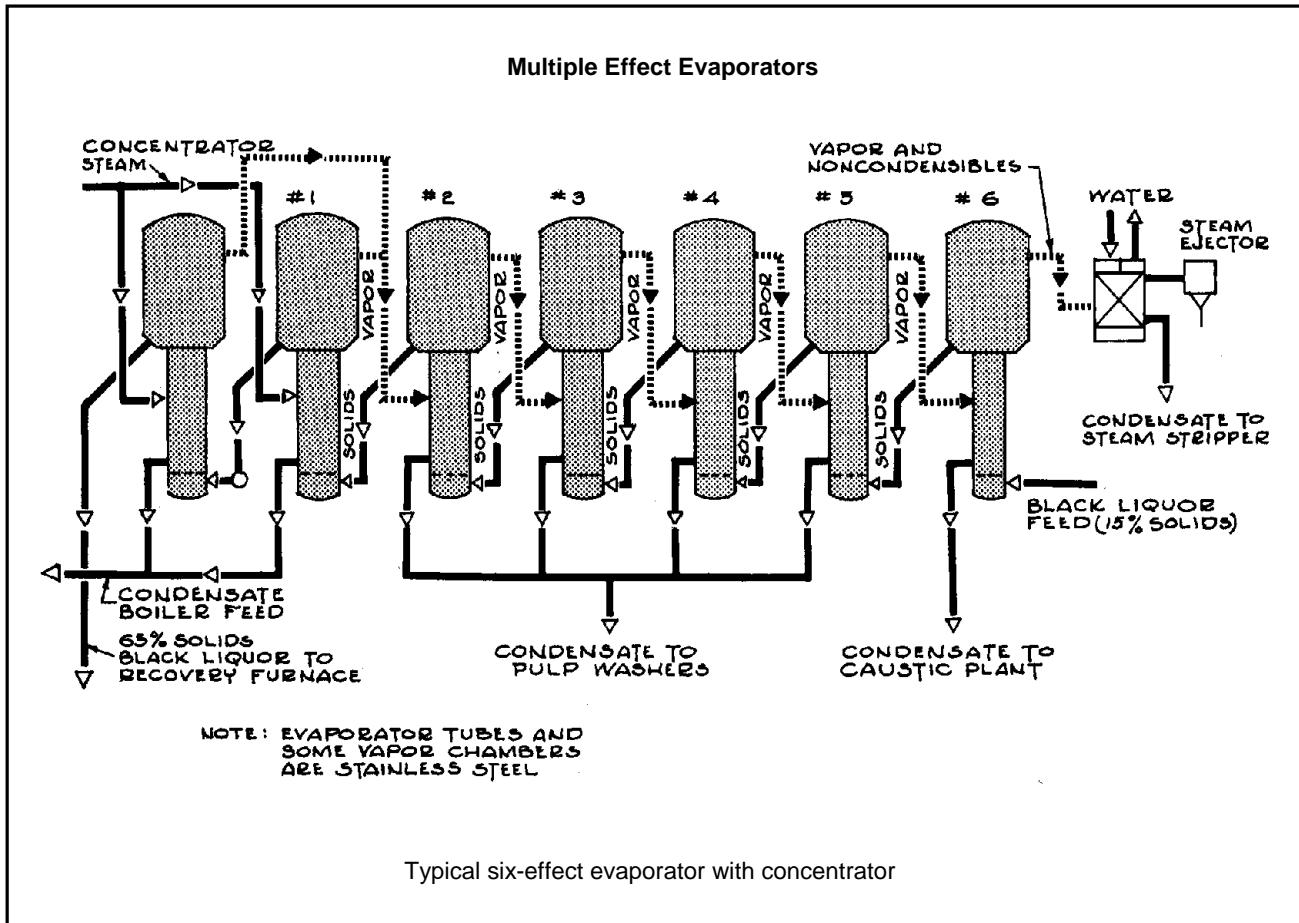


Figure 31

PULP AND PAPER

In the Kraft process a solution of sodium sulfide in caustic soda digests the wood binder, lignin, yielding a fibrous pulp that is converted into coarse Kraft or very fine white papers. Following digestion of the lignin, the cooking chemicals (referred to as black liquor) are washed out of the pulp, concentrated, and burned in a recovery furnace. The organic material burns away leaving molten sodium carbonate and sodium sulfide, which after slaking with water are recausticized with lime and recycled to the pulp digester. The Kraft process is popular in the United States because it can be used for pulping almost any wood type, it yields fibers of comparatively high strength and chemical recovery improves plant operating economics.

There are numerous heat exchanger applications in Kraft pulp and paper mills for heating pulping chemicals, for concentrating black liquor, for condensing odorous vapours in air pollution control systems, and for recovering process heat. The design of these heat exchangers, however, is as varied as their applications; including flat plate, spiral, and the more conventional shell-and-tube types.

An important feature of the Kraft process is the recovery of heat and pulping chemicals by burning black liquor in a furnace. However, in order to support combustion, the liquor must first be concentrated to about 65% solids, usually in a series of five or six vertical-tube evaporators (Figures 31, 32, and 33). In a multiple effect unit, it is common practice to tube the entire series of evaporators with stainless steel,



Figure 32
Ecodyne Unitech Division

either Type 304 or 316 depending upon conditions. Stainless steels were originally used only in the first two and last two evaporators to help reduce problems with scale. However, mills are increasing their efforts to contain pollution discharges. Strong wastes from spills are being piped to evaporators, consequently exposing them to more severe corrosive conditions. Now, even the shells and vapour chambers are being fabricated of Type 304 or 316.

One of the principal reasons for using stainless steels in pulp and paper mill heat exchangers is to prevent iron contamination or discoloration of chemical pulps, which are made into paper. Stainless steels are also used for their resistance to oxidation at elevated temperature, low sparking characteristics (especially important where turpentine vapours, acetone, alcohol, and other hazardous vapours are present), and light-weight design potential. Stainless steel pipe runs and heat exchangers at various plant elevations require less supporting structure.

