Modular Steam Condenser Replacements Using Corrosion Resistant High Performance Stainless Steel Tubing

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Abstract

Condenser performance and reliability have a significant impact on the electric generation of a power plant. This engineering fact is of particular importance in view of the current climate of the very high price of many fuels. Fuel price pressure combined with unregulated market competition and its extraordinary opportunities to sell power make today's power generation market unique. Rebuilding an old condenser using a modular rebuild, opposed to a simple re-tube, offers the owner a chance to obtain optimum performance by evaluating a number of tube material choices.

This paper addresses modular bundle replacement scenarios that would use thin walled stainless steel tube materials. These materials have traditionally had a very acceptable corrosion resistant service when applied to saltwater cooling systems. Discussed will be the major engineering areas of consideration for modular tube bundle replacements using stainless steel tubing. These include tube wall thickness, tube joints, bundle capital costs, the new station performance and generation effects. Seasonal generation aspects of a modular condenser replacement will be presented. Historical tube costs and past industry experience shall be listed. The application of these highly corrosion resistant stainless tube materials to new combined-cycle stations that use salt or brackish cooling water will also be reviewed.

In the paper, a 30-year old copper alloy tube condenser in a 400 MW fossil plant will be taken as a reference case study in order to typify the modular bundle replacement project. The reasons for retubing will include the problem of frequent forced outage caused by tube failures, the effect of plugged tubes and the elimination of copper carry-over to the feedwater and steam system. Some comparisons of the stainless steel replacement bundle to the costs and thermal performance of titanium tubing shall be provided. The study concludes that condenser replacement modules using corrosion resistant stainless steels can provide a renewed operational reliability with reasonable overall economics.

Introduction

The objective of this paper is to help an engineer who is contemplating a modular replacement of an older steam surface condenser to select a tube material for that replacement and to provide him with a real perspective on modular replacement choices and costs.

Presented will be the properties of modern thin-walled stainless steel condenser tubing materials that would be considered in the retubing to both restore the condenser to its original reliability and at the same time provide superior corrosion resistance. Through a case study, the paper provides the results of a typical economic optimization that was used to select the tubing and surface area for a condenser replacement. The case study is complete with recent economic data to indicate the separate cost impacts of the selection on station generation and capital costs.

There are many design issues arising from condenser refurbishment using modular tube bundles. A primary concern in tube bundle design is often that of the choice of tube material. Besides capital cost, in today's market, the basis of any retubing is tied to long term plant performance and availability. It is the blend of these three parameters that drives the decision-making process and has forged an increase in the number of modular tube bundles. This study reviews the associated benefits of using stainless steel materials in modular tube bundles. The study further addresses some of the subtle issues surrounding tube material choice.

Reasons for Considering Retubing

The most compelling reason for a tubing replacement is the issue of reliability. Today, even infrequent forced outages for tube leak detection and plugging may be unacceptable.

The majority of older condensers, particularly those in salt water or brackish water service, contain copper alloy tubing. The 30-year-old condenser likely has experienced a large number of failed tubes from a variety of reasons that range from sulfide pitting and inlet end erosion-corrosion to tube vibration. That loss of tubing surface area and the general condition of the tubes, increases the turbine exhaust pressure causing a relatively appreciable permanent loss of station generation. The generation loss resulting from a loss in turbine exhaust vacuum is also an effect that increases during the summer peak periods of operation. As a consequence, industry reports have shown the performance of the condenser has a substantial effect on the overall station heat rate [1]. But it does not stop there. The rate of tube failures in older condensers is higher and forced outages can be expected to increase proportionally. Depending on the plant policy, its operating capacity factor and the specific market price charged for the generation at the time of the tube leak, the lost revenue to find and plug the failed tube can be large. Finally, since there is always a small metal leacheate from the tubes that dissolves into the condensate, replacing copper alloy condenser tubes also rids the steam cycle of its major source of copper containing material. Copper contributes to steam generator corrosion and turbine blade plating in both fossil and nuclear power plants.

