90/10 Copper-Nickel vs. Aluminum Brass
A Functional Comparison of Two Heat Exchanger Tube Alloys

Copper alloys find widespread use in heat transfer applications because of their excellent heat transfer properties and their natural inherent resistance to biological fouling. Two of the more commonly used copper alloys used in MSF and MED desalination plants, and in seawater power plants, are Aluminum Brass and 90/10 Copper-Nickel. These alloys are used in the evaporators, brine heaters, and heat reject sections of desalination plants, and in the air removal, steam impingent, and main body sections of power plant steam surface condensers. To facilitate the selection of the optimum alloy for these applications, the corrosion resistance, heat transfer capability, and cost of both alloys are compared in this paper.

Composition

The chemical compositions of Alloy C706, 90/10 Copper-Nickel, and Alloy C687, Aluminum Brass, are shown in Table 1 below [1].

Table 1 - Nominal Composition in Percent (maximum if not stated as a range)

Alloy	Cu	Ni	Fe	Zn	Al	As	Pb	Mn
C687 00	76.0-79.0	- - -	0.06	Balance	1.8-2.5	0.02-0.06	0.07	- - -
C706 00	Balance	9.0-11.0	1.0-1.8	1.0	- - -	- - -	0.05	1.0

Corrosion Resistance

The corrosion resistance of all copper alloys depends upon the formation of a protective oxide film. Alloying elements such as zinc, nickel, tin, or aluminum affect the tenacity and adherence of the protective films that form, and thus the relative corrosion resistance of the individual alloys. The general corrosion rate of most copper alloys in seawater is very low and decreases quickly over time as the protective oxide films form. For this reason, premature failure from general corrosion is rarely experienced. However, high water velocity, ammonia, and sulfides can contribute to localized selective attack. The resistance of aluminum brass and 90/10 copper-nickel to these forms of localized attack, as well as several others, is discussed in the following paragraphs.

High Water Velocity

Excessively high water velocities can lead to a type of selective corrosion known as erosion-corrosion. This form of accelerated corrosion is caused by localized turbulence that exerts shear forces on the inside surface of a tube sufficient to remove the protective oxide film. In seawater, the critical shear stresses required to strip away the protective oxide films that are formed on each alloy are shown in Table 2. As can be seen, the critical shear stress needed to strip away the protective oxide film on 90/10 Copper-Nickel is more than twice that of Aluminum Brass. In Table 3, the generally accepted design velocities for each alloy in seawater are listed. Most power plant steam condensers are designed in accordance with the flow rates listed in Table 3. However, many more units that are tubed with Aluminum Brass experience inlet and outlet end erosion-corrosion than do units that are

Table 2 - Critical Shear Stress to Remove Protective Oxide Films [2]

Alloy	Stress, N/m^2
C687	19.2
C706	43.1
C715	47.9

Table 3 - Generally Accepted Design Velocities for Seawater Service [3]

Alloy	Meters Per Second	Feet Per Second
C687	1.7 - 2.0	5.5 - 6.5
C706	2.0 - 2.3	6.5 - 7.5
C715	2.4 - 2.9	8.0 - 9.5

tubed with 90/10 Copper-Nickel. Given that the turbulence at the tube inlet and outlet is higher than within the tube, the critical shear stress data in Table 2 provides an explanation for this phenomenon. 70/30 Copper-Nickel Alloy C715, well known for its resistance to erosion-corrosion, was included in both table 2 and table 3 for reference purposes.

Sand

Sand, which is common in seawater from open channels in shallow waters, can be detrimental to copper alloy tubing. High sand loadings can damage the protective film, exposing bare metal to high unfilmed corrosion rates. Sato and Nagata [4] determined that, for any given sand loading, damage increases with the size and sharpness of the sand present. Fine beach sands which are the most likely to be encountered are less damaging than larger angular particles encountered in some estuaries. The general order of resistance to sand of various copper alloys was determined to be:

1) C68700 - least resistance
2) C70600 - more resistant
3) C71500 - more resistant
4) C72200 - outstanding resistance
4) C71640 - outstanding resistance

Ammonia

Ammonia increases the general corrosion rate of copper alloys and, in steam power plants, ammonia is often used to adjust the pH of the feedwater. In the steam surface condensers of these power generation plants, ammonia and oxygen concentrations in the main body are typically low enough that problems do not arise. However, the service conditions in the air removal section are more severe and only materials that are resistant to ammonia attack should be specified. The resistance to ammonia attack by Aluminum Brass and 90/10 Copper-Nickel is shown in Figure 1. Alloy C715 (70/30 copper-nickel) and Alloy S304 stainless steel, traditionally considered to be highly resistant to ammonia attack, are included for reference.

