

# Selecting Tubing Materials for Power Generation Heat Exchangers

Daniel S. Janikowski  
Plymouth Tube Co. – East Troy, WI

*Presented at the Southwest Chemistry Workshop (Irving, TX): July 28-31, 2003*

---

## Abstract

A power plant engineer has many choices when selecting tubing materials for his condenser, feedwater heater or balance-of-plant application. The wide variety of stainless steel choices available (ASTM lists over 75 alloys) gives the engineer greater flexibility to choose the best candidate to meet budgetary constraints and still provide the performance needed for the lifetime of the plant. Unfortunately, upset conditions can be common in power generation, and these can result in premature unexpected failure of tubing and piping materials. These may include differences in operation modes from design, changes in water chemistry due to leaks in other parts of the system, corrosion from unexpected sources, impact of improper lay-up practices, and the effect of corrosion product transport to other parts of the system. The motivation to build modern combined-cycle power plants for the lowest cost per kilowatt has stretched the envelope for materials performance.

This paper provides an overview on a number of factors known to cause failure of a tube or pipe material. Knowing the limitations of material is crucial when making a selection for a specific application. This paper helps to identify the factors that need to be considered when selecting a material. Properties compared in this paper include corrosion resistance, stress corrosion cracking potential, thermal and mechanical properties, erosion resistance, vibration potential, and temperature limitations. The property comparison guides are intended to be quick tools to assist the user in selecting a cost-effective material for a specific application.

## Corrosion

Corrosion may be grouped into two broad categories, general corrosion and localized corrosion accelerated by an electrochemical mechanism. The latter group can be divided into several well-known specific mechanisms.

### General Corrosion

General corrosion is the regular dissolution of surface metal. The two most common encountered are the rusting of carbon steel and the wall thinning of copper alloys. General corrosion is normally not catastrophic. With proper planning, a heat exchanger can be designed to accommodate general corrosion, and in many instances, an alloy susceptible to this type of corrosion may be a cost-effective design option. Heat exchanger designers commonly add a "corrosion allowance" to a high-pressure carbon steel feedwater heater to allow for a 10 to 25 year lifetime.



2061 Young Street • East Troy, WI 53120 USA  
Visit us online at <http://www.plymouth.com>

DSSelMatsforPwrGen Copyright © 2005, Plymouth Tube Co.

Phone: **1-262-642-8370**  
Fax: 262-642-8486  
Email: [sales@plymouth.com](mailto:sales@plymouth.com)

Copper alloys are often chosen for condensing and BOP heat exchangers, and 25-year lifetimes are not uncommon. In some applications, copper alloys are expected to slowly dissolve to maintain some resistance to biofouling as the copper ion can be toxic to the microorganisms that attach to the tube wall. Unfortunately, on the steam side of the tubing, copper transport to other locations due to this slow dissolution may cause other problems. The copper can replate on turbine blades, resulting in a loss of efficiency, or on boiler tubes, resulting in premature failures. Although the discharge values on the cooling water side may be in the ppb concentration range, total copper metal discharge for a medium-sized condenser over the tubes' lifetime can exceed several hundred thousand pounds per unit. In some North American regions, high discharge levels have prevented the reuse of copper alloys in power plant heat exchangers.

### ***Electrochemically Driven Mechanisms***

Several corrosion-related mechanisms are electrochemically driven, and these can be very unpredictable. Therefore, they cannot be accommodated by design. These failure mechanisms usually have two stages: an incubation or initiation period, and a propagation mode. The time of initiation can be very unpredictable. It could happen in a few days or last for years. Once initiated, the second mode can occur rather quickly, driven by the electropotential between the two regions. Conductivity of the water may be a dominant factor. Higher conductivities allow higher current densities. Higher current densities are proportionately related to metal removal rates.

### ***Pitting***

Pitting corrosion is a highly localized attack that can result in through-wall penetration in very short periods of time. Failures may occur in less than four weeks. Once a pit is initiated, the environment in the pit is usually more aggressive than the bulk solution because of the pit's stagnant nature. Even if the bulk solution has a neutral or basic pH, the pH in a pit can drop below two. When this occurs, the surface inside the pit becomes active. The potential difference between the pit and the more noble surrounding area is the driver for the galvanic attack. As the surface area of the anode (pit) is small and the cathode (the passive surface surrounding the pit) is large, a very high current density in the pit is possible. This drives the very high corrosion rates.

