THE RIGHT METAL FOR HEAT EXCHANGER TUBES

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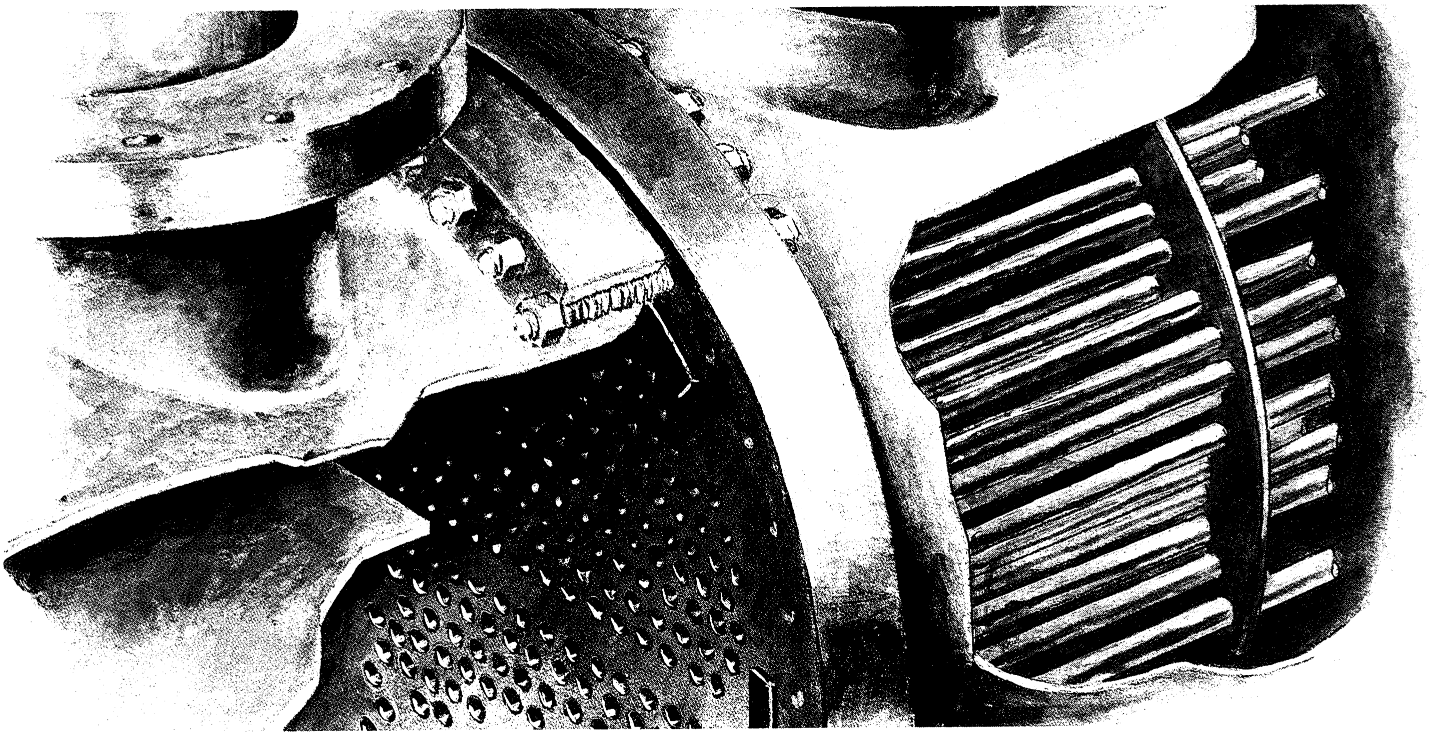

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Attention to this checklist of selection factors will materially reduce heat-exchanger failures

When designing a heat exchanger, an engineer first calculates the surface area needed to carry the heat load. Next, he or she develops the design to meet the standards of the Tubular Exchanger Manufacturers Assn. (TEMA) for heat exchangers, or other codes, and the company's standards. He or she then makes comparative cost estimates, factoring in knowledge from experience, and selects the best tubing metal for the service.