Liquor heaters in both kraft and sulfite mills are another significant

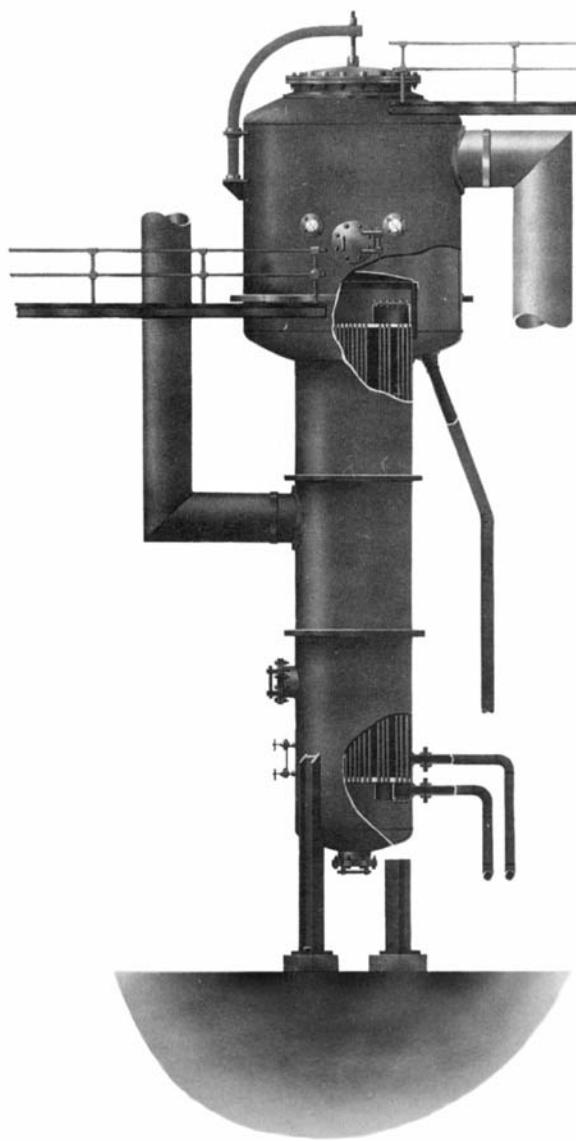


Figure 33
Ecodyne Unitech Division

FOOD PROCESSING

Condensers and other heat exchanger systems are often the most critical components in food processing lines. It is here that heat concentration is most intense and where thin-walled tubing is most vulnerable to corrosive elements. Welded stainless steel tubing is saving many food processing plants from interrupted production and costly repairs because of its ability to resist corrosive damage.

For example, conventional materials for heat exchanger tubing in cane and beet sugar refineries used to be carbon steel and copper-base alloys. The copper alloys, however, were subject to cracking by the ammonia present in sugar solutions. This problem was aggravated by increased use of ammonium phosphate fertilizers.

To eliminate the problem, sugar refineries switched to economical, thin-wall stainless steel tubing, specifically Types 304 and 316, which resist attack by ammonia or carbon dioxide. In addition to excellent corrosion resistance, these austenitic stainless steel tubes resist abrasion from silt-like substances in sugar solution by-products. They also resist scale build-up. (Figure 34)

Although stainless has a heat conductivity only 1/7 that of brass and 1/3 of carbon steel, experience demonstrated that scale buildup in sugar heat exchanger tube surfaces is more important than the thermal conductivity of the metal itself. Stainless tends to reduce the adherence of such deposits.

Stainless steels are not immune to corrosion, however, and while problems are few in sugar refining, proper installation and cleaning techniques are necessary if corrosion is to be avoided.

For example, it was reported²⁵ that one refinery experienced stress-corrosion cracking in the third unit of a five-effect, vertical tube evaporator system. The unit contained 750 Type 316 stainless tubes, 2" OD x 0.063" wall thickness X 20' long (50.8 x 1.6 X 6096 mm). Eighty of the tubes cracked after only two years of service.

Laboratory examination confirmed the failed tubes to be annealed Type 316 stainless. Inspection of the evaporators, however, revealed the following probable causes:

1. The holes in the tube sheet were as much as .035" (0.889 mm) over the nominal tube dimension.
2. Approximately .5" (12.7 mm) of each tube protruded above the upper tubesheet.
3. The tubes were cleaned with hydrochloric acid without adequate neutralizing or flushing after cleaning.
4. During standby, steam continued on the shell side with nothing but air on the tube side.

Conditions for chloride stress-corrosion cracking were present. The weirs created by the tubes protruding above the tubesheet provided an ideal situation for the entrapment of chloride ions; the temperature was sufficiently high to concentrate the chlorides; oxygen was present; and the stresses resulting from over-rolling were above acceptable limits.

In another beet sugar processing plant, a heater is used for pre-heating reconstituted nonsugar products prior to evaporation. Sulfuric acid is added to the process and temperatures reach 200F (93C). To minimize the chances of stress-corrosion cracking and pitting in this low-pH environment (containing chlorides), the plant is using Type 329 stainless steel tubing, which provides better resistance to corrosion and somewhat higher strengths than Type 304.

In a soybean processing plant, nonferrous tubing in a solvent extraction system was suffering corrosion from steam, hexane vapours, and amino acids. The brunt of the corrosive attack was absorbed by two condensers-a pre-evaporator unit and a desolventizer-toaster condenser. The two units contained 1247 tubes $\frac{3}{4}$ " OD x 10' (19.05 x 3048 mm). Cooling water is circulated on the tube side at 22 psi

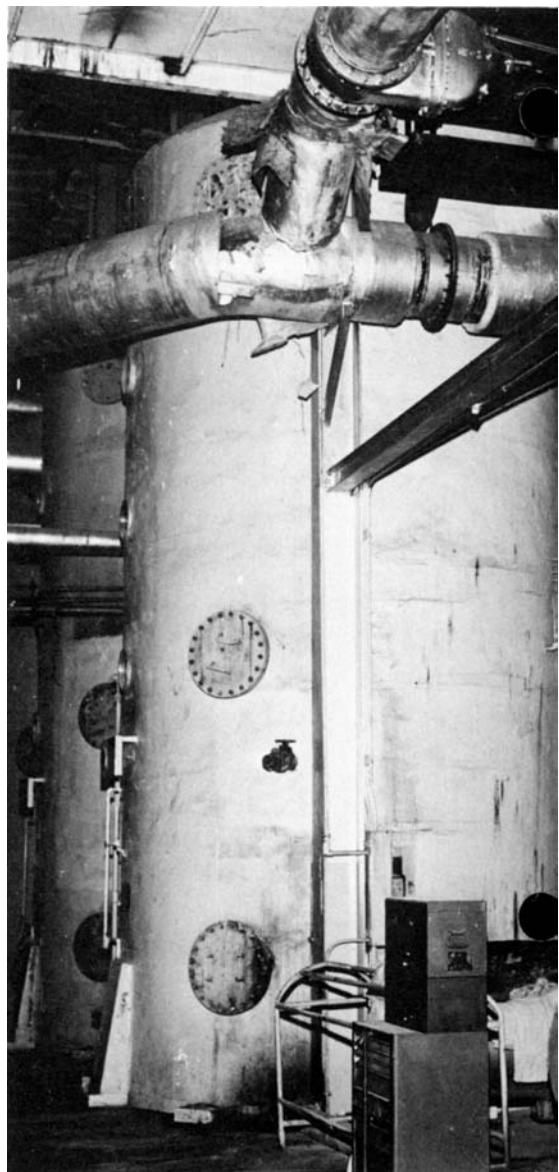


Figure 34

(152 MPa), 60-100F (16-38C). Hexane, steam, and amino acids at 200F (93C) circulate on the shell side. The first set of tubes was phosphorized Admiralty tubing. This set failed in two years from stress-corrosion, fatigue cracking, and pitting and was replaced by 18-15 red brass, which failed by fatigue in two years. The final installation, which is still in service after several years, was made with Type 304 stainless steel.

Innovation is a part of the food processing industry, and fairly recent is the use of heat exchangers for continuous processing of foods instead of the steam kettle batch process. Continuous processing utilizes a scraped surface exchanger, such as shown in Figure 35; and stainless is preferred when high-temperature and low pH are involved.