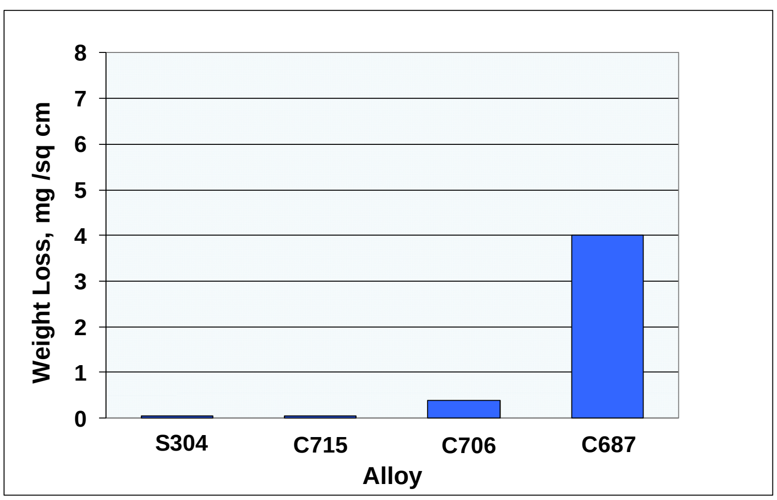

Figure 1 - Weight loss of various alloys after exposure to 1000 ppm NH_3 contaminated condensate at 38C (100F) for 10 days [5].

Ammonia can also cause stress corrosion cracking in some copper alloys. For the occurrence of stress corrosion cracking, there are three requirements - the presence of a corrosive environment, the presence of applied or residual stresses, and a susceptible material. For copper alloys, ammonia represents the required corrosive environment (similar to how chlorides are a corrosive environment for stainless steels). Stresses can be present from cold work imparted during the tube manufacturing process or from subsequent operations such as tube bending or the rolling-in of tubes into a tubesheet. The susceptibility of an alloy to stress corrosion cracking depends largely upon alloy composition, and the susceptibility of many copper alloys, including Aluminum Brass and 90/10 Copper-Nickel, was evaluated by Thompson [6] by subjecting them to an applied stress in an ammoniacal environment, and then measuring the time that it took for the materials to exhibit a 50% relaxation in stress level; a 50% relaxation in stress level was considered to be indicative of a point that stress cracking had initiated. The results for Aluminum Brass and 90/10 Copper-Nickel are reported in Table 4.

Table 4 - Time to 50% Relaxation in an Ammoniacal Environment

Alloy	Time in Hours
C687	0.6
C706	234

As can be seen, Aluminum Brass is a highly susceptible material whereas 90/10 Copper-Nickel is highly resistant; the 90/10 Copper-Nickel is almost 400 times more resistant to stress corrosion cracking than Aluminum Brass. Further, with special processing to fully solutionize the iron in the alloy, 90/10 can be made to be essentially immune [7].

Ammonia may also be present in the seawater feed to desalination plants as a result of agricultural runoff or industrial plant discharges near the intake. The relative lack of literature on this topic suggests that ammonia attack is not a primary concern for heat transfer tube in desalination plants.

Sulfides

Pitting of copper alloys can occur in polluted waters as a result of the deposition of sulfides [8] onto the surface of an alloy to create cuprous sulfide, a black non-protective film. Pitting occurs because the sulfide layer is cathodic to the base metal. Pitting is less severe when the tubes have first been exposed to clean seawater and have had time to fully develop the desired cuprous oxide film, whereas pitting is usually very severe when the cooling water first introduced to the new tubes contains sulfides. In general, when there are only brief exposures to sulfides during normal operation, problems rarely exist, but 90-10 Copper-Nickel does add a margin of safety over Aluminum Brass, as shown in Figure 2.