Most unexpected failures of heat exchangers can be traced to a factor that had not been fully taken into account when the tube material was selected. In Tables 1, 2 and 3, these factors are arranged according to, respectively, water quality, the character of operation and maintenance, and exchanger design. Tube materials considered are copper alloys, stainless steels (Types 304 and 316), and high alloys (6% molybdenum, superferritics[*] and titanium).

The impact of each factor is noted without it necessarily being related to that of other factors. In the tables, the impact of each factor is rated one of three ways: green means the tubing alloy or alloy group has given good performance under the stated conditions; yellow designates that the tubing may give good performance, but may require a closer study of the conditions at the site and relationships with other factors; and red signifies that the material has not performed well under the stipulated conditions, and special precautions are required to achieve good performance.

Water quality

Water quality encompasses: cleanliness, and the content of chloride, dissolved oxygen and sulfides, and residual chlorine and manganese. It also includes pH, temperature and scaling tendency (Table 1).

Water cleanliness — Design engineers tend to assume that cooling water will be clean. This occurs only if the right screens and filters have been installed and operators have made sure that they work properly. Debris (such as sticks and stones) and sediment (such as sand and mud) that are passed through or around the screens and filters have been responsible for many tube failures.

Long term, copper-alloy and stainless-steel tubes perform excellently in clean water (i.e., free of sediment, debris and fouling organisms). Too often, however, sediment and debris find their way into exchanger tubes. Corrosion under sediment is common with tubes of these two materials. A high

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[*] A new family of stainless steels high in chromium content (25-30%).

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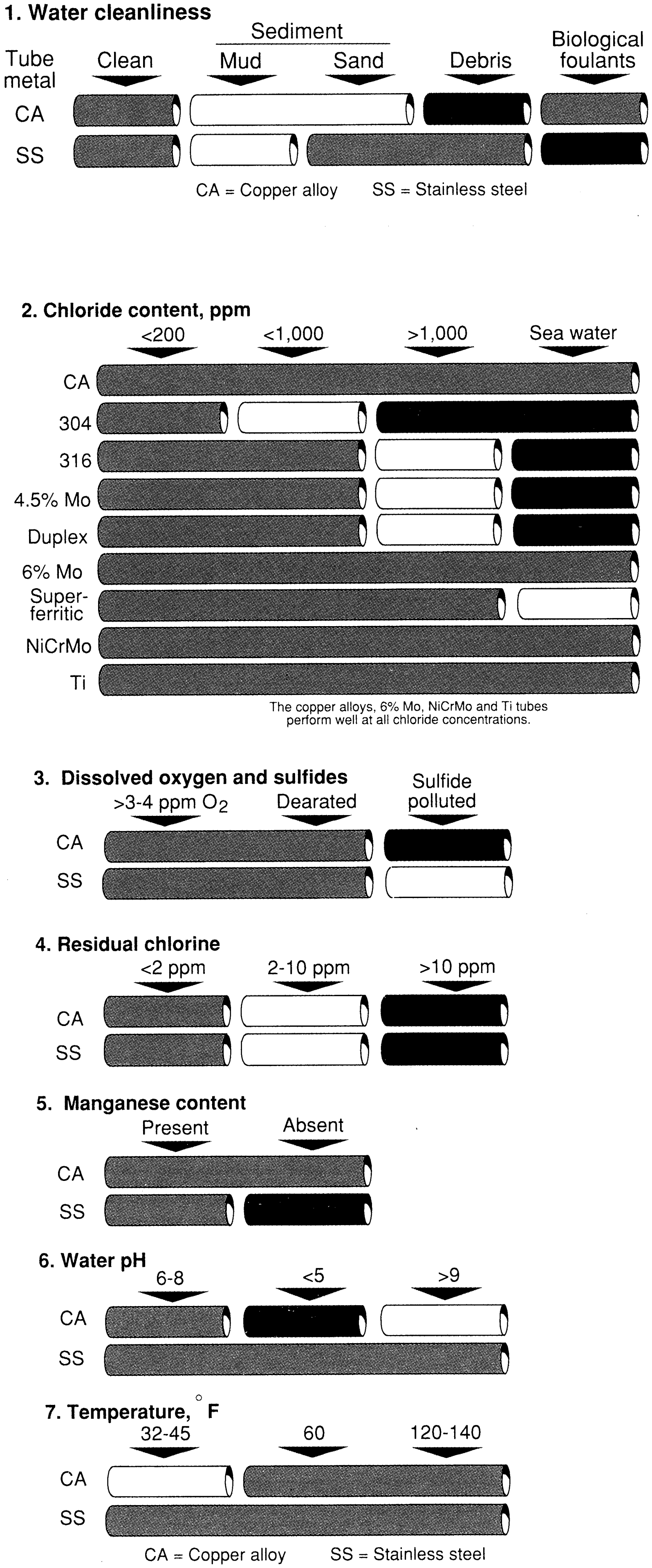
concentration of sand can abrade the protective film on copper-alloy tubes.† Such service, therefore, requires a 70-30 CuNi-2Fe-2Mn alloy in the copper-alloy series, or stainless steel. A lodgment of sticks, stones and shell fragments creates downstream turbulence, which can cause pinholes in copper-alloy tubes.

