DISCUSSION OF STAINLESS STEELS FOR SURFACE CONDENSERS AND FEEDWATER HEATER TUBING

A DESIGNERS' HANDBOOK SERIES

Nº 9030

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Originally, this handbook was published in 1974 by the Committee of Stainless Steel Producers, American Iron and Steel Institute.

The Nickel Institute republished the handbook in 2020. Despite the age of this publication the information herein is considered to be generally valid.

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INTRODUCTION

In July 1958, the Monongahela Power Company placed in operation at the Rivesville Station in West Virginia a 54,997-square-foot surface condenser completely retubed with Type 304 stainless steel. This is the first all-stainless tubed unit. The 88-10-2 brass tubes previously used had lasted only an average of nine years; whereas several stainless steel tubes, being tested in the same condenser prior to 1958, lasted 17 years before they were removed for examination. They were found to be free of corrosion.

Between the years 1958 and 1973, the use of stainless steel for power plant condenser service rose from a mere one per cent of the total usage to a point today where it is approximately 50 per cent. A combination of several factors contributed to this growth:

1. Operating experience since the 1940's in air-removal and peripheral sections demonstrated stainless steel to be an effective condenser tube material.

2. There was an increasing requirement during these years for a material more resistant to corrosion than the then-popular nonferrous alloys.

3. Long-term tests measuring actual in-service heat transfer characteristics demonstrated stainless steels can be equal to, if not better than, nonferrous tubing in heat exchange performance, considering all factors.

4. Experience with tube cleaning, either in-service or during shutdown, showed that stainless steels can be maintained at significantly higher levels of cleanliness, as compared with nonferrous tubing, thus greatly improving their heat transfer qualities.

5. As the use of stainless steel increased for both condenser and feedwater service, coupled with proportionately higher material costs for copper-base alloys, the cost of stainless steel tubing for condenser service has actually declined.

This discussion, in two parts, is for design engineers, utility metallurgists and chemists, and those concerned with the best design and most efficient operation of large surface condensers and feedwater heaters. The text in PART ONE covers the condenser operating environment in which tube materials must perform, and it describes the use of stainless steel condenser tubes to combat problems that arise in such an environment.

PART TWO discusses the use of stainless steel for feedwater heater tubing.

The booklet provides design and engineering data, which can be helpful for the engineer approaching stainless steel for the first time, or as a review for those experienced in its use.

Wherever possible, data relates to actual experiences, with information on operating parameters and water conditions. Consequently, not all of the information is favorable to stainless steel; some failures are described with the hope that a forthright discussion of the problems will help to prevent problems of a similar nature in the future.

Stainless Steel

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American Iron and Steel Institute
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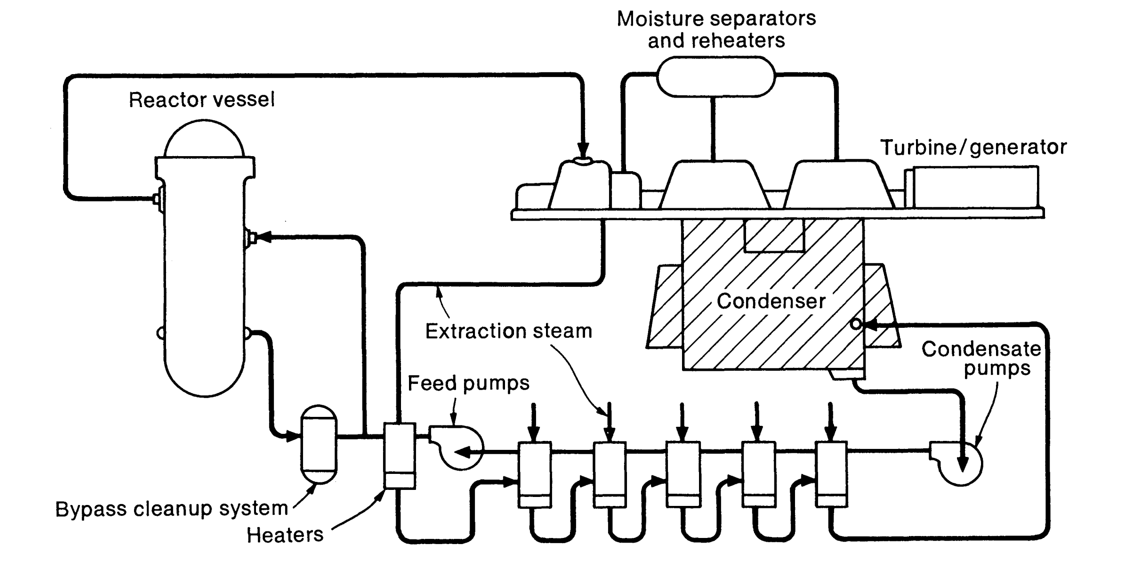


Boiling-Water Reactor

THE CONDENSER ENVIRONMENT

Selecting the optimum condenser tube material is a difficult task. The engineer must design for today's operating and water conditions, yet not overlook changes than can occur during the plant's lifetime. There are many variables to consider, on the steam side as well as on the cooling-water side. Of special importance are those factors that influence efficient heat transfer and those conditions that result in premature failure. It is well to discuss these various aspects and how they relate to tube materials, and to review ways in which material selection eliminates potential trouble spots.

Steam-Side Conditions

Erosion. The trend in recent years toward increasingly larger power plants accentuates the problem of steam-side erosion, which is a function of steam velocity and its moisture content. The problem is the use of larger and larger turbines with longer turbine blades, particularly at the last wheel where blades are as much as five feet long. The net result is wet steam and drops of water exiting the turbine at near sonic velocity, causing severe erosion-corrosion of peripheral tubes. Nonferrous tubes are particularly sensitive to this form of attack.

Any number of preventive measures are available, such as deflection plates, metal shields, etc., but it is difficult to predetermine the exact location and seriousness of the attack until the unit has actually been placed in service. The preferred solution, which dates back to the mid 1950's, is the use of stainless steel tubes at peripheral positions, because they resist the erosive effect of wet steam and drops of water impinging at high velocity.

Vibration. High steam velocity is one cause of tube vibration in surface condensers. Other factors in addition to velocity include distance

TABLE 1

Relative Span Between Supports In Surface Condensers

(Typical Design Example)

Material	Wall Thickness BWG	Allowable Span Factor
Arsenical Copper	18	1.00
Admiralty	18	1.00
Aluminum Brass	18	1.00
70-30 Copper-Nickel	18	1.08
	20	1.006
90-10 Copper-Nickel	18	1.03
	20	.956
Stainless Steel	20	1.07
	22	1.02
Titanium	20	.91
	22	.87
	24	.85

Source: Coit (1)

between supports, tube diameter, modulus of elasticity, moment of inertia, and vibration decay. The net result of vibration is tube damage in the form of stress fatigue, wear at support plates, or wear caused by adjacent tubes rubbing together.

Good condenser design is the best way to prevent vibration; the choice between one material system and another does not appear to be a design limitation. However, when retubing an existing condenser, material choice can be a factor. Table 1, which shows the allowable span factor for various tube materials and wall thicknesses, suggests that vibration would be a problem, for example, if 20-gauge 70-30 copper-nickel tubes (allowable span factor of 1.006) were replaced with 20-gauge or lighter titanium (allowable span factor of .91 or less). On the other hand, 22-gauge stainless steel tubes have an allowable span factor of 1.02 and would be a suitable replacement from the vibration standpoint.

Corrosion. Steam-side corrosion occurs primarily in the air-removal section of the condenser where non-condensable gases, such as ammonia, carbon dioxide, oxygen, etc., are removed. One source of ammonia is the decomposition of amines or hydrazine, which are added to the boiler feed water to inhibit general corrosion of carbon steel tubes and other components.

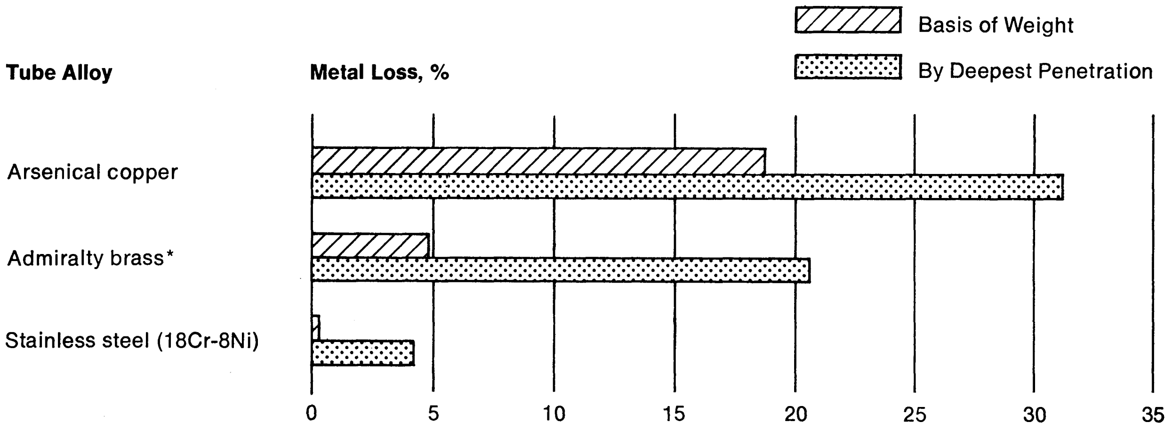
Ammonia gas is readily soluble in condensate (2) with very little subcooling. As the condensate drips down from tube to tube in the air-removal section, or as it runs down a tube-support plate, it absorbs ammonia. Surprisingly high concentrations can be found under certain conditions. Industry sources say that a good deaerating condenser operating under favorable conditions with a pH of 9.5 may have an ammonia concentration of only 0.2 parts per million (ppm) in the hotwell, but can have 500 to 1000 ppm ammonia in the condensate on the tubes or tube-support plates in the air-cooling section.

It is well established that ammonia, as a gas or dissolved in water, contributes to stress-corrosion cracking of Admiralty, aluminum brass, and a number of other nonferrous alloys when oxygen, moisture, and stress are present. Ammonia does not cause stress corrosion-cracking in stainless steels.