The most common cause of pitting of stainless steels in the power industry is chlorides. Several alloying elements, such as chromium, molybdenum, and nitrogen, promote chloride resistance in this group of alloys. Not all have the same effect. By investigating the impact of each element, Rockel developed a formula to determine the total stainless steel resistance to chloride pitting (1):

$$\text{PREn} = \% \text{Cr} + 3.3 (\% \text{Mo}) + 16 (\text{N}) \quad (1)$$

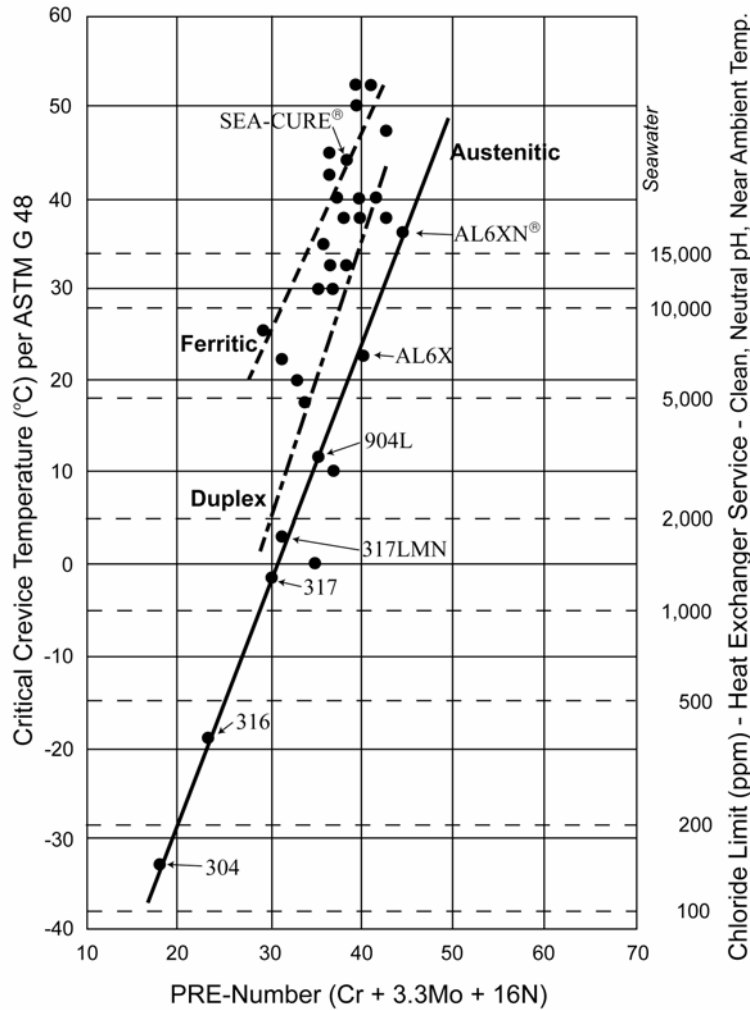
PREn represents the "Pitting Resistance Equivalent" number. Using this formula, various stainless steels can be ranked based upon their chemistry. In this formula, nitrogen is 16 times more effective and molybdenum is 3.3 times more effective than chromium for chloride pitting resistance. The higher the PREn, the more chloride resistance an alloy will have. It is interesting to note that nickel, a very common stainless steel alloying element, has little or no effect on chloride pitting resistance. However, it does have a profound impact in stress corrosion cracking which will be discussed later.

### ***Crevice Corrosion***

Crevice corrosion is very similar to pitting corrosion. However, since the tighter crevice allows higher concentrations of corrosion products (less opportunity to flush with fresh water), it is more insidious than pitting. This drives the pH lower. The end result is that crevice corrosion can happen at temperatures 30°-50° Centigrade lower than pitting in the same environment.

Crevice corrosion is commonly measured by the ASTM G 48 test. Kovach and Redmond evaluated a large database of existing crevice corrosion data and compared it to the PREn number described earlier (2). They developed relationships between the PREn and the G 48 critical crevice temperature (CCT)

and plotted the relationships. Figure 1 is a modified version to be used as a tool for comparing alloys and determining maximum chloride levels.



**Figure 1**  
**Critical Crevice Temperature and Maximum Chloride Levels Versus PREn of Various Stainless Steels**

Ferritic stainless steels were found to have the highest CCT for a particular PREn, followed by the duplex grade, and finally, the austenitics. Plotting the data for known alloys results in three separate almost parallel correlations. After a typical or minimum chemistry is determined, the PREn can be calculated. To compare the corrosion resistance of two or more alloys, a line is drawn vertically from the calculated PREn for each alloy to the appropriate sloped line for the structure. The vertical line should stop at the bottom line for austenitics, such as TP 304, TP 316, TP 317, 904L, S31254, and N08367. Duplex grades, such as S32304, S32003, S33205, and S32750, fall on the center line. The ferritics, such as S44660 and S44735, follow the top sloped line. From this intersection, a horizontal line should be drawn to the left axis to determine an estimated CCT. A higher CCT indicates more corrosion resistance.