The obvious cure for these problems is to screen the water better. As a safeguard, the newer 85-15 CuNi with 0.5 Cr, C72200 alloy and stainless-steel tubes do well in withstanding the effects of lodgment turbulence. Copper-alloy tubes effectively keep organisms from becoming attached, and are preferred when environmental restrictions on the use of biocides would require frequent manual cleaning of stainless-steel and higher-alloy tubes.

Chlorides — These provide a convenient framework for differentiating the stainless-steel alloys. Type 304 stainless steel resists crevice corrosion at chloride-ion concentrations of less than about 200 ppm, and Type 316 does so at levels up to about 1,000 ppm. (The chloride content of U.S. fresh water is typically less than 50 ppm, for which Type 304 stainless steel is therefore normally adequate.)

The 4½% molybdenum alloys suffer crevice attack at chloride-ion concentrations from 2,000 to 3,000 ppm. Both 4½% molybdenum-alloy and duplex (another new family of stainless steels) tubes have been subjected to sea water (20,000 ppm chloride content) and have undergone substantial crevice corrosion beneath fouling. On the other hand, the 6% molybdenum and superferritic alloys, and titanium have proved resistant to crevice and beneath-sediment corrosion in salt water.

Dissolved oxygen and sulfides — Copper-alloy and stainless-steel tubes perform best in water having enough oxygen (about 3-4 ppm) to keep fish alive. These tubes also do well in deaerated water, such as that used in water-flood oil wells. Copper-alloy tubes do not stand up well in severely polluted water in which dissolved oxygen has been consumed in the decay



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†All alloys form a protective film in corrosive liquids; on stainless steel, it is chromium oxide; on copper alloy, it is cuprous hydroxychloride.

process and sulfides are present. Tubes of higher-alloyed stainless steel or titanium have served successfully in such water.

Residual chlorine — Both copper-alloy and stainless-steel tubes have performed well in water containing up to 2 ppm residual chlorine, and have failed in heavily chlorinated water. Although the usual objective is to keep residual chlorine at about 0.5 ppm at the inlet tubesheet, this level is sometimes exceeded and the residual is normally higher at the point of injection.

Acidity — In aerated water of pH less than about 5, a protective film does not easily form on copper-alloy tubes, so they corrode and thin rapidly. In deaerated water of low pH, copper-alloy tubes resist corrosion well. For high-pH water, copper-nickel or stainless-steel tubes are preferred to admiralty- (71% copper, 28% brass, 1% tin) or aluminum-brass tubes, which tend to corrode under highly alkaline conditions. Stainless-steel tubes have performed well at a pH less than 5 and greater than 9.

Temperature — A protective film readily forms on copper alloys in warm water (in about ten minutes at 60°F), but forms very slowly in cold water. It develops almost instantaneously on stainless steel in both warm and cold water.