It is also a known fact that aqueous ammonia at concentrations found in air-cooler sections, and in the presence of oxygen, dissolves copper alloys. This is substantiated by the data in Figure 1, which shows metal loss for three different tube materials after three years of service

FIGURE 1

Tube Metal Loss in Air Removal Zone After Three Years' Service



*Average of both phosphorized and antimonial Admiralty brass.

Source: Harrison (3)

in the air-removal zone of a surface condenser. The data show that the copper alloys are definitely attacked while stainless steel resists attack.

This form of attack is seen as a grooving or thinning of the tube wall, mostly in the vicinity of support plates or other structural members. It should be pointed out that the presence of ammonia does not add to corrosion of copper alloys **if oxygen can be excluded.** The fact is that oxygen cannot be eliminated entirely from the condenser environment.

Other noncondensable gases on the steam side, such as carbon dioxide, also result in corrosive attack of some condenser tube materials but not stainless steels.

The resistance of stainless steels to all forms of corrosion (including ammonia stress-corrosion cracking) in the air-removal section, plus their resistance to erosion-corrosion in peripheral tubes, led to the introduction of stainless steels to condenser tube service many years ago. As an increasing number of utilities used stainless steels in these peripheral applications, plant chemists and metallurgists had the opportunity to observe their behavior on the cooling water side. Based on their observations over many years, utilities began to accept stainless steels as alternate or even as preferred materials for complete condenser service.

Feedwater contamination. Power plant engineers have for years expressed concern over copper contamination of feedwater and the resulting transfer and deposition of metal onto boiler tubes and turbine blades, which seriously impair operating efficiencies. This is particularly true with supercritical (once-through) systems.

Also, metal contamination is a hazard in nuclear plants. The "crud" becomes radioactive and settles out in the system thus necessitating costly cleaning and decontamination procedures.

Feedwater contamination is a problem peculiar to nonferrous materials, not stainless steel. It can originate in the condenser as well as in the feedwater heaters, as one large utility reported. (4) Engineers at that plant measured significant amounts of copper in the feedwater cycle although the heaters were carbon steel, and tubes in the air-removal section of the condenser were Type 316 stainless steel; only the main bank of condenser tubes contained copper. Problems of this nature have been sufficiently serious to justify a plan for using only ferrous materials, such as the stainless steels, in all condensate and feedwater systems. This proposal, however, has yet to be unanimously accepted by utilities, but it is receiving serious consideration.

Water-Side Conditions

It is far more difficult to classify water-side conditions in a condenser than it is for steam-side. Steam and condensate analyses are similar from plant to plant; whereas cooling waters vary widely. Rivers, lakes, oceans, and even sewage treatment plants are common sources for cooling water, and for 100 different plants one would expect to have 100 different cooling water environments.

The use of spray ponds and cooling towers, which are becoming increasingly popular because of water shortages and thermal problems, further complicate cooling-water-related problems because the tendency of these operations is to concentrate impurities. Another growing concern relates to environmental changes; conditions today in any one place may be significantly different several years from now.

For example, during the 1950's the Neches Power (5) Station noted a sharp increase in condenser tube failures after years of trouble-free service. The accelerated failure rate was thought to have resulted from an increase in local industrial expansion and a 10-year decrease in water flow rate of the Neches River. The problems involved both fouling and corrosion.

Fouling and corrosion result in reduced heat transfer efficiencies and premature condenser tubing failures. While it is beyond the scope of this document to discuss in detail each cause and effect, some general observations are worthy of comment.

Fouling and corrosion. Fouling and corrosion in condenser tubes can be simultaneous occurrences; in all probability corrosion accelerates the fouling, and, conversely, fouling increases the rate of corrosion.

Fouling is an accumulation of slime and algae on tube surfaces that become, more or less, a depository for water-borne clay particles, bits of sand, and organic matter, which is the food supply for the bacteria. Carbonate-type deposits are also a form of fouling, but these deposits of scale relate more to water hardness and temperature.

Tube surfaces previously roughened by corrosion, such as the general corrosion of nonferrous tubes in acid- or sulfide-bearing waters, are more prone to fouling; and when fouling does occur on roughened surfaces, it is more difficult to remove. Stainless steels are not subject to general, uniform corrosive attack. Surfaces remain smooth; fouling occurs very slowly compared to fouling rates on nonferrous materials. Even the oxide film on the surface of stainless steels is different than the film on nonferrous alloys, and it is less prone to fouling buildup.

Fouling deposits alter conditions at the tube-surface/cooling-water interface: oxygen is depleted, uneven heat transfer causes localized hot spots, and a favorable environment next to the tube surface gradually deteriorates. Corrosive attack begins. The severity of corrosion depends on the nature of the cooling water, character of the fouling, plant operating conditions, tubing material, and whether or not the utility employs adequate tube cleaning.

Perhaps the most important observation that can be made relative to corrosion and fouling is that no tube material in common use today is completely immune. Some materials are less prone to fouling and corrosive attack than others, and these help minimize surface condenser problems. (Stainless steels are discussed on page **13**.)

Under any circumstances it is never good practice to allow fouling buildup on any tube material since this interferes with heat transfer and increases the potential for corrosion. Higher cooling water velocity (which is possible with stainless steels because of their resistance to erosion-corrosion), chemical treatment, and various mechanical means can be used to clean tubing. (Cleaning is discussed in greater detail beginning on page 18.) It has been demonstrated by many utilities that stainless steels can be maintained to a higher degree of cleanliness than most nonferrous materials.

Erosion. Stainless steel has never suffered from erosion problems in condenser service, whereas, this has been a major problem area with brass. Inlet end erosion frequently destroys the first six inches leaving the remainder of the tube in good shape. Debris lodged inside a brass tube is another focal point for erosion and serious thinning of the tube wall.

Cooling Water Types

Fresh water. In fresh water as found in virtually all inland locations in the United States and Canada, it can be said that **clean** stainless steel condenser tubing resists all forms of corrosive attack. However, there have been some reports of stainless steel tubing failures in fresh water, but such reports are extremely rare. (6) The total amount of stainless steel tubing that has failed in service (including salt water applications) is approximately ½ of 1 per cent, which is exceptionally low in comparison to nonferrous tubing failures. Furthermore, investigations of these failures revealed that most were preventable. The principal problem was dirty tubes. Chlorides were allowed to concentrate under spotty conditions of fouling and scale, resulting in localized corrosion attack and failure. (See the section on maintenance beginning on page 18 for ways to prevent these problems.)

Utility chemists and metallurgists generally know that fouling occurs in two ways: as a solid continuous coating on the tube 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 applications, whereas spotting or localized fouling can create concentration cells that are potential corrosion sites.

Polluted fresh water. Stainless steels offer special advantages (7) in handling so-called fresh water contaminated by acid resulting from coal mine drainage and sometimes supplemented by waste material from metal pickling operations. A good illustration described by Long (7) is the Monongahela River near Pittsburgh, Pennsylvania. The acidity of this water, which is indicated by a pH that drops to as low as 3, plus the presence of ferric ions, increase the corrosivity towards copper-base alloys. The stainless steels outlast copper-base alloys in water of this character. In tests on specimens exposed to these

Note: Metric equivalents have been provided throughout the booklet. The figures are approximate, not exact values.

waters, those of Type 304 stainless steel showed no measurable corrosion, while Admiralty brass was corroded at a rate of over 0.01 inch per year (10 mils per year).

Polluted salt water. Where polluted salt water has been used for cooling, the stainless steels have demonstrated greater reliability than copper-base alloys under circumstances of abnormally high sulfide pollution in the cooling water. Sulfide attack of copper-base alloys is sufficiently rapid and sufficiently certain to make failures from this cause far more important than an occasional failure of stainless steel by chloride-induced pitting. Furthermore, the danger of chloride pitting can be minimized in brackish water by using Type 316 stainless steel and by avoiding the accumulation of localized deposits that are potential pitting sites. (8)

It is also well for the engineers to be aware of new higher-alloy stainless steels (non-AISI types) that have been proven effective under severe conditions in brackish water. In one test, conducted by a stainless steel producer in cooperation with a utility, for example, one such stainless steel was exposed to polluted brackish water in a full size condenser. The tube inlets were partially plugged to adjust the cooling water velocity to a very low one foot (.305m) per second (fps) and even to 1/10 (.0305m) fps. On removal after 18 months, heavy fouling was observed inside the tubes, but no corrosion. The utility where this test was conducted has retubed one entire condenser with this new stainless steel. This and other stainless steels are discussed in greater detail beginning on page 13 and table 4.

Fresh salt water. Stainless steel in sea water is another story altogether. Some plants document successful use (9) of Type 316 for sea water cooling but only if care is taken to keep tubes free of fouling. Spotty or continuous fouling in sea water leads to pitting corrosion. Nonferrous materials are not always the best answer either for sea water service, so it would be well for utility engineers to investigate the higher alloyed stainless steels. Many of these new materials have proven performance in sea water, and they are still less expensive than titanium or 70-30 copper-nickel.

Cooling towers. Water shortages and public objections to thermal effects have resulted in many plants using cooling towers. From the standpoint of corrosion of condenser tubes, cooling towers can be both an asset as well as a liability.

Because cooling tower water is recirculated, the utility can exercise some control over water quality, such as pH control. With once-through cooling, such controls are out of the question because water quantities are prohibitively high.

On the other hand, cooling towers concentrate impurities, such as sulfides and chlorides. Laboratory tests and in-service experience over many years show that copper-base alloys cannot tolerate sulfides, whereas stainless steels resist sulfide attack. Also, the concentration of chlorides is usually not high enough to concern stainless steel users, but this depends on fouling rate and degree of cleanliness. Since the 1960's many power plants with cooling towers have used Type 304 stainless steel.

Cooling tower applications have been highly successful as demonstrated by the increasing use of Type 304 stainless steel, and in some cases Type 316. For instance, some plants in the Southwest, where ground water supplies are scarce, use sewage effluent for cooling tower water make-up. Sewage effluent has fairly high chloride concentrations, and Type 316 provides a very high degree of protection against pitting corrosion.