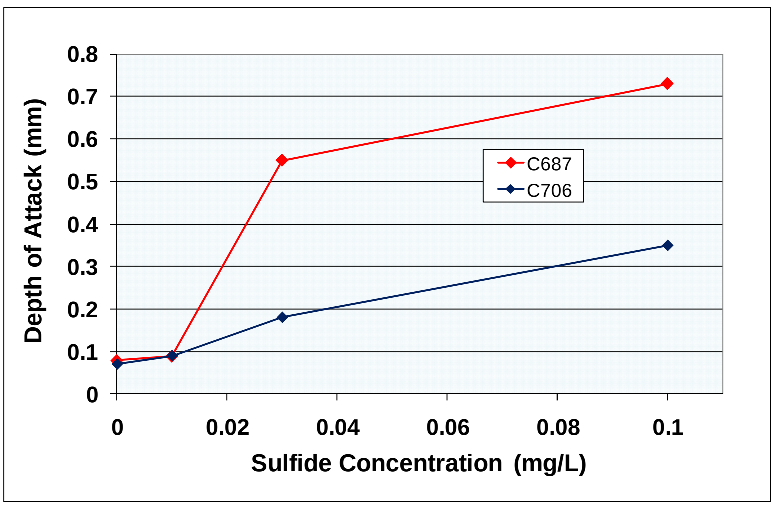

Figure 2 – The Effect of Sulfides on the Pitting Corrosion of 90/10 Copper-Nickel and Aluminum Brass at 7 m/sec at 5-20 °C [9].

Sulfides are typically present as either hydrogen sulfide or cystine, both of which are found in polluted waters, but sulfide-related pitting can also occur in waters that do not contain either sulfides or cystine. This could happen during a shutdown if the cooling water contained sulfates and it was not drained or periodically aerated. In this situation, anaerobic bacteria convert the naturally occurring sulfates to sulfides. When long term exposure to seawater containing greater than 3 ppm sulfides is expected, the use of any copper alloy should be avoided [10].

Chlorination

Chlorination practices vary considerably from site to site, as both the need for chlorination and local governmental regulations affect the amount actually used. The effect of chlorine residuals in the 0.5 to 3.0 ppm range on alloys C687 and C706 is shown in Table 6. Although the corrosion rates vary with the specific chlorination regime being employed, it can be generalized that the corrosion rate for C687 is increased substantially by residual chlorine in the 0.5-3.0 ppm whereas the corrosion rate of C70600 is only slightly increased. Overdosing beyond 3ppm, which unfortunately occurs from time to time, can be detrimental to both alloys. In desalination plants, tubing in the heat reject stage is more likely to be affected by overdosing, while tubing in the heat recovery stage downstream of the heat reject stage, is less affected by overdosing as the residual chlorine is consumed rapidly.

Table 5 - The Effects of Chlorination on Corrosion [11] – mils/year (59-187 days in 60-70°F seawater)

Chlorine Residual	Alloy C687	Alloy C706
0.0 ppm	< 1.0	< 1.0
0.5 ppm Continuous	2.9	1.6
0.5 ppm / 2 hr on-2 hr off	3.1	0.7
1.0 ppm / ½ hr on-5-½ hr off	3.7	0.7
1.5 ppm / 2 hr on-2 hr off	0.9	0.5
3.0 ppm / 2 hr on-2 hr off	2.4	0.3

Steam Impingement

Steam Impingement occurs in power plant steam condensers when the kinetic energy of the high velocity steam entering the condenser is great enough to strip off the protective oxide film on the condenser tubes. Experimental data simulating the effect of high velocity steam doesn't appear to exist. However, impingement data for high velocity water jets does exist as shown in Figure 3, and