## Maximum Chloride Levels

One of the most common questions asked is “What is the maximum chloride level that can be tolerated for a particular grade of stainless steel?” The answer varies considerably. Factors include pH, temperature, presence and type of crevices, and potential for active biological species. A guide is added along the right axis of Figure 1 to help in this decision. It is based upon having a neutral pH, 35° Centigrade flowing water (to prevent deposits from building and forming crevices) common in many BOP and condensing applications. Once an alloy with a particular chemistry is selected, the PREn can be determined and then intersected with the appropriate sloped line. The suggested maximum chloride level can then be determined by drawing a horizontal line to the right axis. In general, if an alloy is being considered for brackish or seawater applications, it needs to have a CCT above 25° Centigrade as measured by the G 48 test.

When using this guide, additional caveats need to be considered:

1. If the temperature is higher than 35° Centigrade, the maximum chloride level needs to be lowered.
2. If the pH is lower than 7, the maximum chloride level should be lowered.
3. This guide is based upon having a clean surface. If deposits are allowed to form, the pH can be significantly lower under the deposits, and the chloride levels may be much higher than the bulk water.

The 300 series maximum chloride levels shown in this guide are approximately 50% of what was considered acceptable 15-20 years ago (3). For example, TP 304 was commonly considered to be acceptable to 200 ppm chloride, and TP 316 was acceptable up to 1000 ppm. The difference is not related to a change in the data, but rather to a change in the steel making process. Because of improvements in stainless steel melting practices and competition, typical 300 series stainless steel chemistry produced today has a chemistry very near the bottom of the ASTM requirement. See Table 1 for a listing of ASTM stainless steel composition limits. Twenty years ago, typical TP 304 had a chromium level of approximately 19%, and TP 316 had a molybdenum content of typically 2.6%. These earlier alloys had a higher PREn than today’s versions, and thus, the higher chloride limits were justified. Today, for the 300 series grades, the minimum ASTM limits should be assumed to do the comparison. For grades other than the 300 series, contact the manufacturer of the alloy for typical minimum chromium, molybdenum, and nitrogen levels before calculating the PREn to rate the alloy.

**Table  
ASTM**

**Composition**

**Limits  
Minimum Unless Otherwise Specified**

**of  
Stainless**

**Ferritic - ASTM S268**

UNS	Commonly Used Name	Cr	Ni	Mo	Mn	Si	C	N	P	S	Other
S43035	TP439	17.0 - 19.0	0.50		1.00	1.00	0.07	0.040	0.040	0.030	0.15 Al, Ti = 0.20 + 4 (C+N) min.
S44660	SEA-CURE®	25.0 - 28.0	1.00 - 3.50	3.0 - 4.0	1.00	1.00	0.06	0.040	0.040	0.030	(Ti +Cb) = 0.20 - 1.00; (Ti + Cb) = 6(C+N)
S44735	AL29-4C®	28.0 - 30.0	1.00	3.60 - 4.20	1.00	1.00	0.03	0.045	0.040	0.030	(Ti +Cb) = 0.20 - 1.00; (Ti + Cb) = 6(C+N)

**Duplex - ASTM A789**

UNS	Commonly Used Name	Cr	Ni	Mo	Mn	Si	C	N	P	S	Other
S32205	2205	21.0 - 23.0	4.5 - 6.5	3.0 - 3.5	2.00	1.00	0.03	0.014 - 0.020	0.030	0.020	

**Austenitic - ASTM A249**

UNS	Commonly Used Name	Cr	Ni	Mo	Mn	Si	C	N	P	S	Other
S30400	TP304	18.0 - 20.0	8.0 - 11.0		2.00	1.00	0.08		0.045	0.030	
S30451	TP304N	18.0 - 20.0	8.0 - 11.0		2.00	1.00	0.08	0.110 - 0.16	0.045	0.030	
S31600	TP316	16.0 - 18.0	10.0 - 14.0	2.00 - 3.00	2.00	1.00	0.08		0.045	0.030	
S31700	TP317	18.0 - 20.0	11.0 - 15.0	3.00 - 4.00	2.00	1.00	0.08		0.045	0.030	
S31725	TP317LM	18.0 - 20.0	13.5 - 17.5	4.00 - 5.00	2.00	1.00	0.030	0.020	0.045	0.030	
S31254	254SMO®	19.5 - 20.5	17.5 - 18.5	6.0 - 6.5	1.00	0.80	0.020	0.18 - 0.25	0.030	0.015	0.050 - 1.00 Cu
N08367	AL6XN®	20.0 - 22.0	23.5 - 25.5	6.0 - 7.0	2.00	1.00	0.030	0.18 - 0.25	0.040	0.030	0.75 Cu

SEA-CURE® is a registered trademark of Crucible Materials Corp.

AL29-4C® and AL6XN® are registered trademarks of Allegheny Ludlum

254SMO® is a registered trademark of Avesta Polarit

## MIC

Microbiological Influenced Corrosion (MIC) is often confused with pitting corrosion and generally occurs in water normally considering benign. The term “influenced” is used since the bacteria itself does not cause the corrosion. Usually, the bacteria forms a crevice that isolates the water chemistry on the metal surface from the bulk water chemistry or has a waste product that can be very aggressive (4). Table 2 lists common bacteria types known to influence corrosion.