To summarize the discussion of cooling water types:

1. Stainless steel can be used in virtually all conditions. For most cases below 1000 ppm chlorides consider Type 304; for sea water, higher alloyed stainless steels are the better choice.
2. Cooling tower service presents few problems, if any, to stainless steels.
3. For any material, cleanliness improves performance and longevity.

HEAT TRANSFER

The application of the stainless steels to modern condenser service to eliminate problems of corrosion and erosion, is widely accepted. Utilities standardize on stainless to maintain reliability needed for efficient and continuous operation. Trends also indicate that utilities accept stainless steels on the basis of their ability to perform as highly efficient heat transfer materials under condensing conditions.

TABLE 2

Thermal Conductivity of Common Condenser Tube Alloys

Material	Btu/Sq. Ft./In./Hr./°F @ 32°-212° F.	(W/m/deg K)	Ratio of Conductivity to Admiralty Metal
Admiralty Metal	770	(111)	1.00
Arsenical Copper	1344	(194)	1.74
Aluminum Brass	696	(100)	0.90
Muntz Metal	867	(125)	1.12
Aluminum Bronze	552	(80)	0.72
90-10 Copper Nickel	312	(45)	0.40
70-30 Copper Nickel	204	(29)	0.26
Type 304 Stainless Steel	108	(16)	0.14

Source: Coakley (10)

It goes without saying that the ability of a condenser tube to transfer heat efficiently from steam to cooling water is as important as it is for the tube to last a plant lifetime. Poor heat exchange performance adversely affects power station heat rate and efficiency. This is an important factor, particularly in time of energy shortages. In past years it was necessary to prove to utilities and others concerned with specifying, designing, and constructing surface condensers that heat exchange rates in stainless steels are within practical limits. Proving this has been most difficult, as evidenced by the published thermal conductivity properties of Type 304 (Table 2). It shows that stainless steels have a value of 108 Btu/ft^2/in/hr/°F (16 W/m/deg K), which is approximately 1/7 the conductivity of Admiralty brass. Not a very good comparison, it would seem.

Resistance to Heat Transfer

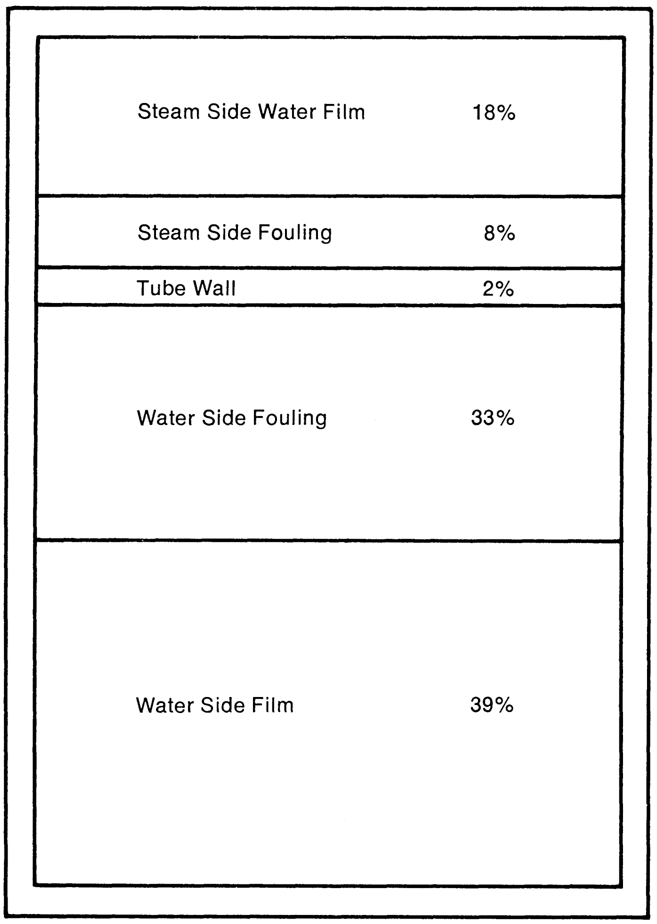
In addition to this, published data from such sources as the Heat Exchange Institute (HEI) have, until recently, placed the stainless steels in a very unfavorable position in comparison to other materials. These "text book" figures have retarded universal acceptance of stainless steels unjustly, because utility-conducted evaluations demonstrate that true stainless steel heat transfer performance is far better than laboratory-type tests indicate.

The heat transfer properties of tubular products cannot be based exclusively on the thermal conductivity of the metal itself. Other factors such as the steam film, corrosion products, deposits, and the cooling water film must be considered.

Figure 2 is a graphic representation illustrating the various factors affecting resistance to heat transfer in actual service. It is obvious that these films affect overall performance to a far greater degree than the metal wall, which accounts for only 2 per cent of the total resistance to heat flow.

Hall (12) pointed out that fouled or dirty condenser tubes adversely affect the heat transfer rates and that the thermal insulation of corrosion products and water-deposited materials reduce the heat transfer coefficients by as much as 50 per cent. He shows how these films become the controlling factors in heat transfer. Potter (13) in his graphical method of calculating heat transfer actually neglects the conductivity of the metal wall since it is insignificant in comparison to the effects of interior and exterior surface films.

FIGURE 2



Source: Lustenador & Staub (11)

The importance of fouling in condenser tubes is also established by other investigators. Actual performance tests by a number of utilities have shown the detrimental effects produced on heat transfer rates. Long (7) (14) and Pell (15) of the Monongahela Power Company documented the results of fouling at their Rivesville Station. Results from United Illuminating as reported by Hoskinson (8) provided additional data on the importance of this factor to heat transfer. In both cases the degree of fouling on brass tubes is far greater than that on stainless steel tubes.

Further evidence to support the adverse effects of fouling on condenser tubes was published by R.A. McAllister and his coworkers at Lamar State College of Technology (5). They used single tube heat exchangers with a variety of tube materials and river water from the intakes of the Neches Steam Station of Gulf State Utilities. Results of this comprehensive study show that stainless steels perform better than copper alloys from the standpoint of heat transfer and fouling. McAllister points out that the rate of fouling for Type 304 stainless steel was about 1/5 that for the copper alloys.

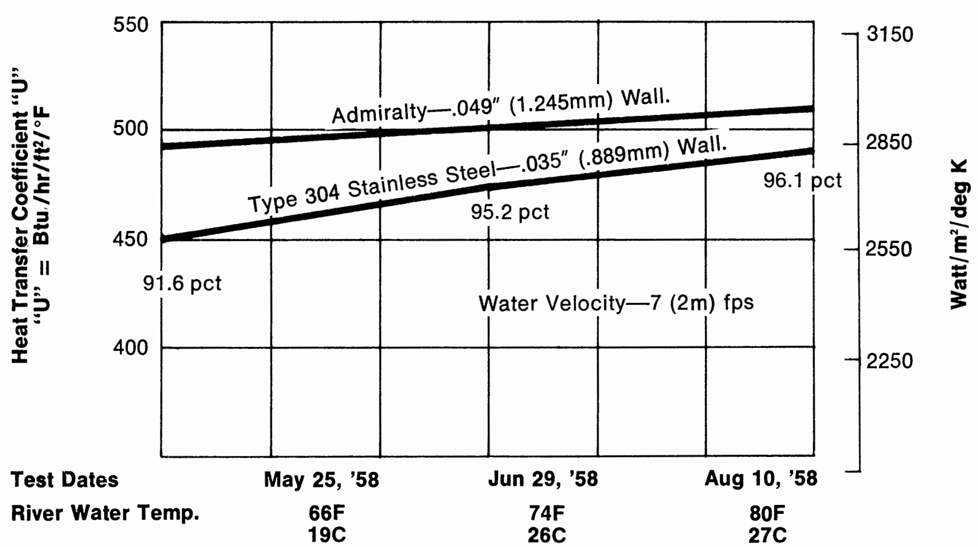
The formation of a corrosion product or oxide film on the tube surface is another factor affecting condenser tube performance. The thermal resistance of oxides and corrosion products are of sufficient magnitude to more than offset the difference of thermal conductivity in metal walls. Because stainless steels are not subject to general surface corrosion and the oxide film on their surface is imperceptible, their heat transfer rates do not deteriorate significantly in actual service.

This point is well established in the literature. Wenzel pointed this out in 1962 (16) in his discussion concerning the operating procedures used to determine the performance of various tube materials for the Heat Exchange Institute. He stated: "Usually only new, clean tubes are desired for testing. Experience has shown that unused tubes cannot be removed from a warehouse and tested if results typical of new tubes are desired. Therefore, tubes taken immediately from manufacturers are usually specified. This has been found to be especially important for admiralty tubes, less so for other copper alloys, and seemingly unimportant for stainless steels or aluminum alloys."

He also states, "shelf aging results in performance losses of at least 10 per cent in some tubes. Although this performance might be recovered with repickling or mechanical polishing, utilities do not use these cleaning procedures. This effect is particularly noticeable with Admiralty tubes."

FIGURE 3

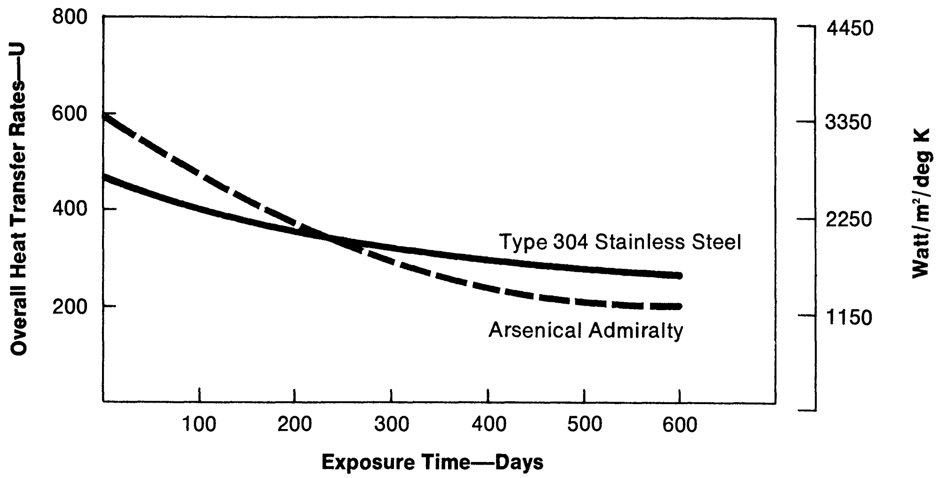
Results of Heat Transfer Tests



Source: Coakley (10)

FIGURE 4

Overall Heat Transfer vs. Exposure Time



Source: McAllister (5)

these cleaning procedures. This effect is particularly noticeable with Admiralty tubes."