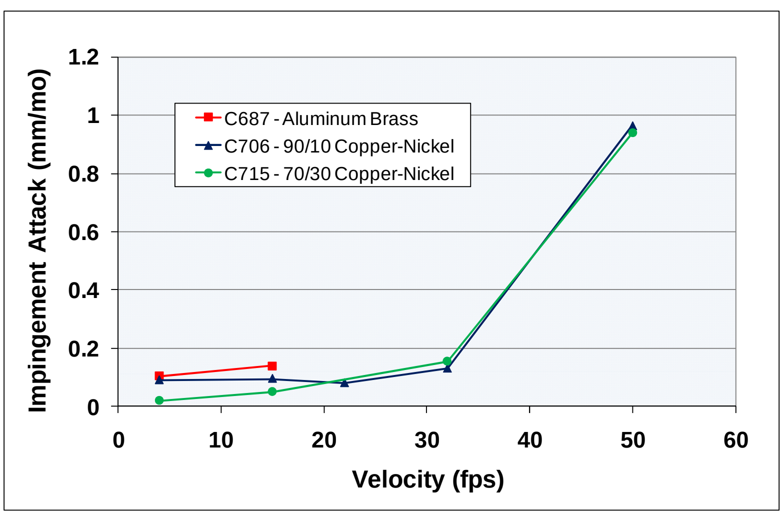

Figure 3 – Jet Impingement Attack at Varying Water Velocities

can be used to predict behavior in high velocity steam. From this data, it can be seen that the impingement attack on aluminum brass was almost twice that of the 90/10 Copper-Nickel at relatively low jet velocities; testing on the aluminum brass was suspended for this reason. Further, the 90/10 Copper-Nickel was able to tolerate twice the velocity of the Aluminum Brass for the same degree of impingement attack. This is exactly what would be expected based on the "Critical Shear Stress Data" that was presented above in the discussion on the effects of high water velocity and erosion-corrosion.

The Effect of Oxygen and Elevated Temperature (12)

The effect of oxygen at 220°F is illustrated in Figure 4 and the effect of temperature at 200 ppb oxygen is illustrated in figure 5. This data was generated at a velocity of 7-8 fps in seawater with a Total Dissolved Solids of 35,000 ppm for a period of 90 days.

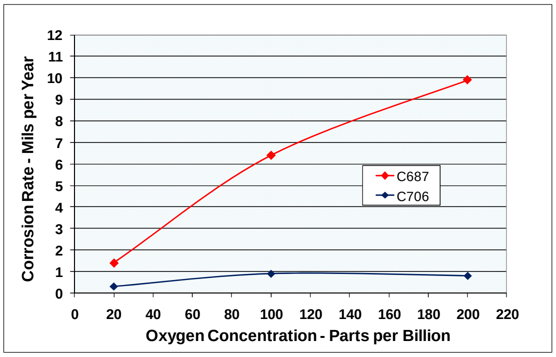

Figure 4 – The Effect of Oxygen

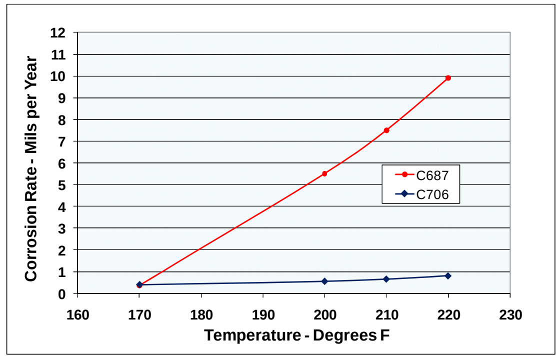

Figure 5 – The Effect of Elevated Temperature

As can be seen, the corrosion resistance of Aluminum Brass is poor under the combined conditions of high temperature and high oxygen.

Heat Transfer Comparisons

The thermal conductivities of both Aluminum Brass Alloy C687 and 90/10 Copper-Nickel Alloy C706 are listed in Table 6. However, the use of thermal conductivity to compare heat exchanger tube materials is misleading since many other factors contribute to heat transfer resistance including water side and steam side water films, the protective oxide films that form on the ID and OD of the tubes, crystalline fouling (scale), and biological fouling. The Heat Exchange Institute (HEI) accounts for the water films, oxide films, and fouling through the use of correction factors for water temperature, the tube material and tube wall thickness, and the tube cleanliness; these are multiplied times an uncorrected heat transfer coefficient to calculate an overall heat transfer coefficient. Values for the "tube material and gauge correction factor" can be used to compare materials, and are also listed in Table 6 for the commonly specified wall thicknesses. Admiralty Brass Alloy C443 is included in this table because it is rated at 1.00 for a wall thickness of 0.049" and is considered to be the standard when making material comparisons.

Table 6 - Comparative Heat Transfer Data for Alloys C687 & C706 (13)

Alloy	Thermal Conductivity (BTU/Sq.Ft/Ft/Hr/°F @ 68°F)	Tube Wall Thickness	HEI Gauge Correction Factor
C443	64	18 BWG (0.049")	1.00
C687	58	18 BWG (0.049")	0.99
C706	26	18 BWG (0.049")	0.93
C706	26	20 BWG (0.035")	0.96

As shown in Table 6, Aluminum Brass has an advantage over 90/10 Copper-Nickel with regard to heat transfer capability. However, as will be shown in the next section, 90/10 Copper-Nickel can be used at a reduced wall thickness versus Aluminum Brass, and this essentially reduces the heat transfer advantage of Aluminum Brass to approximately 3%.