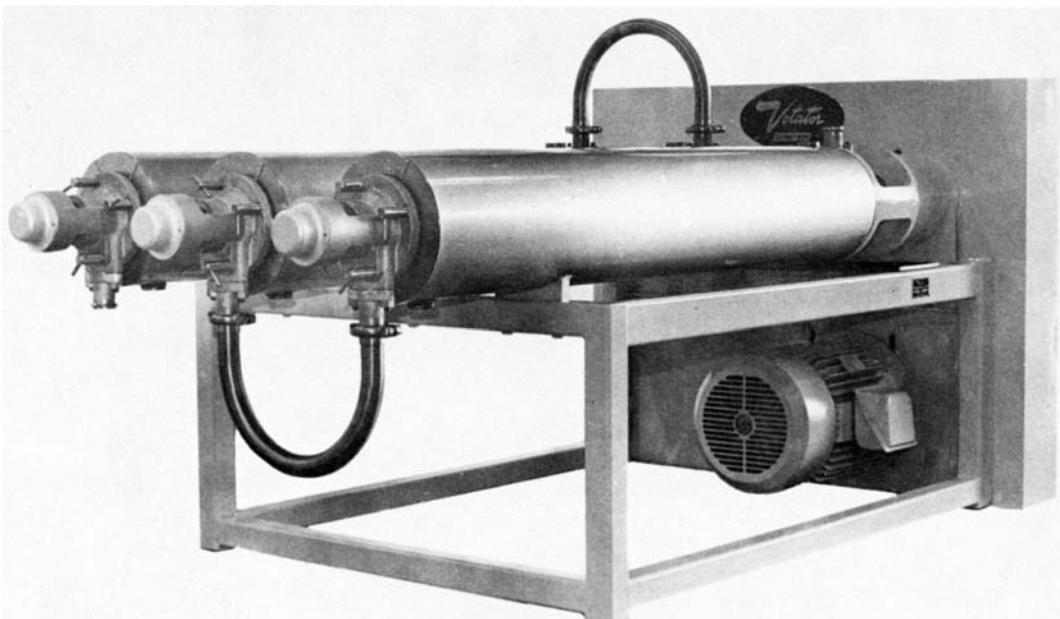
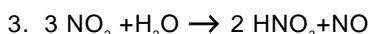
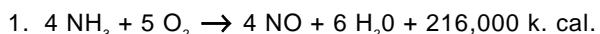


Figure 35
Votator Division, Chemetron Corporation

A typical application is process and hot pack of spaghetti sauce with meat or mushrooms. The food has a pH of less than 4.2, and it requires heating to 250-260F (121-127C). After holding at temperature for a specified period to effect complete sterilization, hot filling is accomplished at 200-205F (93-96C). This system uses Type 316 throughout. Similar applications are encountered in salad dressing processing and in edible oils, which contain high percentages of free fatty acids.

NITRIC ACID PRODUCTION

Nitric acid is produced by the oxidation of ammonia to nitric oxide over a platinum-rhodium catalyst, subsequent oxidation to nitrogen dioxide, and finally reaction with water. The process operates under a pressure of up to 8 to 10 atmospheres. The chemical reactions are as follows:



In the overall process liquid ammonia is vapourized, heated, mixed with compressed air, and passed over the platinum-rhodium catalyst in a burner, or converter. Because the reaction is exothermic, the reacted gases reach a temperature of up to 1760F (960C). To recover energy,

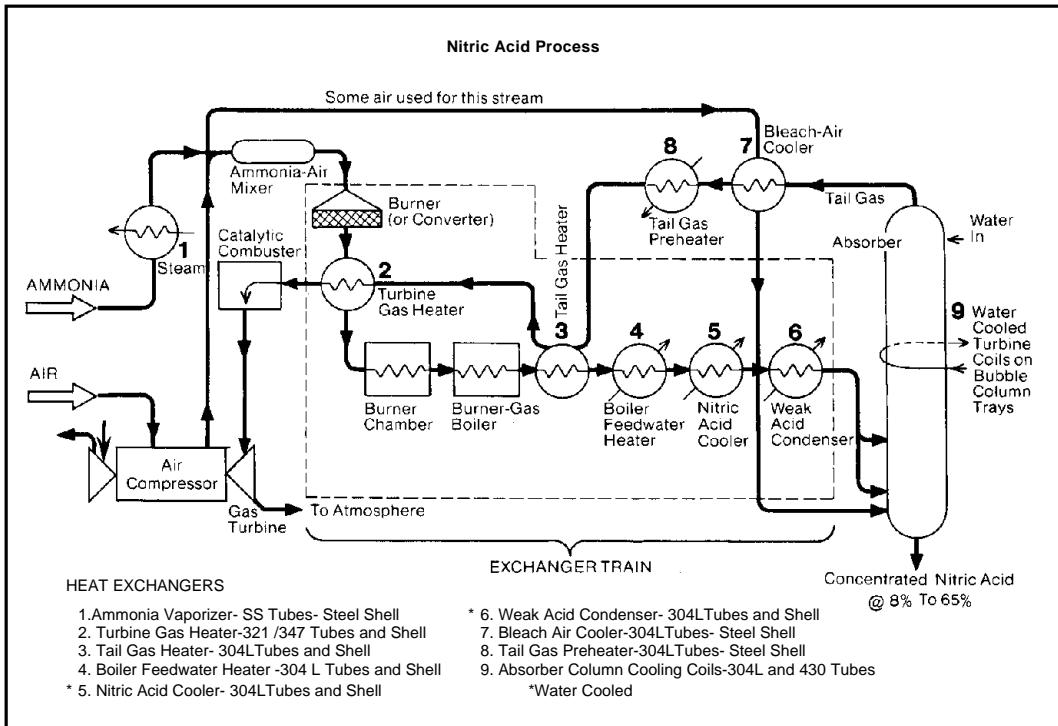


Figure 36

and to cool the gases for water absorption, they are passed through a series of heat exchangers, referred to as the "exchanger train." (See Figure 36.)

Steam generated in the exchanger train is used to drive the air compressor via a steam turbine. The acid gases leaving the exchanger train pass through a nitric acid cooler, and a weak acid condenser (also referred to as a cooler condenser), where the acid which condenses is at about 40% concentration. Both the cooled gas and the condensed acid then pass to the absorption column, or absorber, where they are absorbed in water entering the top. Concentrated nitric acid from 58 to 65% concentration leaves the bottom, the concentration depending upon absorber efficiency.

The stripped gas leaving the top of the absorber, called the "tail gas," is essentially nitrogen, but contains small amounts of nitrogen oxides. Before it is discharged to atmosphere it is heated through the series of heaters (items 7, 8, 3, and 2 in Figure 36) and passes through a catalytic combustor and then the gas turbine.

Stainless steel tubing is used in most of the heat exchangers in this train, as indicated in the sketch, as well as on the trays of the absorption column, for water cooling in the absorption process. (Figure 37)

Type 304L is frequently a suitable choice for the tubing in these heat exchangers, although some plants indicate a preference for Type 329 in exchangers 3, 5, 6, and 8, and Type 405 in exchanger 3. Because of the high gas temperature in the turbine-gas heater, Type 347 or 321 is generally used for this heater. In some cases Type 310 stainless has been employed.