It has been well established that heat transfer in condenser tubes is greatly affected by environmental conditions, but environmental variations are not accurately reflected in the HEI materials and gage factors. A better evaluation method is needed because, as it was pointed out earlier, the copper-base tubes are affected by environmental conditions to a far greater degree than stainless steel tubes.

In-Service Tests

In 1958, a welded-tube producer carried out a series of in-service heat transfer tests (10) in a single-pass condenser at the Edge Moor Generating Station of Delmarva Power and Light Company. One half of the 40,000-square foot (3716m²) unit was fitted with .049 inch wall (18 BWG or 1.245mm) arsenical Admiralty tubing and the other half with .035 inch wall (20 BWG or .889mm) stainless steel tubes. Since the condenser was of the divided water box type, it was possible to set up a test procedure in which each side of the unit could be operated independently of the other. Over a three-month period, three complete test series were conducted on each material using five different water flow conditions with the steam throttle flow held constant.

The results are summarized in Figure 3, and they indicate that the heat transfer rates obtained with stainless steel ranged between 91.6 and 96.1 per cent of those with Admiralty brass tubes. (Today, 22 BWG or .028-inch [.711mm] is the standard wall thickness for stainless steel condenser tubing, which will reduce the difference somewhat.) These findings were supported by the results of another comprehensive study on single-tube heat exchangers operating on water from the intake of the Neches Power Station of Gulf States Utilities, Beaumont, Texas.

The curves shown in Figure 4 are based on an exposure of almost 600 days. In this test, condition of the cooling water and the velocities were the same for both Admiralty and Type 304 stainless steel. Initially the relative performance of both materials corresponded to the values established by the HEI. As service time progressed, however, it can be seen that overall heat transfer performance of both materials deteriorated. Significant is the fact that the overall heat transfer rate of stainless steel, which was lower initially than that of the Admiralty brass, reversed position with Admiralty after exposure for 120 days. In the case of Admiralty, the reduced performance was due to a combination of fouling and corrosion; the reduced performance of stainless steel was the result of fouling only.

Consider, for example, the following illustration and how it also demonstrates the superior overall heat transfer capabilities of stainless steel. In 1968, as reported by POWER ENGINEERING Magazine (9), Hookers Point Unit 5 of the Tampa Electric Company, which had a condenser containing 9354 copper-nickel tubes, was completely retubed but with only 7934 Type 316 stainless steel tubes. (The unused holes were plugged.) The original tubes were 18 BWG (.049-inch or 1.245mm); the stainless steel replacements were 22 BWG (.028-inch or .711mm). Both sets of tubes were ⅞-inch (2.223mm) outer diameter. Despite the fact that there are 1420 fewer stainless steel tubes, plant operating data indicate that the vacuum-readings are equal or better with the stainless steel tubes.

These tests illustrate the necessity of a continued program to evaluate the actual performance characteristics of a tube material.

When all factors governing the heat transfer performance of a tube material are considered, it must be concluded that stainless steels are efficient tube materials for surface condenser applications.

Design Illustration

As an example of the design potential of the stainless steels and how their properties can be applied, the condenser requirements for a given set of conditions were calculated using methods outlined by the C. H. Wheeler CONDENSER HANDBOOK. For this calculation, the following assumptions are used:

1. The material and gage factor for Admiralty is 1.0 as established by the HEI; the value of .79 is chosen as the HEI material and gage factor for 22 BWG (.028-inch or .711mm) Type 304 stainless steel.
2. The cooling water velocity for Admiralty is set at 7 (2m) fps. For stainless steel tubes, the inside diameter permits a greater velocity with the same friction loss level. In addition, the erosion resistance of stainless steel permits the use of any practical velocity. Therefore, for this example, a velocity of 7.5 (2.3m) fps will be used to show the close comparison in performance.
3. The cleanliness factor for Admiralty is 85 per cent based on normal design practice. Since extensive tests and applications show stainless steels capable of maintaining higher levels of cleanliness during operation, a conservative value of 90 per cent is assumed.

The following information is used to establish the conditions of the design (Figure 5):

FIGURE 5

Stainless Steel		Admiralty
700,000 lb/hr	W	700,000 lb/hr
950 Btu/lb	L	950 Btu/lb
.875 in	D	.875 in
22	BWG	18
2	P	2
30 ft	l	30 ft
70 F	t_1	70 F
101.14 F	t_s	101.14 F
2.00 in Hg Abs	P_s	2.00 in Hg Abs
1.00	C_1	1.00
.79	C_2	1.00
.90	C_f	.85
.284	C'	.310
7.5 fps	V	7 fps

Stainless Steel

1. $U_s = 263\sqrt{V}\,C_1C_2C_f$

$= 263\sqrt{7.5}[1.00][.79][.90]$

$U_s = 512$

2. $r_s = C'\dfrac{l}{V}$

$= [.284]\left(\dfrac{30}{7.5}\right)$

$r_s = 1.135$

3. $\log\theta_2 = \log\theta_1 - \dfrac{rU}{1151}$

$= \log[101.14-70] - \dfrac{[1.135][512]}{1151}$

$= 1.4934 - .5050$

$\log\theta_2 = .9884$

$\theta_2 = 9.73$ F

4. $\theta_2 = t_s - t_2$

$t_2 = t_s - \theta_2$

$= 101.14 - 9.73$

$t_2 = 91.41$°F

5. $TR = t_2 - t_1$

$= 91.41 - 70$

$TR = 21.41$°F

6. $G_s = \dfrac{WL}{500TR}$

$= \dfrac{[700{,}000][950]}{[500][21.41]}$

$G_s = 62{,}042$ GPM

7. $A_s = r_sG_s$

$= [1.135][62{,}042]$

$A_s = 70{,}417\ ft^2$

Admiralty

$U_a = 263\sqrt{V}\,C_1C_2C_f$

$= 263\sqrt{7.0}[1.00][1.00][.85]$

$U_a = 591$

$r_a = C'\dfrac{l}{V}$

$= [.310]\left(\dfrac{30}{7.0}\right)$

$r_a = 1.330$

$\log\theta_2 = \log\theta_1 - \dfrac{rU}{1151}$

$= \log[101.14-70] - \dfrac{[1.330][591]}{1151}$

$= 1.4934 - .6800$

$\log\theta_2 = .8124$

$\theta_2 = 6.49$ F

$\theta_2 = t_s - t_2$

$t_2 = t_s - \theta_2$

$= 101.14 - 6.49$

$t_2 = 94.65$°F

$TR = t_2 - t_1$

$= 94.65 - 70$

$TR = 24.65$°F

$G_a = \dfrac{WL}{500TR}$

$= \dfrac{[700{,}000][950]}{[500][24.65]}$

$G_a = 53{,}975$ GPM

$A_a = r_aG_a$

$= [1.330][53{,}975]$

$A_a = 71{,}787\ ft^2$

Terminology used for design calculations

W = Steam flow rates entering condenser (lb./hr.)

L = Latent heat to circulating water (950 Btu/lb.)

V = Velocity of cooling water through tubes (ft./sec.)

l = Effective tube length between tube sheets (ft.)

D = Outside tube diameter (in.)

A = Condensing surface on outside of tubes (sq. ft.)

P = Number of water passes

t_1 = Inlet cooling water temperature (°F)

t_2 = Outlet cooling water temperature (°F)

t_s = Steam temperature of condenser inlet (°F)

TR = Temperature rise of cooling water (°F)

θ_1 = Initial temperature difference (°F)

θ_2 = Terminal temperature difference (°F)

C_1 = Cooling water correction factor (%)

C_2 = Material and gage correction factor (%)

C_f = Tube cleanliness factor (%)

P_s = Steam pressure at condenser inlet (in Hg Abs)

C' = Tube constant

G = Cooling water flow rate (GPM)

r = Ratio of total condensing surface to total cooling water

U = Condenser Heat Transfer Coefficient (Btu/hr./ft.²/°F)

CHOOSING THE RIGHT STAINLESS STEEL

Standard AISI Types

One consideration in designing or retubing with stainless steels concerns the choice of which type to use. There are a number of stainless steels with an American Iron and Steel Institute (AISI) designation that make acceptable welded tubing. Each type differs in chemical analysis, physical properties, and corrosion resistance. Each type offers certain specific advantages, but extensive in-service testing and experience shows that utilities tend to use only two standard AISI types, namely:

Type 304
Type 316

Type 304 contains 18.00-20.00 per cent chromium and 8.00-10.50 per cent nickel. Type 316 is similar to Type 304 in its chromium, it has slightly more nickel, and it also has two to three per cent molybdenum. The propreties of these two materials are given in Table 3.

The choice of which stainless steel to use for a condenser application depends upon the cooling water environment to which it will be exposed. Type 304 is an excellent general-purpose stainless steel that has been employed in many fresh water areas. It also exhibits a high degree of corrosion resistance to contaminated waters where mine drainage increases the corrosiveness of the coolant, and in areas where industrial wastes pollute the cooling water source. Utilities have used Type 316 when an environment exists that causes pitting attack, such as in brackish or sea water installations.

There are some applications for which the choice between Type 304 or Type 316 is difficult. Based on past experiences, Type 304 is normally acceptable for environments containing up to 1000 ppm of chlorides. Above this chloride level Type 316 has been used. This level should not be considered as the final criterion for material selection. While the chloride content of the cooling water might be only 50 ppm, fouling can concentrate the chlorides in contact with the tube surface to several thousand ppm. Where high degrees of cleanliness have been maintained, Type 304 has worked well in waters containing thousands of ppm of chlorides.