Elements of a Modular Replacement Design

Traditional methods of condenser tube restoration use one-for-one tube replacement, i.e. all the tubes are pulled-out and replaced with others of the same diameter and thickness. Sometimes a plant may choose to use the same material. With this kind of retubing, if the same tube material is replaced, it may be subject to the same failure mechanisms but there is no change in the condenser performance. Usually however, the replacement tubing would likely be more corrosion resistant with a lower conductivity. This type of retubing results in a measurable generation loss because without a corresponding upgrade of some other aspect of the circulating water system, the retubed condenser performance will be decreased. To help reduce this adverse effect & cut costs, it is common practice to replace older copper alloy tubing with a thinner replacement. For instance, 18 Birmingham Wire Gauge (BWG) copper alloy tubing of a nominal thickness of .049 in. (1.24mm) might be replaced with 22 BWG (.028 in. (.71mm)) stainless steel tubing.

Modular tube bundles in the past have been often employed for new facility construction but recently more existing power plants have been using the modular tube bundle replacement method [2]. A module is a self-supported structure of an entire tube bundle fabricated in a manufacturer's shop that is complete with tubes. The module is sized to be small enough that it can be shipped directly to the site on a truck, rail car or barge. At the site, the waterboxes of the existing condenser are taken off and its tube bundles are removed including the tubesheets, tube support plates and hotwell supports. Heaters and the shell are temporarily braced for the interim period. The factory pre-fabricated tube bundle(s) are shipped to the site and inserted into the original shell. The modular tube bundle replacement method is applicable to both fossil and nuclear plant condensers that are in fresh and salt-water service. Modular replacement has the following advantages [2],[3]:

- Shorter outage time than one-for-one tube replacement.
- Fabrication in the shop provides better quality control.
- The new bundle design can achieve better deaeration and performance.
- A thermal performance improvement can be achieved by a better bundle design.
- A thermal performance improvement can be achieved by an increase in surface area.
- A thermal performance improvement may be achieved by a reduction in the cooling water hydraulic pressure drop that is accompanied by an increase in cooling water flow.
- Replacement of the tubes with different diameter, material and thickness should increase the condenser's corrosion resistance and thermal performance.
- Replacement of the tubesheets with a material that is compatible with the tube material eliminates the need for tubesheet coating and galvanic protection.
- Tubes can be seal welded to the tubesheets to minimize the possibility of tube joint leaks and to increase tube joint strength.
- The design and installation of appropriately spaced tube support plates during the fabrication reduces the unsupported tube length and eliminates the need for any anti-vibration staking.

A review of the above list indicates that the modular tube bundle replacement method is well suited to use the corrosion resistant, high performance stainless steel thin wall tubing. Thin wall tubing costs less and has a lower thermal resistance.

Historical Use of High Performance Stainless Steel Tubing

High Performance Stainless Steel materials are characterized by high chromium contents together with molybdenum and nitrogen. They include both austenitic and ferritic material. They were developed by companies in the US, Europe and Japan. Table 1 on page 13 lists the trade name, and corresponding UNS number and the manufacturers of representative alloys.

The materials have been in use since the 1970's [4]. There were 190 installations through 1998 representing some 100 million feet (30,480 km) of tubing. The relative sales of these alloys are divided approximately 60% to 40% respectively between the austenitic and ferritic materials. Though the excellent level of resistance of these alloys to chloride attack was the main reason for their application in seawater and brackish water-cooled condensers, approximately 45% of the installations are also installed in condensers handling fresh water.

Thermal and Mechanical Properties of High Performance Stainless Steels

Table 1 contains the thermal and mechanical properties of these alloys.

Of all these properties, the most important is the thermal conductivity. The thermal conductivity affects the heat transfer capability of these alloys; the higher the thermal conductivity the higher the heat transfer capability. Note that a review of Table 1 indicates the ferritic stainless steels have higher thermal conductivity than the austenitic alloys. That means less surface areas are required to condense the same amount of steam when all other conditions are equal. Conversely, at the same conditions and identical surface areas, the higher the thermal conductivity of the tubing, the lower the required condensing temperature and its corresponding steam pressure. The lower pressure provides a lower turbine exhaust end point and so more turbine generation is produced assuming the turbine is not operating choked. The conductivity of the tubing is not directly responsible for the total differences in condensing pressure since all of the heat transfer resistances in the condensation process must be considered in this estimate. Those resistances would include the diffusion resistance, the condensation resistance, the condensate inundation resistance, the tube wall resistance (just discussed), the inside and outside tube fouling resistance, and the hydrodynamic resistance of the cooling water. Listed in the HEI Standards [5] are the factors to be used for a specific tubing material when determining the condensation pressure. These heat transfer factors were developed from the results of tube material heat transfer test programs conducted by both HEI and EPRI [6].