For the water cooled exchangers, such as items 5 and 6, chlorides in the cooling waters at some plants may lead to chloride stress-corrosion cracking from the cooling water side. For such units some plants have upgraded to stainless steels that have greater resistance to stress-corrosion cracking. (See discussion of stress-corrosion cracking on page 13.)

For the absorber vessel and its trays and bubble caps, Type 304L is the normal choice. As heat is generated in the absorption process,

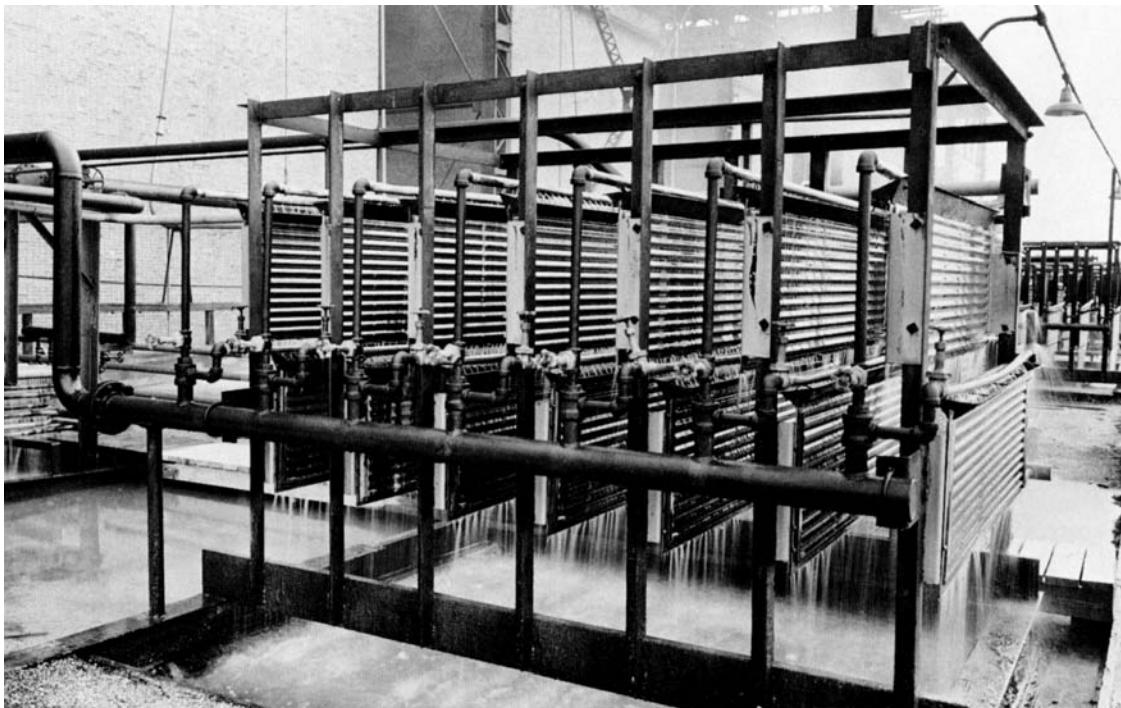


Figure 37
Tranter Mfg. Inc.

water cooling through tubing coils (Types 430 or 304L tubing) on many of the trays is employed.

Typical temperatures through the exchanger train are as follows:

1. Air Inlet—500F (260C) (While not shown in the diagram, the air from the compressor may pass through a heat exchanger just ahead of the tail gas heater.)
2. In the catalyst bed of the burner (or converter)—1760F (960C).
3. Inlet to the tail gas heater—608F (320C).
4. Inlet to the nitric acid cooler—428F (220C).
5. Outlet of the weak acid cooler—104F (40C).

HIGH-TEMPERATURE RECUPERATORS

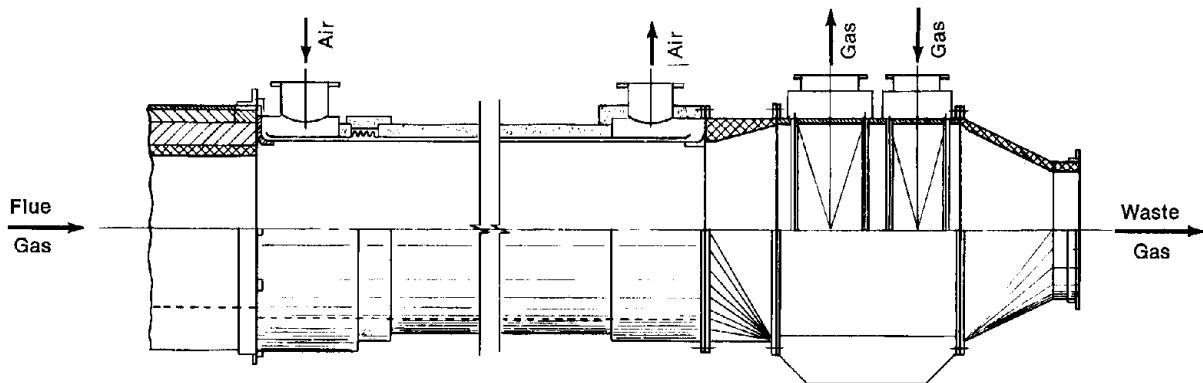
Heat exchange recuperators constructed of stainless steel sheet or tubing recover useful process heat from hot gases that would otherwise be lost to the atmosphere. This is of particular interest not only from the fuel saving standpoint, but also in terms of helping with pollution control. For example, the steel and glass industries use recuperators to cool exhaust gases to a point where they may be filtered through fabric bags. In this manner, most of the particulate matter can be economically removed.

Temperatures of exhaust gases from steel and glass plants usually range up to 2400F (1315C), even as high as 2800F (1540C) in some cases. Present recuperator designs are highly efficient and utilize a variety of wrought and cast stainless steels. Alloys are selected for durability of up to 10 years—considering temperature and the corrosive nature of the hot gases.

There are standard recuperator designs, such as shown in Figures 38, 39, and 40, but most installations are engineered on an individual basis. The most common stainless steels used are Types 309 or 310 for the high temperature applications and Type 304 for temperatures of 1200F (650C) and below. In some applications, straight-chromium stainless steels have been used, such as Types 430 and 446 or Alloy E-Brite 26-1.



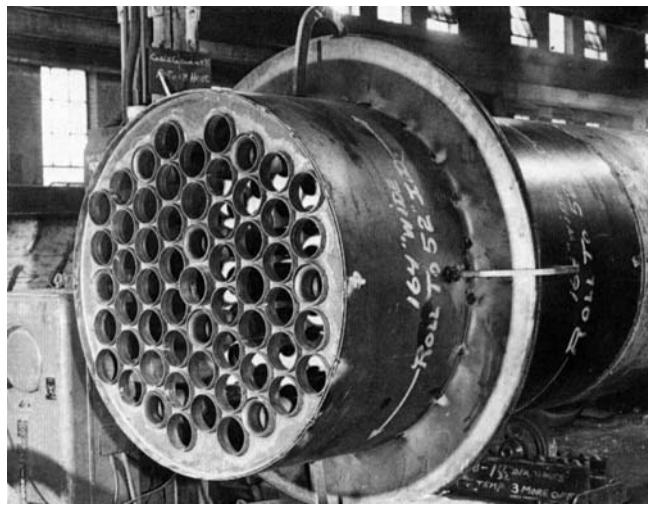
Double-shell radiation recuperator ready for shipment.