TABLE 3

Comparative Properties of Stainless Steel

Physical Properties	**Type 304**		**Type 316**	
Density (lb./in.^{3})	0.29	(8027 kg/m^3)	0.29	(8027 kg/m^3)
Specific Heat (Btu/°F/lb.)	0.12	(502 J/kg • K)	0.12	(502 J/kg • K)
Thermal Conductivity (Btu/hr/in^2/°F/in)	108	(16 W/m • K)	108	(16 W/m • K)
Coefficient of Thermal Expansion (in./in./°F x 10^{-6})	9.6	(17.3 x 10^{-6}m/m/C°)	9.6	(17.3 x 10^{-6}m/m/C°)
Mechanical Properties, annealed				
Yield Strength, lb./in.^{2}	30,000	(207 MPa)	30,000	(207 MPa)
Ultimate Strength, lb./in.^{2}	80,000	(552 MPa)	75,000	(517 MPa)
Elongation, % in 2 inches	50.0		40.0	
Reduction in Area	60.0		50.0	
Modulus of Elasticity (lb./in.^{2} x 10^{-6})	29.0	(200 GPa)	29.0	(200 GPa)
Hardness, Rockwell	B 90 max.		B 95 max.	
Impact Values, Izod, ft.-lb.	85 min.	(115 J)	70 min.	(95 J)

Other Stainless Steels

There are available a number of other stainless steels that are candidates for condenser service. Some stainless steels, such as the higher alloy types, have demonstrated excellent resistance to chloride pitting in brackish or sea water under some extremely difficult conditions of low cooling water velocity and heavy fouling.

TABLE 4

The Chromium, Nickel, and Molybdenum Alloy Content of Stainless Steels Suitable for Power Plant Condenser Tubing

Stainless Steel	% Chromium	% Nickel	% Molybdenum
	(Standard AISI Stainless Steels)		
304	18.00-20.00	8.00-10.50	
316	16.00-18.00	10.00-14.00	2.0-3.0
430	16.00-18.00		
	(Stainless Steels That Do Not Have AISI Designations)		
430 Ti	18		
439*	18		
444L	18		2
18-2 Cb	18		2
18-2 Ti	18		2
216**	20	7	3
20Cb-3	20	34	2.5
6X	20	24	6.5
22-13-5	22	13	2
26-1	26		1
329	28	4.5	1.5

*—Ti .75 Max.
**—Mn 8.25

The ferritic stainless steels were tried for condenser service, but they were never popular because they were generally more expensive than Type 304 and 316—not because of a higher alloy content but because they were difficult to weld into tubular shape. Today, however, developments in refining stainless steels to reduce the impurities and interstitials, new alloys, and new welding techniques have resulted in the development of ferritic stainless steel tubes that offer excellent potential for condenser service.

Specifications and Production Considerations

While the selection of a proper stainless steel is important, it is equally important to select the tube conditions that will give the ultimate performance.

For example, there are two basic categories of tubes that can be used in this application: seamless or welded. The seamless variety, if produced and finished in an acceptable manner, would be perfectly suitable for condenser service. However, since economics is of vital importance, this form of tubing is not considered. It normally costs three to four times that of a comparable welded product, and, therefore, this discussion is confined to the welded variety.

The specification most frequently referred to when utilities purchase stainless steel is ASTM Specification A249-73. This specification is a good starting point, but it does not cover all of the factors important to surface condenser tubing. For instance, the present specification calls for a minimum tube wall thickness. This is based on production considerations relating to seamless tubing, which results in wall thickness variations. Welded tubing, however, is made from flat-rolled strip that has a uniform thickness and, as a result, has little variation in wall thickness. Consequently, utilities specify **average** wall instead of **minimum** wall because of cost differences between the two; i.e., less weight per foot, lower selling price.

ASTM Specification A249-73 permits the use of either a hydrostatic or a nonconductive test of stainless steel condenser tubes. The hydrostatic test is usually eliminated in favor of eddy current inspection, the most commonly used test, **in conjunction with a pneumatic pressure inspection.** The hydrostatic pressures used rarely are sufficient to cause a massive failure of the tube, and weeping types of defects are difficult to observe. The eddy current inspection, as prescribed by ASTM Specification A450-71A, detects defects in any direction on interior or exterior tube surfaces or within the tube wall itself. In addition, pressurizing tubes with air as they are held under water will reveal small perforations that could escape eddy current inspection.

In addition to the difference between welded and seamless tubing, plus minor alterations to the specification as just explained, the utility specifier should also be aware of the fact that there are a number of methods used to produce welded tubes. Each tube manufacturer has his own special techniques. While there may be differences from plant to plant, most practices are standard and are well within the scope of acceptability in terms of meeting performance requirements for condenser service.

An example of the differences that occur is the method for annealing tubing after it has been manufactured. There are two methods for annealing: one is air annealing in a furnace or by the electric resistance method, followed by pickling to remove the oxide scale that has formed on the tube surface during heating.

The other annealing technique is called bright annealing, and this is accomplished in a controlled-atmosphere furnace to prevent scaling or oxidation of the tube. Pickling after bright annealing is usually omitted.

Pickling following air annealing is believed to serve a secondary purpose in addition to removing scale, and that is a form of a quality check. The pickling operation exposes such defects as surface carburization or an incomplete anneal, both of which could result in shortened service life of the condenser tube.

CHLORIDE CONTAMINATION

Material specification engineers often express great concern over chloride contamination of tubing during manufacture for surface condensers or feedwater heaters. Their fear is [1] stress-corrosion cracking, which seems unfounded with respect to condenser and heater tubing because of the long, trouble-free service record for stainless steel, and [2] pitting prior to being placed in service.

In an effort to avoid chlorides at any cost, specification writers often place severe restrictions upon such things as drawing lubricants, cleaning compounds, rinse water, etc., in hopes of reducing residual chlorides that remain on finished tube surfaces. It is thought that such measures will minimize chances of stress-corrosion cracking. Most tube manufacturers comply with such restrictions, although somewhat reluctantly.

In 1969, S. E. Doughty (17) reported on a detailed investigation which revealed that chloride contamination occurs **after** final rinsing. The use of either chlorinated or unchlorinated lubricants, and whether or not tubes are cleaned prior to annealing, appear to make little difference in the total level of residual chlorides. The real danger of chloride contamination is after the tubes are shipped. A typical source is perspiration on the hands of workers installing tubes or simply from airborne sources. He concludes that manufacturing process restrictions only add to tubing cost and do not curb chloride levels.

If chloride restrictions were effective, one could easily rationalize the increased costs involved. The simple fact is that there has never been a confirmed case of chloride stress-corrosion cracking of stainless steel tubes in a utility surface condenser. Pre-installation pitting problems have been traced to in-transit contamination or improper storage at the construction site, not as a result of process contamination.

INSTALLATION

The properties of stainless steel condenser tubes are such that they readily lend themselves to normal fabrication and installation techniques. Tubes are light, easily handled, and readily inserted into the condensing unit. Expanding into a tube sheet presents no problems with conventional tools and procedures, providing tight, leak-free joints that will not loosen with time. Also, tube ends can be flared to suit individual design requirements. However, specifiers should recognize that because stainless steels resist inlet erosion-corrosion, flaring is an extra and costly step that can be justifiably eliminated.

Handling

Trends toward bigger condensers with longer tubes present no difficult problems providing one understands the peculiarities of handling thin-wall tubing and makes proper preparations. For example, care must be exercised in removing long shipping containers from trucks, and storage sites should be selected with consideration for keeping tubes away from heavily trafficked construction areas and potential sources of corrosion. In one classic case, tubes at the site were stored beneath a bridge that was heavily salted during cold and icy winter days. Melting snow and ice with chlorides flowed off the bridge and onto tubes that had been opened for inspection and not properly recovered. Severe pitting corrosion occurred before the tubes were even installed.

Tubes are shipped in adequately strong containers for protection against normal abuse. In removing shipping boxes from the carrier, it is best to use several slings supported by an I-beam. As a rule of thumb, boxes under 30 feet (9m) long should be supported by a minimum of two slings, using a spreader for better weight distribution. Boxes from 30 to 40 feet (9 to 12m) should be moved using a minimum of three slings. Boxes over 40 feet (12m) require an I-beam support and one sling every 10 feet (12m).

On removing tubes from shipping boxes, during tubing of the condenser, several men working together reduce chances of bending and possible kinking. It goes without saying, workers should exercise extreme care and not drop tubes nor allow anything to drop on them.

If it should ever be necessary to store tubes outdoors for any length of time, their containers should be inclined slightly and open at the lower end to permit drainage of any moisture that might collect inside.

Wooden boxes can be piled six high; cardboard boxes should be limited to not more than four high. Wooden spacers should be placed under boxes, and sufficient space should be provided between rows for circulation of air and evaporation of moisture. It is also a good idea to cover the pile of boxes with a suitable, water-proof cover, such as polyethylene, that is held securely in place. Periodic inspections should be made to insure that adequate and proper storage techniques are maintained.

Expanding

The expansion of tubes into tube sheet holes involves a combination of radial stretching and cold metal extrusion. Initial application of internal mechanical pressure expands the tube and establishes close metal-to-metal contact with the tube sheet. Continuing application of radial stress on the tube interior intensifies the contact. The resistance of the tube sheet places the tube wall in compression that results in longitudinal plastic flow of the metal. This elongation is accompanied by a thinning of the tube wall. The behavior of stainless steel undergoing this type of cold work is governed by its ability to stretch under tension and to extrude under compression. Maintaining the outside diameter of the tube as close as possible to the tube sheet hole diameter minimizes cold stretching, work hardening, and residual stresses.

Since joints of this type must provide mechanical and hydraulic strength under varying conditions of temperature and pressure, good metal-to-metal contact is essential. To that end, tube sheets and tube ends must be clean and free of imperfections, such as dirt, oxide scale, lubricants, scratches, dents and machining defects.