**Table**  
**Bacteria Commonly Associated with MIC**

2

Organism	Action	Problem
Thiobacillus	Sulfate Reducer	Produces H <sub>2</sub> SO <sub>4</sub>
Desulfovibrio	Sulfate Reducer	Produces H <sub>2</sub> S
Gallionella	Mn/Fe Fixer	Precipitates MnO <sub>2</sub> , Fe <sub>2</sub> O <sub>3</sub>
Crenothrix	Mn/Fe Fixer	Precipitates MnO <sub>2</sub> , Fe <sub>2</sub> O <sub>3</sub>
Spaerotilus	Mn/Fe Fixer	Precipitates MnO <sub>2</sub> , Fe <sub>2</sub> O <sub>3</sub>
Nitrobacter	Nitrate Reducer	Produces HNO <sub>3</sub>

The most common MIC attack in North America is a result of the influence of manganese reducing bacteria. Although the mechanism is complicated, following is the one most likely. The bacteria assist in the oxidation of the soluble Mg ion to form an insoluble MgO<sub>2</sub> layer on the metal surface. This creates a crevice. Additional chlorination intended to assist in the removal of the slime further oxidizes the layer to a permanganate. Under the layer, hydrochloric acid is formed as the byproduct of the oxidation process. The acid attacks the stainless.

Recent studies have found that manganese concentrations as low as 20 ppb can initiate the problem (5). This mechanism most commonly attacks TP 304 and TP 316, but higher molybdenum containing grades have also been attacked. In general, an alloy needs a minimum CCT of 25° Centigrade in the G 48 crevice corrosion test to be considered resistant to MIC.

## Stress Corrosion Cracking

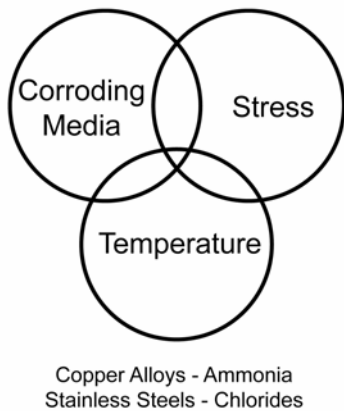
Stress Corrosion Cracking (SCC) is a failure mechanism that can cause rapid failure when the required specific combination of conditions coexist. Figure 2 shows transgranular stress corrosion cracking in TP 304N feedwater heater tubing. This failure mechanism is identified from other brittle-type failures, such as fatigue, by the branching and secondary cracking. In 300 series stainless steels, it most usually occurs in the desuperheating zone of a feedwater heater, where conditions can concentrate chlorides.



**Figure 2**  
**Transgranular Cracking in TP 304N Feedwater Heater Tubing**

Figure 3 shows the three factors needed to cause stress corrosion cracking of an alloy system: tensile stress, the specific corrodent, and a minimum temperature. The stress is a combination of all of the sources that include residual stress, thermally induced stress, load applied stress (such as hoop stresses from the pressure inside the tube), and stress from other sources. Common sources of corroding media in the power industry include ammonia for the copper alloys and chlorides for the stainless steel alloys. In general, the minimum temperature is needed before the problem is evident. For example, chloride SCC in steam surface condensers is not a problem because the metal temperature is below the threshold.

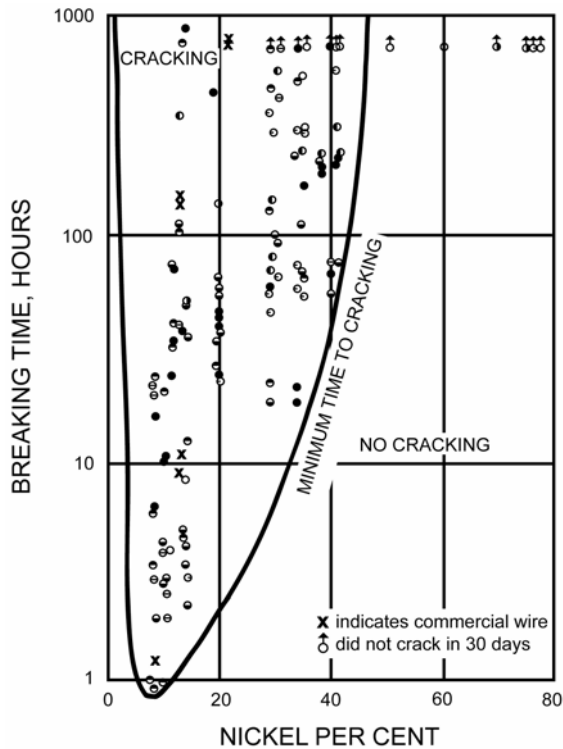
Corroding Media + Stress + Temperature



**Figure 3**  
**Three Factors Necessary for Stress Corrosion Cracking**

Not all stainless steels are equally susceptible to SCC. Copson determined that a direct relationship exists between the time to failure and the nickel content (6). As shown in Figure 4, a combination of time and specific nickel concentrations above the curve failed, while those below the curve did not. The

stainless steel nickel content with the most potential is 8%, which is the same content of the workhorse of the industry, TP 304. TP 316, with a 10% minimum nickel content, is still very susceptible as can be seen by the slightly higher time to failure. Improvements in time to failure come from selecting an alloy with very low nickel, such as TP 439, or very high nickel, such as the 6% molybdenum containing alloys or alloy 20. The high nickel alternative can be very expensive. Surprisingly, this curve shows that non-austenitic alloys can crack!