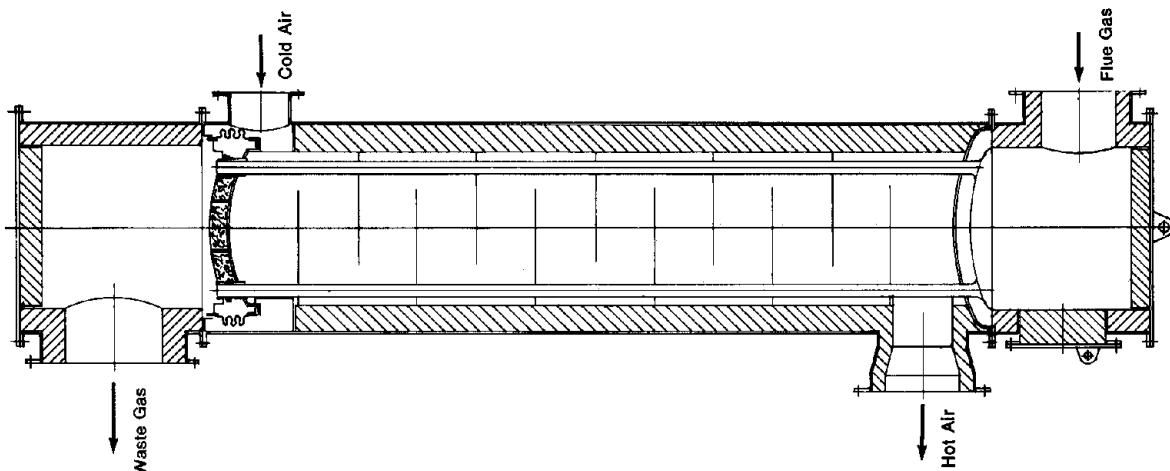
Double-shell radiation recuperator with convection bundle.

Figure 38

The American Schack Company, Inc.



Flue-gas-thru-tube recuperator under assembly.



Flue-gas-thru-tube recuperator.

Figure 39

The American Schack Company, Inc.

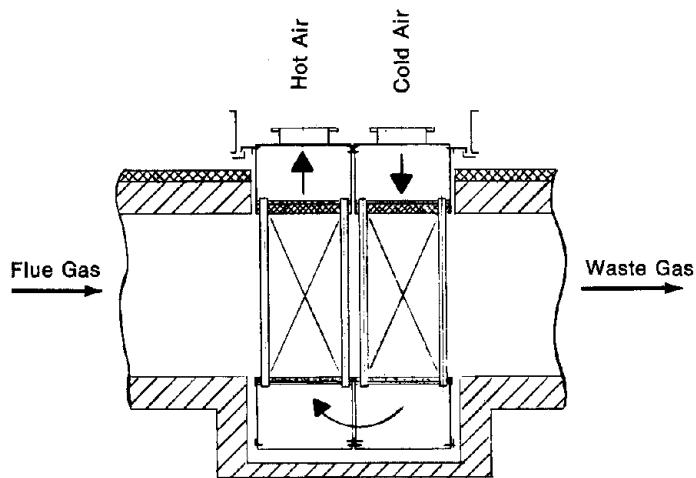


Figure 40

The American Schack Company, Inc.

STATOR COOLING

Removing heat in a steam turbine generator by piping cold gas through the insulation of current-carrying conductors was developed and applied in the early 1950's. Early units used hydrogen gas in these stator "heat exchangers" because of its superior heat characteristics and low friction. Type 304 tubing was used because it is a nonmagnetic material and will not heat up in an extremely strong alternating current magnetic field. Not only does it reduce eddy current loss, but its good strength permits thin-wall tubing—allowing more room for copper in the stator coil and maximum gas space inside the tubes.

Fusion research, which may be applied to electrical generation in the 21st century, more than likely will use Type 304 for similar purposes. According to current fusion research activity, Type 304 tubing and cryogenic gases are used to supercool electrical conductors. By circulating liquid hydrogen or nitrogen around electrical conductors they are supercooled to cryogenic temperatures, at which point electrical resistance is virtually nil. Type 304 prevents eddy current loss and it has excellent properties at cryogenic temperatures.

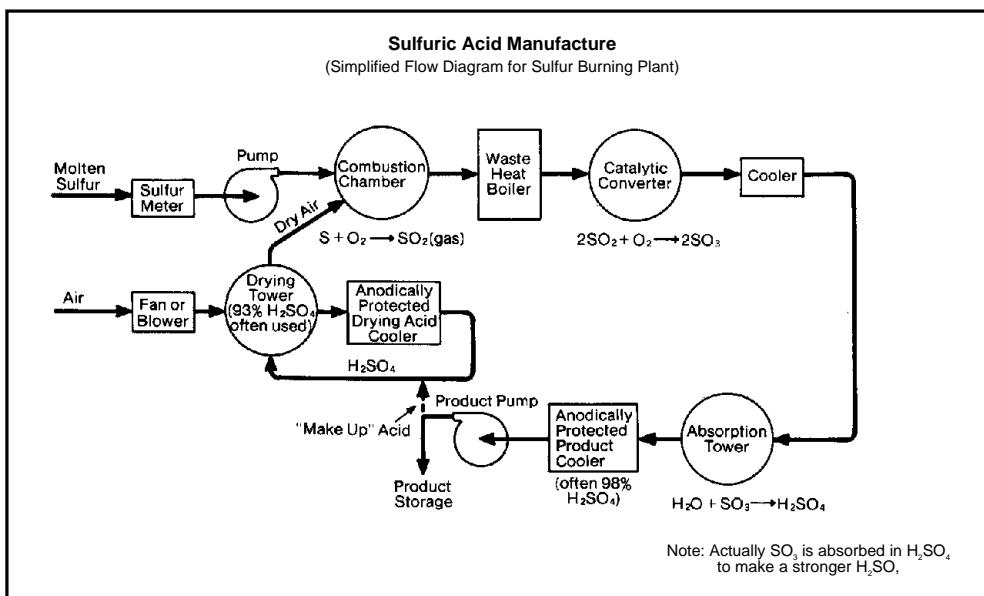


Figure 41

SULFURIC ACID

The standard grades of stainless steels are seldom used in sulfuric acid solutions because of their narrow range of usefulness. According to widely published data, Type 316 gives useful service at room temperature in concentrations lower than 20% and higher than 80%. Between 20 and 80% and at elevated temperatures the corrosion rate of Type 316 increases rapidly, which severely limits its application in heat exchangers*-except for the recent development of anodic protection of Type 316 sulfuric acid coolers.

Manufacturing sulfuric acid involves both drying of sulfur dioxide and absorbing of sulfur trioxide in concentrated acid (Figure 41). These processes generate heat and require cooling of both the "drying" and the "absorbing" acids.