Prior to rolling tubes, calculations to determine the final inside diameter of the tube, such as those illustrated, reveal the amount of rolling required. The normal procedure for rolling stainless steel condenser tubes is based on a wall thinning of five per cent. This method has been used in the majority of condenser applications and is computed by the following equation:

$$FD = HD - OD + .10t + ID$$

The values on the right side of the equation can be measured accurately before installation. These are then included in the equation and the final hole diameter determined.

Setting the torque control of the expander to reproduce this diameter on rolling, will result in sufficiently tight joints. Before proceeding with installation, several short lengths of tubes should be rolled into a sample tube sheet to verify the determinations. Once verified and the torque control set, the entire job usually can be completed without any additional changes in torque. Minute variations in diameter can be expected in rolled tubes; it is the uniform torque that assures tight joints.

Stainless steel tubes can be expanded into muntz metal, naval brass, silicon bronze, steel, stainless steel and clad metal tube sheets.

Flaring

Tubes that have been rolled can be flared to reduce inlet turbulence. Flaring is not really necessary, however, with stainless steel because of its excellent resistance to inlet erosion. But if the design calls for flaring, the same tools used with other materials are satisfactory.

FIGURE 6

Rolling Technique

The procedure most commonly employed to produce a satisfactory tube-to-tube sheet seal between stainless steel condenser tubing and various tube sheet material is as follows:

(a) Determine average tube sheet hole diameters;

(b) Determine average tube outside diameters;

(c) Determine average wall thickness or inside diameters;

(d) Calculate final inside diameters of the tube after rolling using equation provided;

(e) Roll several tubes into sample tube sheet at various torque settings;

(f) Measure final inside diameters to obtain proper torque setting;

(g) Roll several additional tubes to insure proper choice of torque setting.

Example

Assume the tube sheet hole diameter is either 1.010″ or 1.005″. (25.654mm or 25.527mm). On the basis of a tube 1″ (25.4mm) O.D. x 22 BWG (.028″ or .711mm wall) the calculations are:

$$FD = HD - OD + .10t + ID$$

FD = Final inside diameter of the tube after rolling.
HD = Tube sheet hole diameter.
OD = Original outside diameter of tube.
t = Wall thickness of tube.
ID = Original inside diameter of tube.

1.010″ (25.654mm) Hole

FD = 1.010 — 1.000 + (.10) (.028) + .944
= .010 + .003 + .944
= .957″ (24.308mm)

1.005″ (25.527mm) Hole

FD = 1.005 — 1.000 + (.10) (.028) + .944
= .005 + .003 + .944
= .952″ (24.181mm)

Facing

Occasionally a condenser design will call for both ends of the tube to be flared to permit reverse flow. When this double flaring operation is required, tubes are generally ordered longer than necessary. The excess length is then removed at one tube sheet, after rolling, to permit the proper flare. The method used is to mill or face one end of the tube. This is accomplished quite easily with stainless steel by using tube facers designed specifically for stainless and using carbide bits. The driving tool should produce a cutting speed of approximately 200-250 surface feet per minute. Feed should be continuous and heavy. The tool should not be allowed to ride on the surface after the cut is made. Several practice runs should be made to develop the proper technique. Excessive burr cannot be tolerated and should be removed prior to flaring.

Welding

There has been little need to weld stainless steel condenser tubes into tube sheets. However, welding is routine for feedwater heaters and there is no reason why it cannot be used for surface condensers, if the design engineers elect to do so.

MAINTENANCE

It's difficult to discuss maintenance and cleaning of condenser tubes without giving the impression that stainless steel tubes **must** be cleaned. It is true that stainless steels perform best when clean, but so does any tube material for that matter. The important facts are [1] stainless steels in fresh water generally do not require cleaning, and [2] if cleaning is used in fouling or polluted water to maintain peak performance, stainless steel tubes will be easier to clean and they will achieve a higher degree of cleanliness than most other materials. This has been demonstrated many times in plants using periodic or continuous cleaning techniques.

Each installation should be evaluated to determine the need for and frequency of cleaning. In many cases, cleaning will not be necessary, such as with heavily silted waters that tend to scour tubes. On the other hand, if fouling is heavy, cleaning may be absolutely necessary, either manual or in-service. For in-service cleaning, automatic systems are offered by the Amertap and the American M.A.N. Corporations.

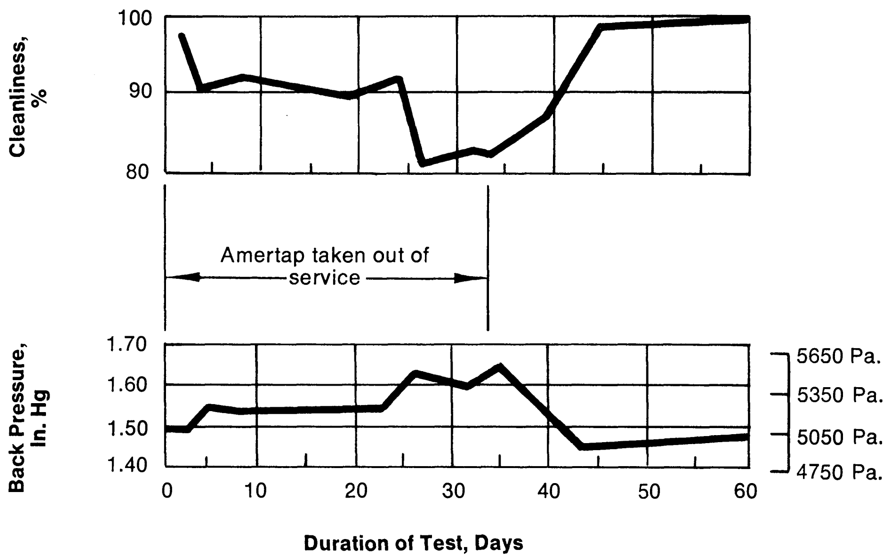
The Amertap system circulates sponge-rubber balls in the cooling water. The balls pass through the condenser tubes to provide a scrubbing action that removes scum and fouling and prevents further buildup. (See Figures 5 and 6 for performance data on an Amertap installation.)

During a planned shutdown of one month, the cleanliness of the stainless steel condenser tubes dropped to 81 per cent and the back pressure increased to 1.65 in. Hg (5572 Pa) at the rate of 0.0032 in. Hg (10 Pa) per week. When the in-service cleaning was restarted, the original back pressure of 1.49 in. Hg (5032 Pa) and 98 per cent cleanliness factor were fully recovered within ten days. (Figure 7).

After an Amertap in-service cleaning system had been shut down for an extended period and then restarted, the copper-base tubes wore out sponge balls very rapidly because the tube surfaces were roughened and deeply pitted from exposure to polluted sea water. Performance of the Type 316 stainless steel tubes was significantly better. (Figure 8).

FIGURE 7

Cleanliness and Back Pressure vs. Time for Stainless Steel Tubes

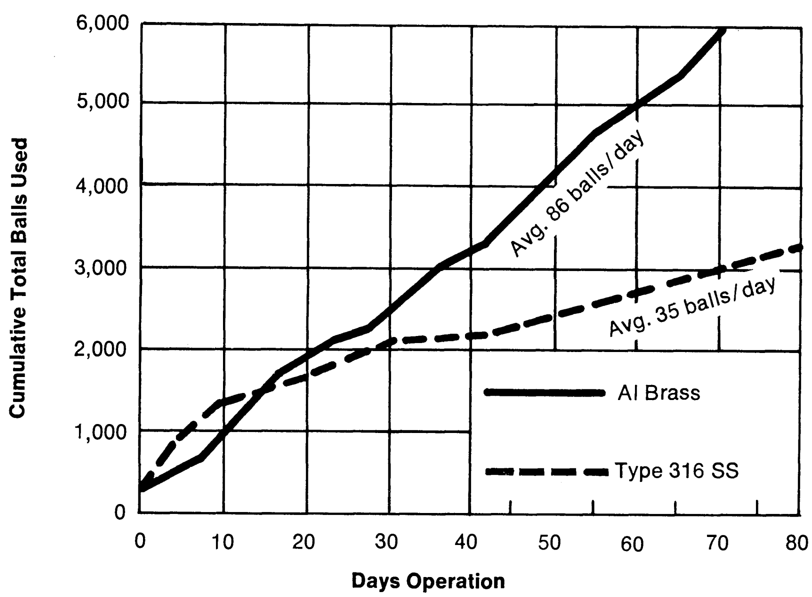


Source: Kuester & Lynch (18)

FIGURE 8

Amertap Ball Consumption Rate

(Ball consumption is a measure of tube fouling.)



Source: Kuester & Lynch (18)

The M.A.N. system employs non-metallic brushes that are restrained in the tubes by plastic baskets attached to the ends of each tube. By reversing the flow of the cooling water, the operator can automatically clean the tubes with the brushes.

Manual procedures are also employed by several utilities, especially in coastal installations where marine fouling from shells, crab claws, and grass may plug tubes and prevent effective cleaning by an automatic system. Plastic, rubber or metal plugs are shot through the tubes with water pressure.

The important effects of tube cleaning on heat transfer have been thoroughly investigated. It can be concluded that greater efficiency results when condensers are cleaned regularly, regardless of the tubing alloy.