**Figure  
Copson Curve**

Crucible Research tested a group of ferritic, duplex, austenitic, and high performance stainless steels in a series of autoclave tests duplicating faulted feedwater using u-bent strip samples (7). Table 3 shows the results. Mirroring the Copson curve, the alloys containing 8% nickel failed first. Interestingly, one of the most popular choices for high pressure feedwater heaters, TP 304N, failed more quickly than the non “N” version. Although this suggests that the chemical nature of the nitrogen addition makes the alloy more susceptible, the more likely reason is that the u-bend TP 304N specimen had higher stresses than the non “N” version due to its higher yield strength. However, the higher allowable stresses allowed in the code for the “N” derivative are the precise reason that the alloy is so popular. In this testing, only TP 439, the alloy containing no nickel, escaped cracking.



**28 Day Stress Corrosion Cracking Tests of Strip U-Bend Specimens in Aerated Neutral Chloride-Containing Waters\***

Grade	Ni %	Test Temperature (°F)							
		250			350		450		
		Chlorides (ppm)							
		100	1,000	10,000	100	1,000	100	1,000	
TP 439	0.4	---	---	---	---	0	0	0	0
SEA-CURE <sup>®</sup>	2.0	---	---	---	---	0	0	0	X
2205	5.0	---	---	---	---	0	X	X	---
TP 304L	8.0	0	0	X**	X	X	X	X	X
TP 304LN	8.0	0	X	X**	X	X	X	X	---
TP 316L	11.0	0	0	0**	X	X	X	X	---
254SMO <sup>®</sup>	18.0	---	---	---	---	0	X	X	X
AL6XN <sup>®</sup>	25.0	---	---	---	---	0	X	X	X

- \* = Constrained U-Bend Specimens
- \*\* = Testing Terminated After 15 Days
- 0 = No Cracks in 28 Days
- X = Cracked During Test
- = Not Tested

### Effect of Other Material Properties

Table 4 is a listing of mechanical and physical properties for common copper base, titanium, and stainless steel tubing. These properties have a direct impact on many of the concerns considered in the selection process for an alloy in heat exchanger service.

### Erosion-Related Problems

Erosion resistance is a function of the ability of the protective layer to remain attached to the substrate and the strength (hardness) of the substrate directly below the protective layer. Two types of erosion commonly cause problems in the power industry - flow assisted erosion/corrosion and water droplet/steam impingement erosion.

### Flow Assisted Erosion/Corrosion

Flow assisted corrosion is caused by the removal of the protective scale on the ID surface of a tube because the fluid velocity is too high. Table 5 summarizes commonly selected flow rates that are the maximum safe values for an alloy. For improved heat exchanger performance, higher velocities have two advantages: they allow higher heat transfer, and they keep surfaces clean, reducing the surface interface resistance. In general, a minimum velocity of six feet per second is considered necessary to keep the tube surface relatively clean. Biofilms have been known to develop in lower flow rates.

**Table**  
**Mechanical & Physical Properties of Various Heat Exchanger Tube Candidates, Typical Unless Otherwise Noted**

<b>Property</b>	<b>Admiralty Brass C44300</b>	<b>Aluminum Brass C68700</b>	<b>90/10 Cu/Ni C70600</b>	<b>70-30 Cu/Ni C71500</b>	<b>TP 439 S43035</b>	<b>TP 304/TP 316 S30400/S31600</b>	<b>AL6XN® N08367</b>	<b>SEA-CURE® S44660</b>	<b>Ti Grade 2</b>
Ult. Strength	53 ksi	60	50	50	60*	75*	100*	85*	50*
Yield St.	22 ksi	27	15	25	30*	30*	45*	65*	40*
Elongation	60%	55%	35%	25%	20%*	35%*	30%*	20%*	20%*
R. Hardness	RF 75	RB 50	RB 30	Rb 20	RB90**	RB 90**	RB 100**	RC 25**	RB 92**
Mod. Of Elast.	16 x 10 <sup>6</sup> psi	16.0	18.0	18.0	29.0	28.3	28.2	31.5	14.9
Density	.308 lbs/in <sup>3</sup>	0.301	0.323	0.320	0.280	0.29	0.29	0.278	0.16
Thermal Expan.	11.2 x 10 <sup>-6</sup> in/in/degree F	10.3	9.5	9.5	5.6	9.5	8.7	5.38	5.2
Thermal Cond.	64 BTU/ft-hr-F	58	23.0	17.0	12.3	8.6	7.9	9.9	12.5
Fatigue Endur.	20 ksi	20	20	22	20	30	33	35	16 ksi