Traditionally this cooling has been accomplished in coolers made of cast iron, in which the concentrated acid flows inside the coolers, and the cooling water cascades over tiers of pipes. Problems with these

coolers are rather frequent resulting in high maintenance costs, acid losses, and pollution. The coolers also require considerable space.

* Note: Because of the narrow range of the standard stainless steels, it is frequently necessary to upgrade to higher alloyed materials, such as Alloy 20Cb-3.

In the late 1960's, a Canadian company²⁶ introduced Type 316L stainless steel coolers with an effective anodic protection system. These coolers have performed well in almost six years of service and have resulted in substantial savings due to: 50% saving in space, elimination of ground pollution due to acid leakages, a sharp reduction in maintenance, higher heat transfer efficiency, a high purity product with an iron content of less than 5 parts per million, higher operating temperature, and higher acid velocities without suffering erosion/corrosion effects.

The anodic protective system for sulfuric acid coolers has also been developed for air coolers for areas in which cooling waters are not readily available. Temperatures for 90% sulfuric are 230F (110C) for a shell and tube exchanger and 115F (46C) for air coolers. If the anodic protection should be turned off or removed, the system would last for at least six months.

An interesting sidelight is the fact that over 350,000 tube-to-tubesheet joints have been made (by welding) for these sulfuric acid coolers, and all have performed without failure.

PETROLEUM REFINING

Figure 42 is a flow diagram of a petroleum refinery showing typical corrosive environments.²⁷ Specific data on high-temperature corrosivity studies in this environment are contained in API Publication 943, September 1974.

Stainless steels are used quite extensively in petroleum refining heat exchangers for protection against corrosion by sulfur compounds and various acids which may be present in the process. For instance,

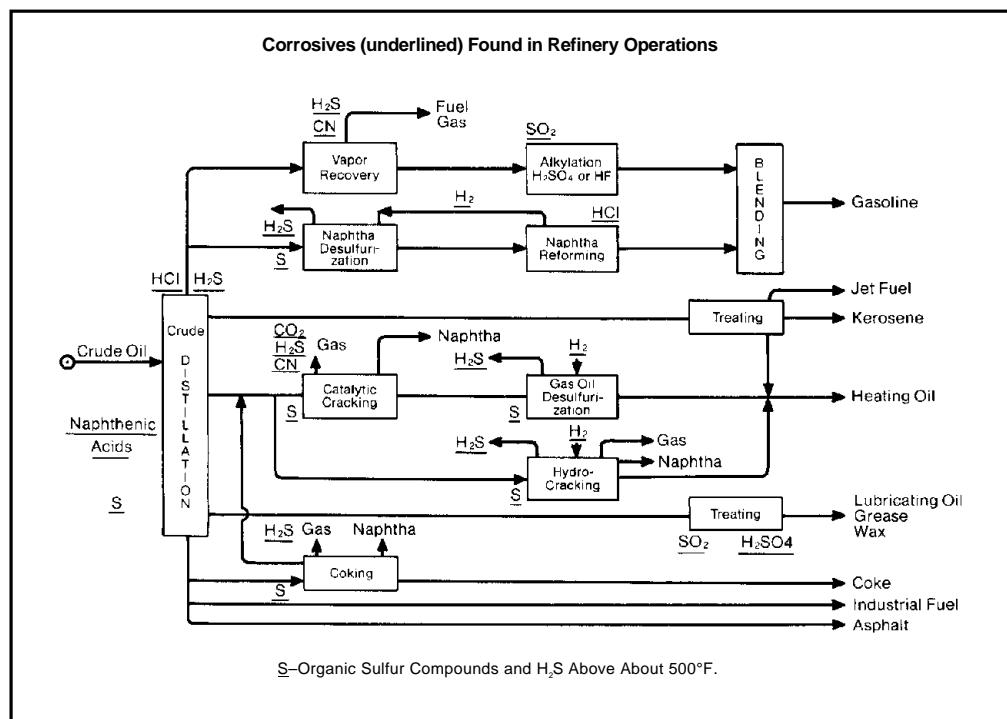


Figure 42

Source: Cooper²⁷

Figure 43 is a diagram²⁸ showing the relative resistance of carbon steel, 5% chromium, 9% chromium steels and 18-8 stainless steels to corrosion by crude containing 1.5% sulfur at a temperature range of 500-900F (260-482C).

The 400 Series stainless steels are not included in this diagram; however, they would show a low corrosion rate, with Types 430 and 446 having about the same corrosion resistance as 18-8.

The diagram in Figure 43 demonstrates only one crude; other crudes are more or less corrosive, which is a particularly difficult problem many refineries must face with different crude sources. However, one point that should be noted is that the starting point of 500F (260C) shows a very low corrosion rate. Usually 450F (232C) is the starting point at which refineries will use stainless steels for sulfur corrosion problems.

The following table gives some general rules as to where stainless steels are used, based on operating temperatures in streams containing sulfur, hydrogen, and nitrogen.

Temperature	Alloys
Above 700F (371C)	Types 304, 321, or 347. (Type 430 is subject to 885F embrittlement at these temperatures.)
450-700F (232-371C)	Types 430, 304, 321, or 347.
Below 550F (288C)	Low alloy or carbon steels.
Below 250F (121C)	Type 430 may be used in some systems containing high hydrogen sulfide and ammonia.

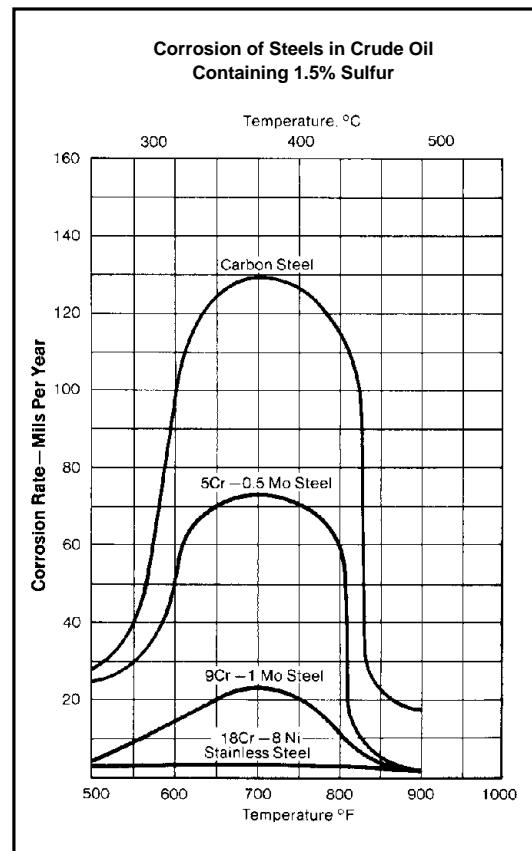


Figure 43

Source: NACE98

Another consideration for using stainless steels in petroleum refining heat exchangers is the presence of naphthenic acids. Naphthenic acids are not too common throughout the world, although they are prominent in California and Venezuelan crudes. The neut number (or acid number) in some of these crudes is 1½-2, with a few side streams as high as 12. (Neut numbers .5 and higher are considered corrosive.)