Manganese — Type 304 stainless steel tubes have failed in fresh water having an appreciable manganese content. However, copper-alloy and higher-alloyed tubes have fared well in such water.

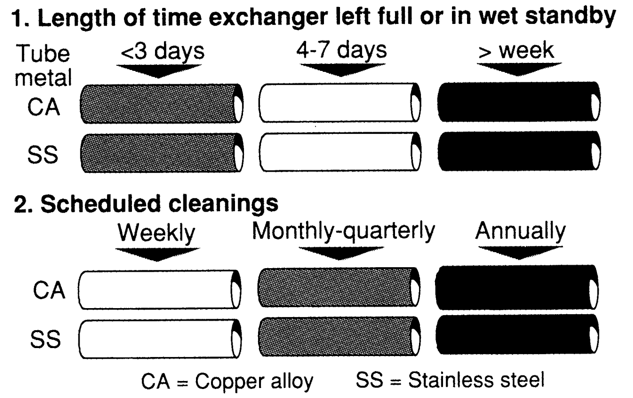
Leaving an exchanger full, or even only wet, invites corrosion

Scaling tendency — Copper-alloy and stainless-steel tubes perform well in both hard (scaling) and soft (nonscaling) water. The Langelier saturation index* is frequently used to distinguish scale-forming from corrosive (to carbon steel) water.

Operation and maintenance

Among these factors are type of operation (regular vs. intermittent) and the frequency of cleaning (Table 2).

TABLE 2-- Operation and maintenance practices that extend tube life



Character of operation — Lengthy startups have been responsible for many failures of copper-alloy and stainless-steel tubes. These occurred because water had been left in, or it had only been partially drained from, tubes for a long time. Such failures have also been caused by extended outages from normal operations.

Leaving an exchanger full, or even only wet, invites corrosion. The water will become foul, creating an environment in which bacteria thrive, promoting microbiologically induced corrosion. Corrosion will also take place under sediment. If an exchanger is to be left full for more than 2 or 3 days, water should be pumped through it once a day to displace the stagnant water. If an exchanger will be down for at least a week, it should be drained and blown dry.

Cleaning schedule — Heat exchangers should be periodically flushed out, opened and brush cleaned, to remove sediment and debris and to restore heat transfer capability. Exchangers handling water high in biological foulants or sediment should be cleaned weekly. Micro-organisms will corrode stainless steel if they and other deposits are not removed.

Monthly or even quarterly mechanical cleanings of copper-alloy and stainless-steel tubes are adequate with most waters. The optimum interval can be critical because the protective film on copper alloy tubes can be damaged by cleaning with metallic brushes and some types of abrasive blasting. Mechanical cleaning is sometimes put off for a year, and even longer, particularly if restoring an exchanger's heat-transfer rate is not critical to plant performance. Be cautioned, however, that corrosion beneath sediment frequently occurs when sediment removal is delayed by more than three months.

Exchanger design

The principal design factors that influence tube performance are water velocity, tube diameter, shape (i.e., once-through or U-bend), orientation, venting, tubesheet material, channel (waterbox) material and channel inlet arrangement (Table 3).

Fluid velocity — At velocities of less than 3 ft/s, sediment deposit, debris buildup and biological fouling in and on tubes can be excessive, resulting in the need for frequent mechanical cleaning, which can cause copper-alloy and stainless-tube tubes to fail prematurely.

Copper alloys can be conveniently differentiated according to their water-velocity tolerance. Approximate maximum design velocities for tubes of copper-base alloys and stainless

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*This index indicates the tendency of a water solution to precipitate or dissolve calcium carbonate. It is calculated from total dissolved solids, calcium concentration, total alkalinity, pH and solution temperature.

steel in salt water are listed in Table 3. Maximum velocity is usually arrived at as a compromise between the cost of pumping and the advantage in heat transfer. The design velocity usually falls in the range of 6-8 ft/s, and may reach 12-15 ft/s when extra cooling demand is placed on an exchanger, such as in summer.