\* Minimum ASTM Value

\*\* Maximum ASTM Value

**Table**  
**Commonly Accepted Maximum Water Flow Rates for Erosion/Corrosion**

<u>Alloy</u>	<u>Maximum Velocity</u>
Admiralty	6 FPS
90/10 Cu/Ni	8 FPS
70/30 Cu/Ni	10 FPS
304/316 Stainless Steel	30+ FPS
Ti Grade 2	30+ FPS
Superferritic Stainless Steel	100+ FPS

**Water Droplet/Steam Impingement Erosion**

In some specialized conditions, it is possible to experience erosion of the tube OD surface due to localized impact of high velocity water droplets. This can occur near diverter plates that may focus steam velocity or during upset conditions. It often occurs in steam dump areas when the outlets are not properly designed. The resistance of this erosion is a direct function of the hardness of the metal substrate below the protective oxide. In general, higher hardness provides higher erosion resistance. Using a water droplet impingement device developed by Avesta Sheffield, alloys can be ranked by time to failure (8). By plotting hardness versus time to failure, a relationship can be determined. Other grades can then be added by comparing the hardness. Using titanium grade 2 as a reference of "1", the relative resistance of other grades can be ranked. The ranking is presented in Table 6.

**Table**  
**Relative Erosion Resistance Bases Upon Water Droplet Impingement Tests**

<u>Alloy</u>	<u>Hardness HV</u>	<u>Relative Erosion Resistance</u>
Admiralty	60 HV	0.4
70-30 Cu-Ni	135 HV	0.8
Ti Grade 2	145HV	1.0
TP 304/TP 316	165 HV	2.0
Ti Grade 12	190 HV	3.6
254 SMO/AL6XN <sup>□</sup>	200 HV	7.0
Ti Grade 9	215 HV	6.2
SEA-CURE <sup>□</sup>	240 HV	7.2
Alloy 2507	290 HV	9.4

Values based upon water droplet impingement work presented in ACOM4-96

**Vibration Resistance**

Vibration is a major concern in condensers and other heat exchangers, especially during upset conditions or when inlet water temperature is very low. Coit, et al, developed a method to compare potential vibration in condensers as a function of material properties and steam velocity (9). Using this, maximum support plate spacing can be calculated in a specific condenser comparing OD, wall, and grade of various alloys. The following formulas are used:

$$L = 9.5 [( E I ) / \rho v^2 D]^{1/4} \tag{2}$$

$$I = \pi / 64 ( D^4 - ID^4) \tag{3}$$

Where:

- E = Modulus of Elasticity (psi)
- I = Moment of Inertia (in<sup>4</sup>)
- $\rho$  = Turbine Exhaust Steam Density (lb/ft<sup>3</sup>)
- v = Average Exhaust Steam Velocity at Condenser Inlet
- D = Tube Outside Diameter
- ID = Tube Inside Diameter

It is clear from the formula, considering the same OD and wall tube, the property that has the largest impact on vibration is the modulus of elasticity. Higher modulus alloys are stiffer and have more vibration resistance. As seen in Table 4, titanium grade 2 has the lowest stiffness followed by the copper-based alloys and the austenitic stainless steels. Because of the very high modulus of the superferritic alloys, such as S44660 and S44735, these alloys have the highest resistance to vibration.

Using Coit's method, Table 7 displays a hypothetical condenser minimum wall using the same steam flow, tube OD, and support spacing for different materials. For a given support spacing, alloys with low modulus may require twice the wall thickness as those with a higher modulus to prevent the risk of vibration damage. Alternatively, if a heat exchanger is newly constructed, the support plates need to be significantly closer on the lower modulus materials. Existing exchangers can be retubed with a lower modulus material if staking is used. However, this can add significant additional cost, and one should be very careful of stake selection as the reliability of stakes can vary significantly.

**Table 7  
Minimum Walls for Various Condenser Candidates for Similar Support Spacing**

<u>Alloy</u>	<u>Wall</u>
Admiralty	.049"
90/10 Cu/Ni	.043"
70/30 Cu/Ni	.034"
TP 439	.025"
TP 304/TP 316	.026"
N08367	.027"
S44660	.023"
Ti Grade 2	.053"

Based upon a typical condenser with identical tube OD, support spacing, steam flow, and back pressure using Coit method for vibration.

## Thermal Conductivity

Although the pure material thermal conductivity of the various power-tubing candidates has a very wide range, as shown in Table 4, the actual range of tubing thermal performance is not as large a spread. Several factors impact the total thermal efficiency of an alloy:

1. Actual wall thickness of the tube material selected. Because of the low modulus and mechanical properties and a potential need for corrosion allowance, copper alloy tubes are normally much thicker than stainless steel tubes.
2. Boundary layers on both the OD and ID surfaces can act as additional thermal resistances.
3. Deposits can form creating additional resistances.