Naphthenic acids follow about the same corrosion pattern as the sulfur compounds. However, it is theorized that these acids dissolve iron sulfide scale that tends to be protective on the low alloy steels. So as sulfur corrosion occurs at 450F-500F (232-260C), some naphthenic acid corrosion can be expected in the same range.

Type 316 is the usual material to use with naphthenic acids, although Type 304 has been used in streams with low neut numbers. Above 5, and in the 650F-700F (343-371C) range, Type 316 with 2.75% minimum molybdenum or Type 317 will offer better protection against corrosion.

Heat exchangers are the most critical areas for naphthenic acid corrosion because the acid has a narrow, 550F-700F (288-371C) boiling range at which it tends to concentrate. Internal condensers and pump-around coolers are typical areas in crude distillation where naphthenic acid will be most severe.

In some refinery applications, the choice of material is predicated on cooling water, which may contain chlorides, which can lead to stress-corrosion cracking. In these cases, Type 329 or one of the higher stainless steel alloys may be a better choice (Figure 44). Below 700F (371C) the new ferritic stainless steels, such as Alloys 18Cr-2Mo and 26Cr-1 Mo may be considered. (see page 13.)

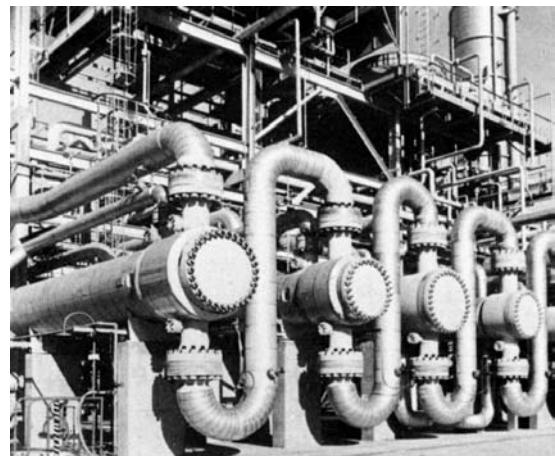


Figure 44

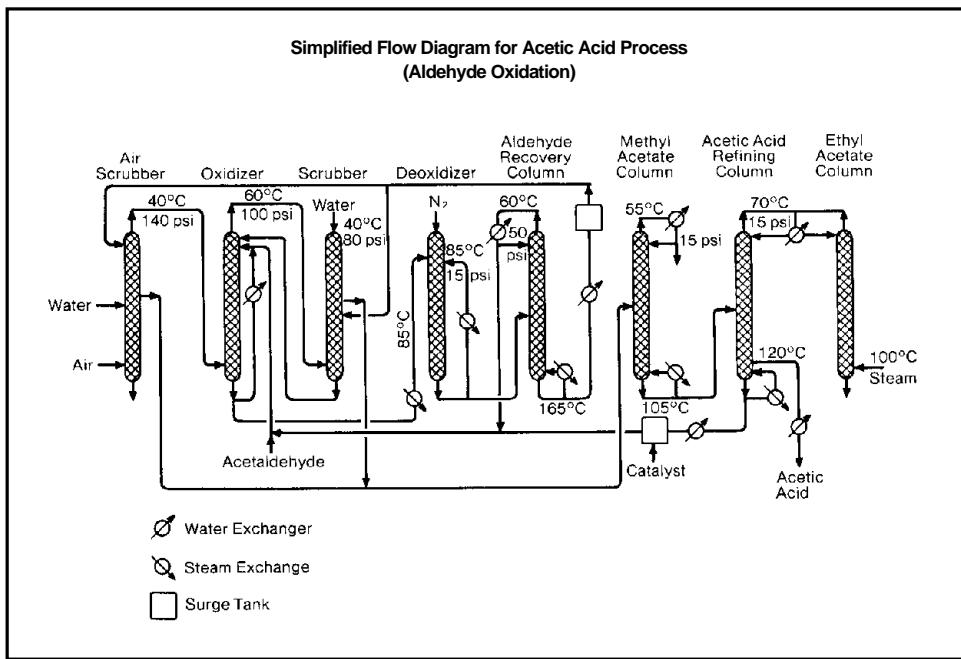


Figure 45

Source: L. S. VanDelinder, P.E.

STAINLESS STEELS IN ACETIC ACID

Heat exchangers used in a chemical unit producing acetic acid can constitute the major equipment cost. These exchangers include condensers, intercoolers, waste-heat boilers, calandrias and coolers, the size and distribution depending on the process used. The simplest (acetaldehyde) requires a minimum of 12 exchangers, as shown in Fig. 45.

Although Type 304 stainless steel has utility in certain exchangers operating at lower temperatures, the workhorse of the acetic acid industry is Type 316 (2-3% molybdenum) or its low-carbon counterpart Type 316L. In some specific instances, Type 317 with a higher molybdenum content (3-4%) has better resistance to organic acids, such as acetic acid. With Type 316, corrosion rates of less than 10 mils per year should be experienced, as indicated by the data in Tables 7, 8 and 9.

TABLE 7

Field Corrosion Test for 82 Days in 99% Acetic Acid Vapours at 212-250° F²⁹

MATERIAL:	Indicated Corrosion Rate, ipy
Type 304.....	0.066
Type 316.....	0.003

TABLE 8

Field Corrosion Tests in Glacial Acetic Acid at 1250° F. Vapour Velocity 175 ft/sec. Specimens exposed in inlet leg of reaction coil.²⁹

MATERIAL:	Indicated Corrosion Rate, ipy		
	Test A 450 Hours	Test B 1769 Hours	Test C 1384 Hours
Hastelloy C	0.0001 (gain)	0.0001	Not Tested
Type 317 S.S.	0.0004	0.0004	0.0012
Type 316 S.S.	0.0004	0.0006	0.0017
Type 316 L	Not Tested	0.0006	Not Tested
Illiium	0.0002	Not Tested	Not Tested
Alloyco 20	Not Tested	0.0001	Not Tested
Type 309 S.S.	Not Tested	0.0004	Not Tested
Hastelloy B	0.0003	0.0007	Not Tested
Hastelloy A	0.0033	Not Tested	Not Tested
Inconel	0.13	0.11	Not Tested
Monel	Corroded Away	Not Tested	Not Tested
Nickel	Corroded Away	Not Tested	Not Tested
Type 410 S.S.	Not Tested	Not Tested	0.0015
Type 430 S.S.	Not Tested	Not Tested	0.0012
Type 446 S.S.	Not Tested	Not Tested	0.0002

TABLE 9

**Corrosion Rates (in of Materials in 99.6% By mpy)
Wt Acetic Acid³⁰**

Material	Specimen Temperature, Degrees F				
	Without Heat Transfer	With Heat Transfer			
	230	244	230	257	284
Type 304L		69	260	340	20
Type 316		<1	<1	13	10
C.S. 20-Cb		7	5	2	100
Hastelloy B		<1	7	7	3
Inconel	3	22	36	45	14
Monel		1	120	68	220

Generalized isocorrosion curves are shown in Figures 46, 47 and 48. Such data do not provide accurate corrosion rates for a specific application, but they allow a comparison of materials for economic analyses or as a basis for further testing. Note that Type 430 stainless steel has reasonably good resistance to acetic acid. However, the use of 400 Series stainless steels should be limited to emergency repairs. For the small additional cost required, the use of Type 316 is warranted.