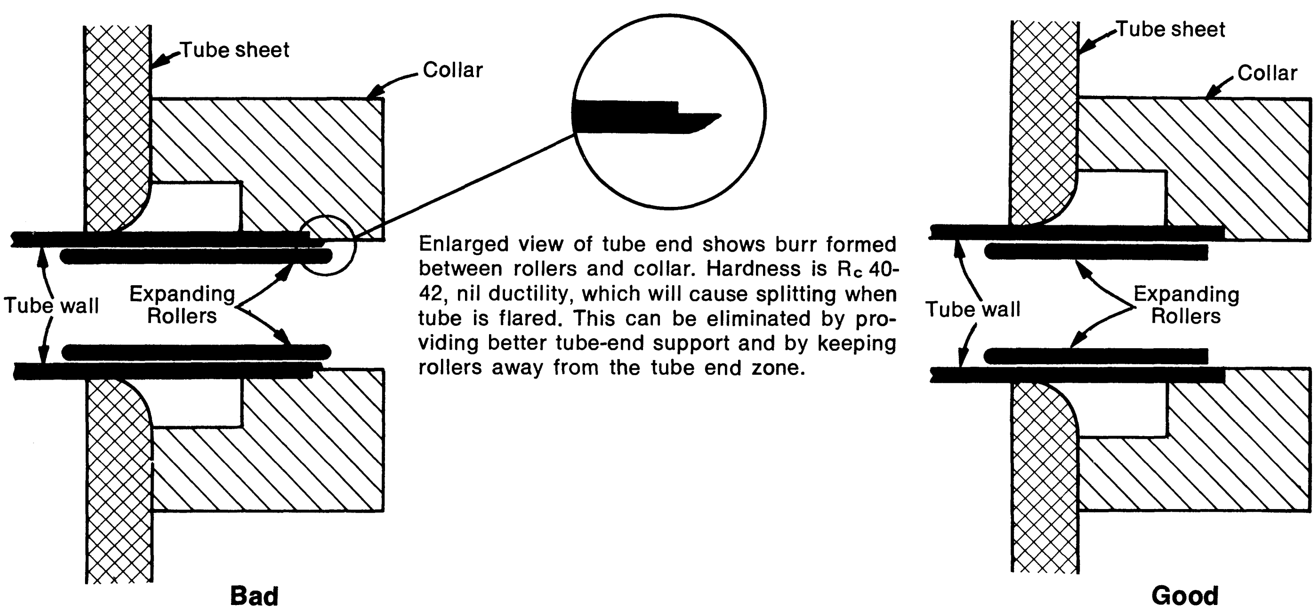
Chemical cleaning is also possible. At present the best acids to use are citric, formic, or sulfamic. These should be used under the supervision of a qualified metallurgist or corrosion engineer. WARNING: Under no circumstances should hydrochloric or inhibited hydrochloric acids be used with stainless steels.

When a condenser is shut down for a long plant outage, the condenser should be drained to eliminate stagnent water in the tubes. This is the case in all kinds of cooling water environments. An outage of a few weeks duration where fresh water is used will not require draining and flushing is never a requirement. Salt and brackish water environments are another matter. Drainage is always important if shutdowns in excess of 48 hours are contemplated. The operation of the cooling water circulating pumps during outage in salt waters negates the need to drain.

ELIMINATION OF POTENTIAL PROBLEMS

There have been a few reports of problems with stainless steel condenser tubing. Investigations of these problems, however, reveal that most

FIGURE 9



Enlarged view of tube end shows burr formed between rollers and collar. Hardness is R_c 40-42, nil ductility, which will cause splitting when tube is flared. This can be eliminated by providing better tube-end support and by keeping rollers away from the tube end zone.

Proper Expanding Tool Prevents Tube-End Splits.

resulted in deviation from proper installation or operating practices and could have been avoided. Little attention to proper cleaning when needed, the use of wrong chemicals, improper storage, carelessness during tube installation or during plant shutdowns, and the misapplication of stainless steel are principal problem areas. An understanding of these problems and elimination of their sources should prevent further difficulty.

Cracking During Installation

While expanding tubes into tube sheets, care should be taken to prevent over-rolling. While there can be some damage to the tubes themselves, damage to the tube sheet is more likely to occur. Over-rolling can distort adjacent holes and ligaments producing conditions that simply cause more work for the utility.

Another problem to avoid in rolling stainless steel tubes into a tube sheet is a tiny burr that sometimes forms at the end of a tube between the expander rollers and collar. Burrs that occur on stainless steel tubes during rolling (see Figure 9) can cause the tubes to split if they are flared. This can be avoided easily by using a rolling tool designed specifically for stainless steel. Such a tool adequately supports the ends of the tubes, thus preventing the formation of hard, low-ductility burrs. These burrs have a hardness in excess of Rc40 and less than one per cent elongation, and are focal points for splitting when tube ends are flared 20-30 per cent.

Split ends in stainless steel tubes, however, are not a problem. A study conducted among a number of utilities by a stainless steel producer reveals that the split ends never penetrate the rolled-in portion of the tube, which is under compression. The chances of a split end causing a leaker is unlikely.

Chloride Pitting

Service experiences with stainless steel condenser tubes in units operating with chloride-bearing water, such as detailed by Hoskinson and Kuester (8) and Long (6), show that some severe corrosion problems were experienced. In all cases the problem was pitting corrosion, which in the worst circumstances caused perforation of the tube wall. The localized attack was attributed to chlorides **plus** discontinuous deposits on the tube surface, which presumably set up conditions favorable to the development of concentration cells.

A suggested remedy for such difficulties would include more careful use of chlorination to control bacterial sliming, and prevention of accumulation of deposits by higher water velocities and more frequent or continuous cleaning.

Stress-Corrosion Cracking

The AISI 300 series austenitic stainless steels are susceptible to stress-corrosion cracking, but this form of failure has never been reported in steam surface condenser applications. Such failures normally occur when conditions of stress, temperature, and corrodents are of a sufficient magnitude. The normal temperature in condenser service, 100-130°F (38-54°C), is well below the point at which stress-corrosion cracking is likely to occur in stainless steel.

Ferrous Sulphate Treatment

Recent publications concerning the use of ferrous sulphate indicate that it has been highly successful in maintaining and even increasing the life expectancy of brass tubes. Since it is a treament that induces fouling on the tube surface, it can have a detrimental effect on stainless steel tubes. It should not be used unless the nature of the deposits that it creates on tube surfaces is known. As previously discussed, a continuous thin coating may not have a harmful effect on stainless; but if the treatment produces a loose, flaky and scattered deposit (or any type of deposit in sea water) accelerated pitting attack may occur. On units completely tubed with stainless steel, this treatment should not be used since it has no beneficial effect in preserving or increasing the service life of the stainless and will probably result in premature failure.

Cleaning Solutions

The use of hydrochloric acid was strongly discouraged under the topic of maintenance. Since this acid is used frequently by utilities, this caution bears repeating. This pertains to the straight, diluted, foamed and inhibited varieties. The best way to ruin stainless steel condenser tubes is to use hydrochloric acid for cleaning. It is also recommended that the utility contact its tube supplier whenever acid or chemical cleaning of any type is contemplated.

NEW DESIGN POTENTIALS

Up to the present, condenser design and material usage have been limited to standard procedures. This development of stainless steel as a competitive tube material has offered a new range of possibilities. The efficient utilization of these materials may offer new design concepts formerly considered highly impractical.

One area which should be explored is the use of higher cooling water velocities. The ability of the stainless steels to resist erosion at high velocities is well known. There is basically no limit to the practical velocity other than economics. The possible use of higher velocities should promote new interest in water box design to permit the efficient flow and distribution of cooling water. The present designs are necessary because of the limited velocities required for brass and aluminum alloys. New designs may make the use of increased velocities highly economical.

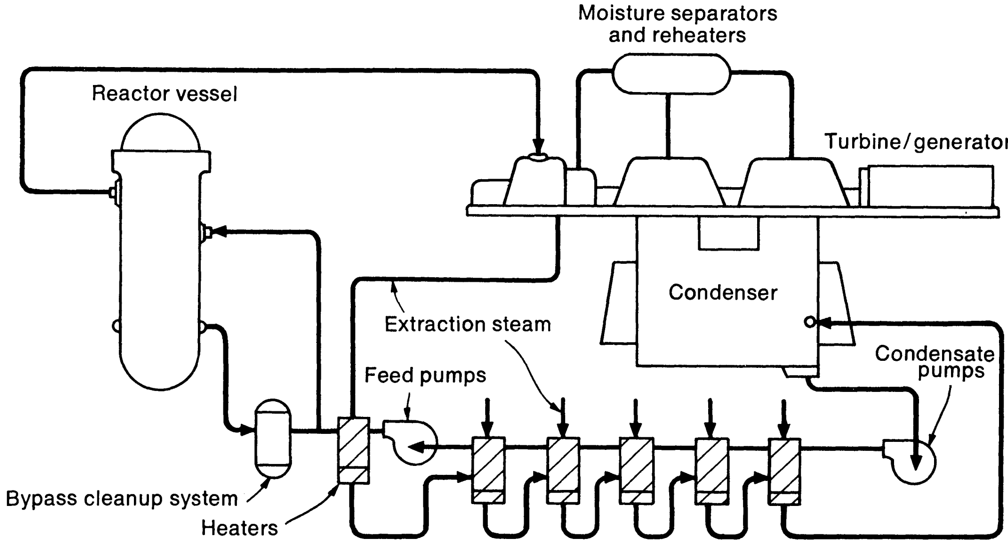
Some interest has already been expressed in new construction techniques. The economical combination of stainless steel tubes and carbon steel tube sheets has made possible several construction changes for the utility industry. The economics of welding the tube sheet and water boxes to the shell and eliminating expensive flanged construction has been documented.

CONCLUSION

The inherent advantages of stainless steels in terms of resistance to corrosion, erosion, and fouling under a variety of service conditions have brought these metals into new prominence in the power generation field. Extensive research by steel producers and utilities alike, in terms of heat transfer and the development of new in-service data, has removed many of the "penalties" originally imposed upon stainless steels.

Along with this, new and efficient production techniques have reduced the relative cost of stainless steel tubing very dramatically, and new alloys are being introduced to solve the problems that have plagued the industry for years. As their application continues to grow in condenser service, stainless steels bring to the power industry new levels of efficiency, reliability, and economy.

PART TWO: Feedwater Heater Tubing



Boiling-Water Reactor

INTRODUCTION

Within the past decade, stainless steel has grown from a virtual unknown for feedwater heater service to where it is now the material most preferred by utilities. Several factors contributed to this growth:

1. Greater emphasis on the importance of corrosion resistance.
2. A need for a material system that is compatible with carbon steel, especially at high pH levels.
3. An urgent need to eliminate feedwater contamination.
4. Good high-temperature strength.
5. Increasingly more attractive from the cost standpoint, in comparison with nonferrous materials.

Feedwater heaters resemble surface condensers in many respects: Both are shell-and-tube heat exchangers, and both condense turbine steam on the shell side. Both heaters and condensers in one plant are exposed to essentially the same condensate and to the same impurities in the condensate. Both contain different operating zones within the shell. And both benefit greatly by the use of stainless steel tubing.