Condensing studies done at Rochester Institute of Technology, used to develop heat transfer parameters for the HEI 9<sup>th</sup> Edition, show realistic differences between the alloys (10). The test results (Figure 5) are based upon new tubes, prior to the formation of oxides, scales, and slimes common after a few months of use. Once scales and deposits develop with time, the difference between the copper alloys and the stainless steels is less evident. In many cases, the stainless steels can be an advantageous selection. In condensing applications, copper alloys commonly develop steam side thermal barriers resulting from corrosion reactions with the chemicals normally added for oxygen control. This does not occur on stainless steels. Generally, the degradation of copper's overall conductivity gradually declines over the first year in fresh water service and even more quickly in sea and brackish water service (11). To account for this difference in condensing applications, the HEI method assigns different cleanliness factors to the different alloy groups. The cleanliness factor chosen for copper alloys is commonly 85%, while 90-95% is normally assumed when stainless steels and titanium tubes are used.

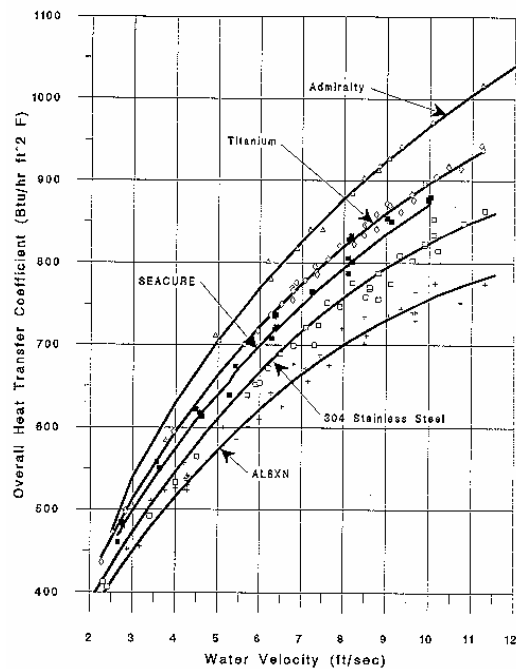


Figure  
Heat Transfer Rates

5

## Economic Considerations

A recent tube price comparison of various alloys is shown in Table 8. Prices can vary considerably depending upon quantity purchased, availability, and OD-to-wall ratio. Nickel prices have varied dramatically in the last few years, ranging from under \$2 per pound to over \$5 per pound. Major swings

have occurred in only a few months. Therefore, one should be very careful when assembling long-term budgets for alloys that have higher nickel contents such as TP 304, TP 316, cupro-nickels, and the 6% molybdenum containing alloys. Alloys with low nickel such as admiralty brass, TP 439, and the superferritics are more stable and predictable.

**Table**  
**Relative Prices of Heat Exchanger & Tubing Candidates**

8

**1" OD – 22 BWG, .028" Wall Unless Otherwise Noted**

Grade	Wall	Relative Price
TP 304		1.0
TP 316		1.2
TP 439		1.2
TP 317		1.6
Al Brass	18 BWG	1.6
90/10 Cu/Ni	20 BWG	1.9
SEA-CURE <sup>®</sup>	25 BWG	2.0
2205		2.1
Ti Grade 2	25 BWG	2.4
SEA-CURE <sup>®</sup>	22 BWG	2.4
Ti Grade 2	22 BWG	3.1
AL6XN <sup>®</sup>		3.5
70/30 Cu/Ni	20 BWG	3.8

Approximate values as of 6/2003, Nickel at \$4.00 on LME, Mo at \$6.00

### **Precautions**

Appendix 1 includes a ranking system for commonly chosen alloys in different environments. Not all stainless steels are good choices for every application. In addition to the concerns identified earlier, following are additional caveats that need to be considered during the material selection period.

### **885° F Embrittlement**

Ferritic and duplex stainless steel alloys containing 12% chromium or greater are susceptible to 885° F embrittlement. This is caused by the formation of brittle secondary phases during prolonged exposure to elevated temperature. ASME cautions the use of these materials above 500° F (12). Although several thousand hours of exposure may be needed at the lower temperatures before the loss of ductility is noted, it can occur fairly rapidly at the peak temperature of 885° F. The exposure is cumulative. The time is additive for repeated excursions into the embrittlement range. The only way to eliminate this damage is to reanneal the material at the original solution annealing temperature. Once installed into a bundle, this is not normally an option.

### **Hydrogen Embrittlement**

Titanium and superferritic stainless steels, such as S44660 and S44735, can embrittle with exposure to monotonic hydrogen. This commonly occurs in water systems that have poorly controlled cathodic protection. The problem is prevented when the system is controlled so that the voltage is maintained at a

potential more positive than  $-750$  millivolt. When the voltage is more negative, hydrogen bubbles develop on the surface. During the development stage, monatomic hydrogen develops which easily diffuses into the material.