Copper-nickel tubes stand up reasonably well to variations in velocity, although some erosion and corrosion may occur at the inlet. The C72200 alloy resists inlet-end erosion and corrosion, as well as corrosion downstream of lodgments. The 2Fe-2Mn modification of the C71500 alloy resists inlet erosion and corrosion excellently. Copper-nickel tubes, after their protective film has aged, withstand considerable velocity excursions without significant inlet erosion. Stainless-steel tubes perform best at high velocity and are useful up to velocities that induce cativation. Copper will tolerate somewhat higher velocities in fresh water, 10 ft/s being a common design velocity for copper tubes in air-conditioning condensers cooled with fresh water.

Tube diameter — Tubes of large diameter are preferred for heat exchangers because any solids that pass through screens will also flow through the tubes. By one rule of thumb, tube diameters should be at least twice the diameters of the screen openings. Tubes should not be less than ½ inch if the water to the exchanger is not filtered.

Once-through or U-bend — Because U-tube bundles are difficult to clean, the water must be very clean (e.g., boiler feedwater quality), or at least well-filtered. Both stainless-steel and copper-alloy tubes are liable to corrode beneath sediment. U-tubes are particularly prone to such corrosion if sediment and debris are not removed from their bends. Once-through and 2- to 4-pass bundles are easily cleaned by flushing, water lancing, or brushing.

Orientation — Heat exchangers, particularly condensers, are normally placed horizontally, with water flowing through the tubes. Both stainless-steel and copper-alloy tubes perform well in such exchangers. In those unusual circumstances that require that

TABLE 3 -- Exchanger design features that influence tube performance

1. Recommended fluid velocities for tube materials

Tube metal	Salt water velocity, ft/s					
	<3	3-5	5-6	6-9	9-12	>12
Copper	■	□	■	■	■	■
Admiralty	■	□	□	■	■	■
C70600	■	▨	▨	▨	□	□
C71500	■	▨	▨	▨	□	□
C72200	■	▨	▨	▨	▨	▨
70-30 2Fe 2Mn	■	▨	▨	▨	▨	□
SS	■	□	▨	▨	▨	▨

2. Tube diameter, inches

	Exchangers		Condensers
	5/8-1	3/8-1/2	7/8-1½
CA	▨	■	▨
SS	▨	■	▨

3. Type of tube flow

	Once-through	2-4 pass	U-tube
CA	▨	▨	□
SS	▨	▨	□

4. Exchanger orientation and water location

	Horizontal		Vertical
	Tubeside	Shellside	Shellside
CA	▨	■	▨
SS	▨	■	■

5. Venting arrangement

	Vented	Not vented
CA	▨	□
SS	▨	□

6. Tubeshell material

	Steel	Copper alloy	Stainless steel
CA	▨	▨	■
SS	▨	■	□

7. Channel material

	Steel		Copper alloy (CuNi)	Stainless steel (316)
	Bare	Coated		
CA	□	□	▨	□
SS	□	□	▨	▨

CA = Copper alloy SS = Stainless steel

the cooling-water flow on the shellside of a horizontal exchanger, sediment and debris cannot be kept from building up around the support plates and lower tubes. This results in corrosion beneath the sediment. The buildup can be eliminated, or at least restrained, by upstream filters, but these will not prevent fouling organisms from thriving in low-flow areas. When the water, even clean water, must be on the shellside, the tubes should be of high alloy.

A condenser is sometimes oriented vertically, with the cooling water on the shellside, to improve heat transfer. This allows noncondensable gases to collect under the top tubesheet, letting the temperature of the tube walls in the gas pocket get almost as hot as the incoming gas being condensed, evaporating the water and depositing scale on the hot tube surfaces. Sediment also tends to build up in the bottom of a vertical condenser.

> **TEMA standards recommend that exchangers be installed level, but they should really be sloped**

In vertical installations, both Type 304 and Type 316 stainless-steel tubes are prone to stress corrosion and cracking just under the top tubesheet. Remedies include: venting gas through the top tubesheet; changing to copper-alloy or copper alloy-stainless steel bimetallic tubing or to high-alloy tubing, or orienting the exchanger horizontally. Although the TEMA standards recommend that exchangers be installed level, exchangers should really be sloped slightly so that they will drain completely when shut down, avoiding corrosion where tubes sag between support plates and retain water even after being drained.