The text discusses factors that utility chemists and engineers must consider in determining a material system for feedwater heater tubing.

THE FEEDWATER HEATER ENVIRONMENT

While there are a number of similarities between condensers and feedwater heaters, there is a world of difference in operating conditions. Principal among these differences are temperature and pressure, which can be limiting factors in tube material selection. Higher temperatures and pressures act to increase the severity of corrosion, which appears to be the single most important cause of tubing failure in feedwater heaters.

Temperature and Pressure

Increasing temperature and pressure requirements in recent years complicate the design of feedwater heaters and make the choice of materials for tubing more difficult for these reasons:

Prior to the introduction of high-temperature, high-pressure power plants, annealed nonferrous tubing proved adequate for heater service. Light-wall copper-nickel tubes rolled into the tube sheet was a normal construction that proved to be reliable for mild, low-pressure service.

As temperature and pressure increased, new specifications were drafted; tube wall thicknesses increased. When these heavier tubes proved insufficient and expensive, engineers then turned to cold-worked and tempered nonferrous tubing to accommodate changing conditions. A new set of problems soon developed. Many of these high-strength cold-worked materials proved to be susceptible to corrosion so industry attention quickly turned to inexpensive carbon steel, which was proven suitable for high-pressure heaters in European applications.

Carbon steel, however, is susceptible to inlet erosion-corrosion, and it is also difficult to weld to the tube sheet, which adds to the cost. Additionally, many utilities are not accustomed to operating at the high pH levels needed to inhibit corrosion of carbon steel. It requires a pH of 9.5, which is not the ideal level for the nonferrous tubing in the low-pressure heaters.

Furthermore, because carbon steel is subject to severe corrosion on the shell side during shutdowns, plants developed the practice of blanketing heaters with either steam or nitrogen—and as one engineer succinctly stated, "we're in the power business, not gas." He was referring to the large tanks and extra piping necessary for nitrogen gas storage and handling.

The power industry in the past several years has expressed its concern over these problems, as evidenced by numerous articles, technical papers, and industry conferences (19, 20, 21). Now, many engineers in the power industry are beginning to recognize the value of stainless steels for feedwater heater service.

Stainless steels are suitable for both low- and high-pressure service; and if the utility desires to keep carbon steel in high-pressure heaters, a pH of 9.5 can be safely maintained with stainless. (Refer to Table 5 for maximum temperature values for feedwater heater tubing.)

Corrosion

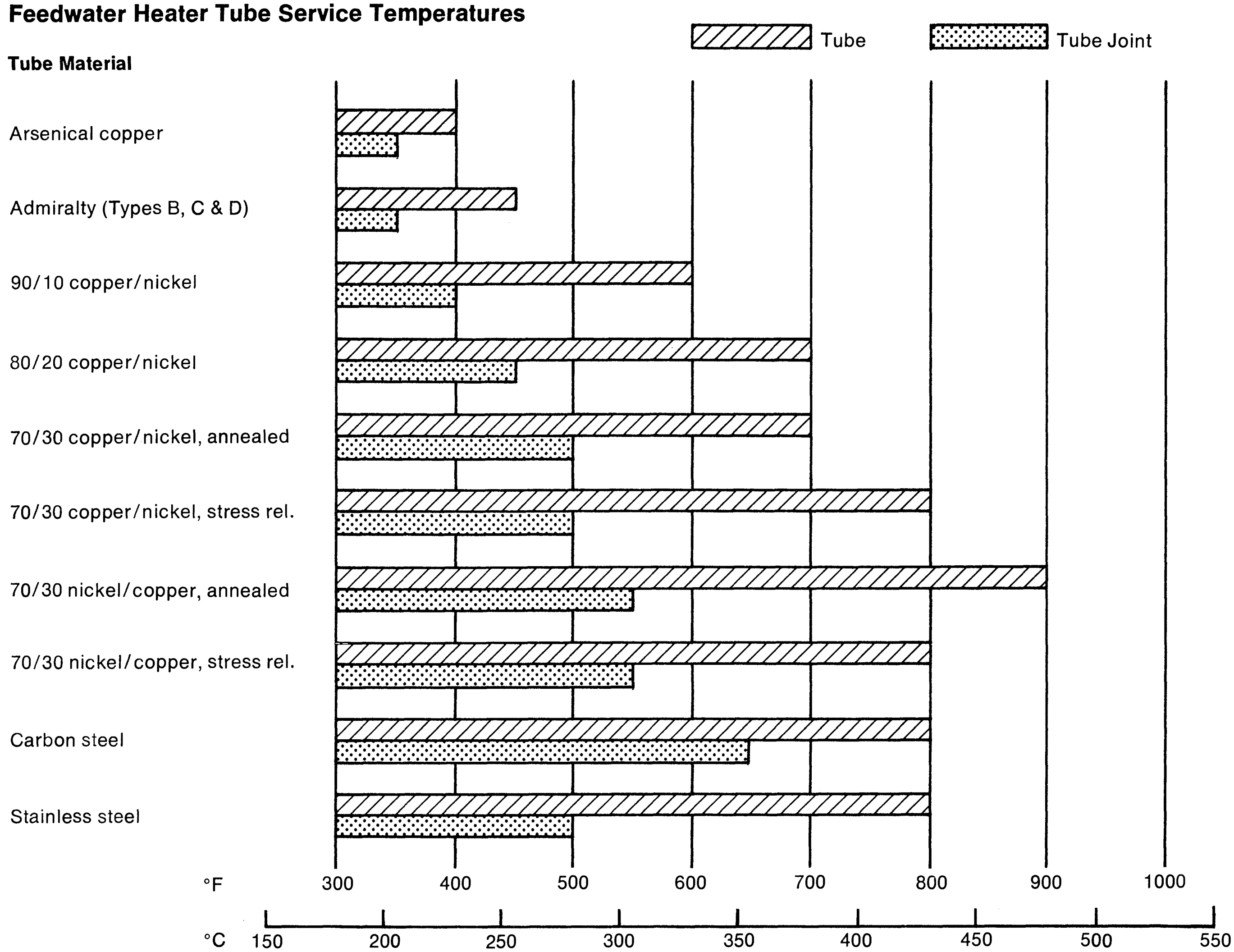
General corrosion. Carbon steel tubing can be expected to suffer general corrosion when pH levels are maintained for the benefit of nonferrous tubing, as previously discussed. Uhlig and others reported that carbon steel corrosion rates in water relate to pH.

Also, serious metal erosion has been observed near the inlet of carbon steel heater tubes when exposed to unfavorable water chemistry. Velocity also affects carbon steel corrosion rate.

Carbon steel is also prone to general corrosive attack anytime prior to its entering service, so it must be protected. Heater manufacturers accomplish this by sealing the unit and blanketing it with nitrogen. Of course, as time passes before heater service begins, blanketing must be checked and gas pressure maintained. Stainless steel is not subject to general corrosion of this nature.

TABLE 5

Feedwater Heater Tube Service Temperatures



Heat Exchange Institute recommends these temperatures where tubes are installed in steel tube sheets by expansion only. Joint temperature is assumed equal to that of Max. Temperature °F feedwater.

Source: HEI (22)

Exfoliation. The exfoliation problem developed when power stations were placed on peak-load service; that is, when they are shut down overnight or on weekends. The attack is characterized by formation of a dark grey-black scale that flakes off to a point at which the tube ruptures.

Hopkinson's (23) analysis of service failures indicates that exfoliation attack occurs most readily on 70/30 and 80/20 copper-nickel tubes, but not on Monel alloy 400 and 90/10 copper-nickel. Air entering the heater during shutdown and low-load service may be a contributing cause of exfoliation, despite careful operation.

Evaluations by Wiedersum and Tice (24) demonstrated that AISI Types 304, 316, and 347 resist exfoliation of heater tubes.

Stress-corrosion cracking. Heater manufacturers have given much attention in past years to the development and use of high-strength nonferrous materials for feedwater service. To obtain the high strengths, however, many nonferrous materials are used in other than a fully annealed condition. Observation of these materials over several years revealed that they are not 100 per cent reliable, the culprit most often being stress-corrosion cracking. S. D. Reynolds, Jr., (20) provides detailed analyses of stress-corrosion cracking problems in high-pressure feedwater heater tubing, particularly of the drawn and stress relieved nonferrous materials. He also discusses feedwater heater conditions that could lead to stress-corrosion cracking of stainless steel. In his summary, however, he states that **"austenitic stainless steel tubing so far has resisted stress-corrosion cracking in feedwater heaters."** This cannot be said for many nonferrous materials, and he cautions plant chemists to exercise great care during chemical cleaning to prevent injection of harmful corrodents; to monitor mercury manometers so as to prevent accidental loss of mercury into the stream; and to minimize concentrations of ammonia and caustics on the shell side.

Feedwater contamination. Although corrosion product accumulation is of concern to operating engineers in fossil plants with drum-type boilers, it is not of major importance because these systems can be chemically cleaned rather easily. In supercritical fossil-fueled and nuclear central stations, the problem of contamination is far more acute.

Corrosion products in any nuclear plant can adversely affect core pressure drop and flow. In addition, radioactive corrosion products are the major source of radioactivity observed during shutdown periods. By curtailing contamination, maintenance and waste-disposal are less difficult.

In plants with copper-alloy feedwater heater tubing, reactor water analyses indicate corrosion-product concentrations vary from about 0.2 to 1 ppm. Similar analyses at plants with stainless steel tubes in heaters show corrosion-product levels about one-tenth as high. (25)

For example, at Nine Mile Point, where heaters have stainless tubes, corrosion-product levels in primary coolant fell between 50 and 100 ppb (parts per billion). Similar performance was obtained at Oyster Creek and Tsuruga (Japan).

SPECIFICATION

The new ASTM Specification A688-73 for stainless steel feedwater heater tubing covers manufacture, testing, and packaging. It includes composition, mechanical properties, tolerances, stress relieving, nondestructive testing, cleaning, corrosion tests, inspection, etc. It is a good starting point for specifying stainless steel tubing for feedwater heaters.

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