The Young's modulus of elasticity affects the stiffness of the tubes. The value of the Young's modulus has an influence on the rolling of the tube into a tubesheet of a particular material and also its potential for tube vibration. The higher the Young's modulus the stiffer the tube and among other structural advantages, the higher its ability to resist flow induced vibration. Flow induced vibration is a fluid-elastic phenomenon produced by high velocity steam flows through the tube bundle on the shell side of the condenser. For a stiffer tube, the unsupported tube span can be longer when all other conditions are the same. With a longer unsupported tube span, the number of tube supports can be reduced. While the Young's modulus of the austenitic and the ferritic alloys is similar, the difference between stainless steel and their counterpart non-ferritic alloys, such as the copper alloys and titanium, can be significant. Hence, the larger unsupported length for stainless steels may significantly reduce costs and provide more insurance against damaging tube vibration during operation.

The tube material density determines the overall weight of the bundle. In some replacement cases, a lower tube bundle weight may hinder the ability of the condenser bolting to hold the condenser on its footings. The thermal expansion coefficient affects the stresses on the tubesheet when temperatures on the tubes and shell are different, however it is generally small. The yield strength measures the alloys ability to contain pressure and its pullout load from the tubesheet. Typically, all of these last properties do not contribute significantly to the complexity of the average condenser replacement bundle design or its costs.

Case Study Assumptions

The case study approach has been taken to illustrate the modular condenser replacement optimization process and its costs. A typical modular condenser replacement scenario is now developed. As is obvious, it must be very detailed to ensure an accurate cost simulation and final size optimization results. For the conceptual design to be as close to reality as possible, the replacement module study must take into account the operating characteristics of the turbine generator and the circulating water pumps at the time of the evaluation.

The condenser to be replaced in this study is assumed to be a 30-year old condenser with 90-10 copper nickel tubing serving a 400MW fossil station using brackish cooling water. This condenser is a single pass, once through, open cycle, siphonic unit with three circulating water pumps. There are two tube bundles containing a total of 22,470 tubes of 1 in.(25.4 mm) OD, 19 BWG,(.042 in.(1.1mm.)) tubing with a 40 ft.(12.19 m.) effective length. The total condenser surface area is 235,305 sq ft.(21,859.8 sq m.) The cooling water velocity through the tubes is 6.5 fps.(1.98 m/s). The original design conditions include 300,000 GPM (1,137 m^3/min) of cooling water at 70F(21.1C) inlet temperature with 13.8F(7.67 C) temperature rise, 85% cleanliness factor and 1.63 in. Hga (5.52 kPa) backpressure. Each bundle is 10 ft (3.05 m.) wide by 13 ft (3.96 m.) high. Note that these parameters are typical of many 30-year old condenser designs. The tube material rating factor in HEI Standards [3] for 90-10 CU-NI however has improved slightly since then so that the backpressure would now be determined as 1.61 in. Hga (5.45 kPa) under the same conditions. Notice also that one of the initial reasons for the replacement is likely that the condenser presently does not perform as well as these industry standards suggest. The current condenser backpressure due to plugged tubes or past water treatment practices and scaling is likely much higher. Any well defined, original reference heat transfer coefficient or condenser pressure can be used as an incremental basis for the optimization study. In the case herein, the original condenser design condition was chosen to be as determined by the HEI standards.