Venting — Exchangers are normally fitted with vent cocks so they can be purged to clear gas pockets. Condensers, particularly when chlorine is used as a biocide, tend to suffer corrosion when gases are not vented.

Tubesheet material — Tubesheets of carbon steel, common copper alloy, Muntz metal (a brass composed of 58-61% copper, up to 1% lead, with the remainder zinc), admiralty brass and aluminum bronze are anodic to copper-alloy tubes. The galvanic protection that these tubesheet materials afford copper-alloy tubes does not eliminate all inlet-end corrosion, but often does help to keep it at a tolerable level.

Stainless-steel tubesheets are rarely used with copper-alloy tubes, because stainless steel is cathodic to copper alloy. Installing stainless-steel or titanium tubes in copper-alloy tubesheets has accelerated the corrosion of the tubesheets. Stainless steel and titanium polarize so readily that the entire inside surface of the tubes (not just the part adjacent to the tubesheet) must be considered as the cathode to the copper-alloy tubesheet anode.

The normal cure for this anode-cathode problem is to protect the copper-alloy tubesheet with an impressed-current cathodic protection unit. The unit's potential must be controlled to avoid hydrogen embrittlement of ferritic stainless steel, or hydriding of titanium. An alternative is to resort to tubes of 6%-molybdenum, which resist hydrogen embrittlement without the need to carefully control an applied potential.

Tubesheets for austenitic stainless steel should be of identical composition. Tubesheets of high-alloy austenitic stainless steel are used with tubes of ferritic stainless steel, because tubesheets of matching composition are not available. Solid or clad titanium tubesheets are preferred with titanium tubes.

Channel material — Corrosion products from bare-steel and cast-iron channels (exchanger inlet chambers) have occasionally caused the corrosion failure of copper-alloy and stainless-steel tubes. Coatings applied to steel and cast-iron channels for the purpose of reducing corrosion sometimes deteriorate and spall, leading to tube corrosion and failure. Coated channels are also liable to deep local corrosion at pinholes in coatings brought on by an adverse galvanic couple between the steel channel and the alloy tube and tubesheet.

Copper-nickel and aluminum-bronze (solid or weld-overlaid surface) channels are preferred with copper-alloy tubes, and may also be used with high-alloy tubes. The adverse galvanic effect is diminished in such installations, because the area of the channel is larger than that of the tubesheet, and the channel and tubes are not contiguous. Channels of Type 316 stainless steel (solid or overlaid) are preferred with stainless-steel tubes.

Channel inlet arrangement — Uneven flow, restricted water passages and poor inlet-piping entry arrangements have caused numerous failures of copper-alloy tubes, as well as a few failures of stainless-steel tubes. Basically, the entry and flow pattern in both large and small channels should distribute the water uniformly to all tubes with as little swirling as possible.

If a review of the foregoing factors indicates that an exchanger's tubes must be of a metal that is even more corrosion resistant than a copper alloy or stainless steel, an engineer frequently resorts to a more highly alloyed metal, such a 6%-molybdenum stainless steel, a superferritic or titanium. These materials provide outstanding resistance to corrosion in crevices and beneath sediment. ■

The author

Arthur H. Tuthill, a materials and corrosion consultant (2903 Wakefield Dr., Blackburg, VA 24060; tel.: 703-953-2626), has had extensive experience in the fabrication, use and performance of metals, particularly involving heat exchangers, piping and pumps, in a wide range of industries. Holder of an M.S. in metallurgical engineering from Carnegie-Mellon University and a B.S. in chemical engineering from the University of Virginia, he is a licensed engineer (metallurgy). Among the many articles that he has had published is a five-part series in Chemical Engineering: "Installed Cost of Corrosion-Resistant Piping" (Mar. 3 and 31, Apr. 28, May 26 and June 23, 1986).