Steel shells may be used in these heat exchangers if the product is on the tube side. Galvanic action between the mass of stainless steel in the tube bundles and the steel shell is not excessive in most industrial waters. Tie rods and baffles, however, are generally made of stainless to assure long life and to provide proper expansion characteristics within the unit. Also, the design should consider the possibility of vibration that might develop, which results in the hammering of tubes within the baffles.

Because most process waters contain chlorides, there is always the possibility of stress-corrosion cracking of the 300 Series stainless steels. To minimize the possibility, it is good practice to vent the tube sheet (in vertical exchangers) to prevent concentration of the chlorides. Safe ending-welding short lengths of a stress-corrosion crack-

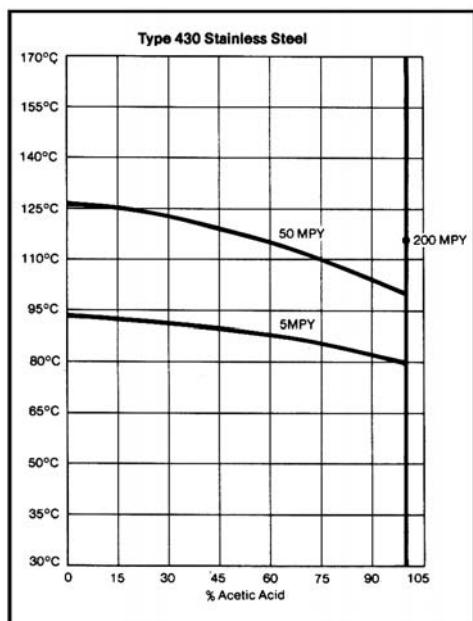


Figure 46

Source: L. S. VanDelinder, P.E.

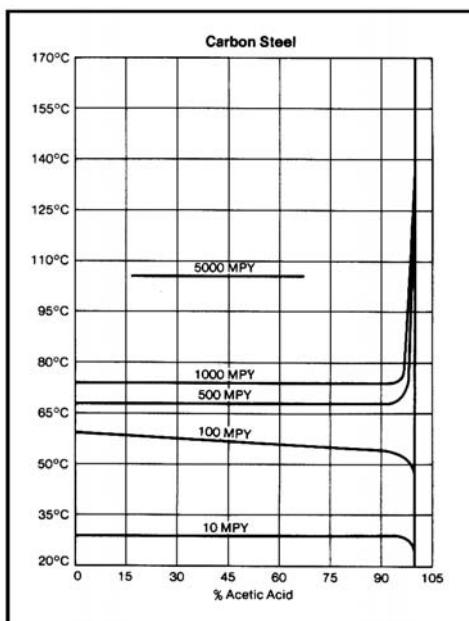


Figure 47

Source: L. S. VanDelinder, P.E.

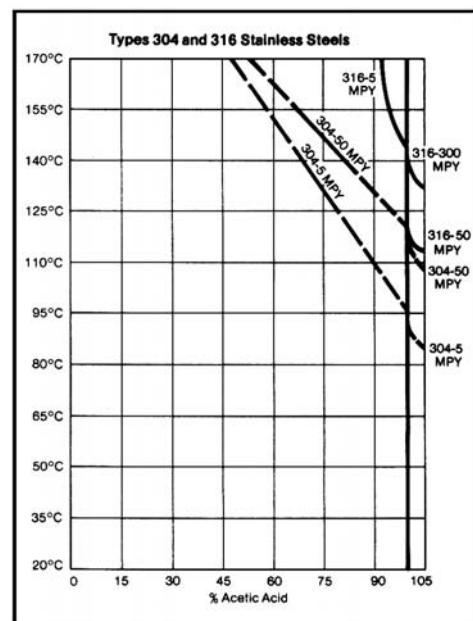


Figure 48

Source: L. S. VanDelinder, P.E.

ing resistant stainless at the problem end of tubing—will also minimize the problem. If a crack-resistant material is desired, consider the use of Type 329 or the straight-chromium alloys described elsewhere in this publication.

In some heat exchange applications in acetic acid plants, such as esterification kettles in which the heating coil is internal, the use of Type 316 may be borderline. The sulfuric or other acid catalyst added to the acetic acid can produce excessive attack. However, Type 316 can be used with minimum corrosion simply by reducing the temperature slightly or adding oxidizing ions, such as cupric or ferric that tend to ameliorate the corrosive attack.

Contaminants in acetic acid can increase corrosion rates. In some processes the sulfur dioxide or sulfur trioxide present in the stream can increase corrosion in an overhead condenser in which condensation occurs at high temperatures. The addition of formic acid to acetic acid will increase the rate of attack on stainless steels, although the increase can be tolerated by Type 316.

Acetic anhydride in the acid stream will also increase corrosion rates. When operating condensers, calandrias, or interchangers at acid values higher than 100%, it may be necessary to use higher alloyed material, such as Type 317, Alloy E-Brite 26-1, or Alloy 20Cb-3.

The presence of aldehydes, ketones, esters, and other organic products in the acid stream does not increase corrosion rates; in fact, their presence may even result in a decrease.

When consulting published corrosion data on candidate materials for acetic acid heat exchangers, the temperature is a critical parameter. The anticipated wall temperature of the tubing on the process side should be calculated and correlated to the test data. If this factor is an unknown, the inlet temperature of the process stream must be used as a basis for design.

At times, it's desirable to seal-weld tubes to tube sheets to forestall intermixing of the two streams in a heat exchanger. When welding is required, it is good practice to use Type 316L stainless to minimize carbide precipitation in the weld zone.

STAINLESS STEELS IN SYNTHETIC NATURAL GAS

In a double methanation, substitute natural gas plant, stainless steels are used in heat recovery exchangers between the first and second methanators.

In the high-pressure boiler, heat from the gas leaving the first methanator is recovered by heating boiler feedwater. This gas is a mixture of water vapour, carbon monoxide, carbon dioxide, hydrogen and methane. The boiler feedwater cools the gas to a temperature below the dew point of the water vapour. The condensed water forms a dilute carbonic acid with carbon dioxide present. Low-alloy steels are subject to a rapid erosion/corrosion failure in this atmosphere, consequently, Type 304 stainless steel is used throughout.

In the low-pressure boiler, heat from the process gas is used to produce low-pressure steam. Because chlorides in the boiling water may induce stress-corrosion cracking of the 300 series stainless steels, the straight-chromium 400 series are a better choice. They are resistant to both stress cracking and carboxylic acid erosion/corrosion.

If there is also a hot potassium carbonate reboiler, to remove carbon dioxide from the product stream, Type 304 stainless is used—again to resist the carbonic acid erosion/corrosion mechanism associated with the wet process gas.

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* Stainless Steel Industry Data.

For additional information on alloys or applications referenced, write to:

Committee of Stainless Steel Producers
American Iron and Steel Institute
1000 16th Street, N.W.
Washington, D.C. 20036

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