Embrittlement of titanium occurs as an intermetallic phase develops on the surface in contact with hydrogen. This layer grows with exposure and eventually progresses through the entire wall. These embrittled tubes have little or no mechanical strength. Tubes can be broken simply by leaning on them. This process is not reversible.

Fortunately, unlike titanium, the hydrogen in superferritic stainless steels stays at interstitial sites in the lattice structure. The embrittlement in the stainless is easily reversed. Once the source of the hydrogen is eliminated, the atoms in the stainless diffuse out of the structure, and the ductility returns. This normally occurs within 24 to 48 hours at  $80^{\circ}$  F, and the ductility can return in as soon as one hour at  $200^{\circ}$  F.

## Conclusion

Stainless steels can be the most cost-effective heat exchanger tubing choice. A number of factors need to be considered including potential for corrosion and erosion, maximum temperatures, vibration potential, and mechanical property requirements. When all factors are considered in the material decision, this group of alloys can provide service for the life of a plant.

## References

1. M. Rockel, "Use of Highly Alloyed Stainless Steels and Nickel Alloys in the Chemical Industry," Achoma Conference, Frankfurt, Germany (1928).
2. C.W. Kovach and J.D. Redmond, "Correlation Between the Critical Crevice Temperature "Pre-Number", and Long-Term Crevice Corrosion Data for Stainless Steels," presented at the NACE Annual Conference Corrosion 93, New Orleans, LA (April 1993).
3. Ivan Franson, "Selection of Stainless Steel for Steam Surface Condenser Applications," presented at the Jt. ASME/IEEE Power Generation Conference, Milwaukee, WI (October 1985).
4. John Tverberg, Kenneth Pinnow, and Lawrence Redmerski, "The Role of Manganese Fixing Bacteria on the Corrosion of Stainless Steel," presented at the NACE Annual Conference Corrosion 90, Las Vegas, NV (April 1990).
5. W.H. Dickinson and R.W. Pick, "Manganese-Dependent Corrosion in the Electric Utility Industry," presented at the NACE Annual Conference Corrosion 2002, Denver, CO (April 2002).
6. H.R. Copson. *Physical Metallurgy of Stress-Corrosion Fracture*. New York: Interscience, 1959, p. 247.
7. Internal Research. Pittsburg, PA: Crucible Research, 1987.
8. Jūri O. Tavast, "Steam Side Droplet Erosion in Titanium Tubed Condensers – Experiences and Remedies," ACOM. Schaumburg, IL: AvestaPolarit, Inc., April 1996.
9. R.L. Coit, CC. Peake, and A. Lohmeier, "Design and Manufacturing of Large Surface Condensers – Problems and Solutions," *Volume XXVIII - Proceedings of the American Power Conference*. 1966, pp. 469-483.
10. Dr. Robert J. Hefner. *Effect of Tube Material SEACURE on Steam Condensation*. Rochester, NY: Rochester Institute of Technology, July 1993.
11. R.A. McAllister, D.H. Eastham, N.A. Dougharty, and M. Hollier, "A Study of Scaling and Corrosion in Condenser Tubes Exposed to River Water," *Corrosion*, Vol. 17, No. 12, December 1961, pp. 579t-588t.
12. ASME Code, Section II, Part D, Appendix 6, paragraph 6-630, 2001 Edition, no addenda.

**Appendix  
Common Power Materials Ratings**

1 is Best, 5 is Worst

Alloy	UNS Designation	Property/Environment								
		Chloride Pitting	Steam Droplet Erosion	Erosion/Corrosion	Ammonia SCC & Grooving	Chloride SCC	Vibration Resistance	Sulfur/MIC Resistance	Fe/Mn MIC Resistance	Hydrogen Embrittle
Admiralty	C44400	4	5	5	5	1	5	5	3	1
90/10 Cu/Ni	C70600	3	4	4	4	1	4	5	3	1
70/30 Cu/Ni	C71500	2	3	3	3	1	4	4	2	1
TP 304/L	S30403	5	2	2	1	5	2	3	5	1
TP 304N	S30451	5	2	2	1	5	2	3	5	1
TP 316/L	S31603	4	2	2	1	5	2	3	4	1
TP 317/L	S31703	3	2	2	1	4	2	2	3	1
TP 439	S43035	5	2	2	1	1	2	4	5	1
2205	S32205	2	1	1	1	3	2	2	3	1
904L	N08904	2	1	1	1	3	2	1	3	1
254SMO®	S31254	1	1	1	1	3	2	1	2	1
AL6XN®	N08367	1	1	1	1	3	2	1	1	1
SEA-CURE®	S44660	1	1	1	1	2	1	1	1	4
Ti Grade 2	R50400	1	3	2	1	1	5	1	1	5