Wall Thickness Considerations

The superior corrosion resistance of 90/10 Copper-Nickel as compared to Aluminum Brass allows the use of a reduced wall thickness for the 90/10 in a maintenance retubing situation. For a given material, a reduction in wall thickness would increase tube vibration and deflection which could lead to tube fretting and mid-span collision. However, the higher modulus of elasticity of 90/10 Copper-Nickel allows it to be used at 20 BWG Minimum Wall (0.035" minimum) in place of 18 BWG Average Wall (0.049" average) Aluminum Brass without these concerns.

"The Design and Manufacture of Large Surface Condensers – Problems and Solutions" [14] by Coit, Peake, and Lohmeier (Westinghouse Heat Transfer Division) offered the following formula for calculating the maximum allowable tube span (L_c):

$$L_c = 21.8 \{S_c E I \delta / \rho V^2 D\}^{1/4}$$

where:
- S_c = Severity Factor (conservative value = 1.7, 2.0 = acceptable)
- ρ = Steam Density (lbs/ft^3)
- V = Average Steam Velocity @ Inlet (ft/sec)
- D = Tube Diameter (in.)
- δ = Logarithmic Decrement of Vibrating Tube
- E = Material Modulus of Elasticity (psi)
- I = Cross Sectional Moment of Inertia (in.)

The material related factors in this equation are the tube material modulus of elasticity (E), the tube outside diameter (D), and the tube cross sectional moment of inertia (I).

When considering the substitution of one condenser tube material for another, as might be done at the time of a maintenance retubing, the minimum allowable wall thickness for a potential replacement material can be calculated by equating $(EI/D)^4$ for the material being replaced with $(EI/D)^4$ for the potential replacement material.

This calculation can be reduced to:

$$EI \text{ (existing material)} = EI \text{ (replacement material)}$$

where: $I_{tube} = I_{OD} - I_{ID} = \pi(OD)^4/64 - \pi(ID)^4/64$

When calculating the moment for the tube ID, the theoretical minimum wall thickness of the material being replaced should be used. For example, if 18 BWG (0.049") average wall Aluminum Brass tubing was being replaced, a wall thickness of 0.0445" (or an ID of 0.911) would be used to calculate the tube moment of inertia since ASTM B-111 and ASTM B-543 both specify a wall thickness tolerance of 0.0045".

The modulus of elasticity for Aluminum Brass is 16.0 x 10^6 psi and the modulus of elasticity for 90/10 Copper-Nickel is 18.0 x 10^6 psi. Thus, if 1.000" OD x 18 BWG (0.049") average wall Aluminum Brass is being replaced, 90/10 Copper-Nickel could be used at a theoretical minimum wall thickness of 0.0389" without concern for vibration or mid-span collision. Since wall thickness is controlled with great uniformity in welded tube (per ASTM B-543), 20 BWG minimum wall, with an actual wall thickness of about 0.038", could be specified for welded tube. While 0.038" is slightly less than the theoretically calculated 0.0389", 20 BWG min wall can be used because of the safety factors that are used in condenser designs; in fact, many installations across the USA have used 20 BWG average wall 90/10 Copper-Nickel to replace 18 BWG average wall brass without any problems. Similarly, in desalination applications where Aluminum Brass is often used at an average wall thickness of 0.028", 90/10 Copper-Nickel could be substituted at an average wall thickness of 0.025".

Cost Comparisons

Cost indices for Aluminum Brass and 90/10 Copper-Nickel for the wall thicknesses commonly used for each alloy are shown in Table 7. These cost indices are based on the metal values in effect as this comparison is being written. Since metal values change constantly as “supply & demand” relationships change, quotations should be obtained for both alloys before final material decisions are made.

Table 7 - Cost Indices

Tube Item	Cost Index
1" OD x .049" Avg. Wall x Alloy C687	1.00
1" OD x .049" Avg. Wall x Alloy C706	1.27
1" OD x .035" Min. Wall x Alloy C706	1.03

Conclusion

90/10 Copper-Nickel is clearly superior with regard to corrosion resistance whereas Aluminum Brass has a very slight advantage in heat transfer capability. If a 20 BWG wall thickness is specified for the 90/10 Copper-Nickel, then cost is approximately the same. Given that retubings generally are done because of a corrosion problem, strong consideration should be given to replacing Aluminum Brass with 90/10 Copper-Nickel.

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