The net station heat rate (NHR) is presumed as 10,000 Btu/KWH (10,550 kJ/KWH) at the 400 MW gross rating and a backpressure of 1.61 in. Hga (5.45 kPa). The turbine is assumed to choke at 1.3 in Hga (4.40 kPa) backpressure and so the station would not be capable of producing more power at lower exhaust pressures. At other than the design backpressure, the NHR varies (typically) as follows:

Table 2– Net Heat Rate Versus Backpressure

BP–in.Hga (kPa)	1.0 (3.38)	1.3 (4.40)	1.61 (5.45)	2.0 (6.77)	3.0 (10.16)	4.0 (13.55)	5.0 (16.93)
NHR-Btu/KWH (kJ/KWH)	9,970 (10,518)	9,970 (10,518)	10,000 (10,550)	10,020 (10,571)	10,120 (10,677)	10,220 (10,782)	10,320 (10,888)

As is the normal case, it is further assumed that the circulating water (CW) pumps will not be changed out during the modular condenser replacement. However, the use of thinner tubing of a smaller diameter will result in a somewhat higher flow because the hydraulic pressure loss across the condenser will decrease, moving the CW pump out on its TDH-Capacity curve. The CW pump curve should characterize its current performance. A typical CW pump curve is shown in Table 3:

Table 3 – TDH Versus Capacity

TDH – ft (m.)	63(19.2)	54(16.5)	46(14.0)	39(11.9)	33(10.1)	30(9.1)	29(8.8)
Flow-gpm (m^3/min)	0	30,000 (113.7)	60,000 (227.4)	90,000 (341.1)	120,000 (454.8)	150,000 (568.5)	180,000 (682.2)
TDH – ft (m.)	28 (8.5)	27 (8.2)	26 (7.9)	24 (7.3)	22 (6.7)	17 (5.2)	
Flow-gpm (m^3/min)	210,000 (795.9)	240,000 (909.6)	270,000 (1023.3)	300,000 (1137.0)	330,000 (1250.7)	360,000 (1364.4)	

Other study parameter details that are necessary in a condenser modular tube bundle replacement optimization evaluation include:

- Incremental generation revenue at $25/MWH
- Auxiliary power cost at $15/MWH
- Capacity factor at 70%
- Net escalation at 4% per annum with an 8% annual discount rate
- Remaining life of plant at 20 years
- Tube cleanliness at 90 %
- Combined efficiency of pump and motor at 85%.
- The salvage value of the old tube bundle based on a 40% wall loss and $.85 per pound.

It was assumed that a higher cleanliness factor of the new bundle will be achieved because its tubes will have higher cooling water velocity and fouling tends to build up less on a stainless steel than the copper alloys. It should be recognized too that during a modular bundle replacement an opportunity exists to more easily install a modern tube bundle ball cleaning system and debris filter to further increase any cleanliness factor. Although the latter introduces more costs to the project and a slight additional hydraulic head loss, the increased performance of the condenser with its resulting extra future generation can often be economically justified.

It is important to understand that the above economic factors can change dramatically and that would alter the condenser bundle optimization results. Within the boundaries of the rigorous constraints associated with the modular replacement, sensitivity and “what if” cost scenarios should be employed in a computer spreadsheet to define and appreciate the impacts of future costs on the final, permanent size of the condenser that will be selected. For instance, though this study was very recent, costs of power in California have had an associated price per MWH of 10 to 50 times the assumption above. An appropriate revision upward of the $25/MWH unit revenue value used in this case study, had the power plant been located in the Western US, could clearly have impacted the outcome of the condenser replacement sizing optimization.

Modular Condenser Upgrade Scenario & Optimization Process

Based on previous experiences with modular bundles, the complete costs of specific, practical replacement modules must be estimated to accurately optimize the replacement module size.

In this case study, the scenario will presume the condenser is to be upgraded from the original copper alloy tubing to modules with either of two types of stainless steel (6% Mo austenitic or 27-29% Cr ferritic) and also titanium tubes. In addition, a slight reduction in the tube diameter will usually not significantly affect the condenser tubesheet to collect and be blocked with debris but the reduction will allow a large surface area increase for the same overall dimensions of the replacement module. Although often there are owner preferences, tube material wall margins and past regional experiences to consider, a complete modular replacement study would often include exploring the effect of very thin walled tubing on the project costs and condenser performance. Hence, in this illustrative example, the upgrade scenario will assume the new bundles will have 7/8 inch (22.2 mm.) OD tubing in 22 BWG (.028 in. (.71mm)) and 25 BWG (.020 in. (.51mm)).

Galvanically compatible tubesheets and tubes of the modules would be employed and so the study will include both solid and clad tubesheets. The tube joint cost is further split into both rolled and welded tube ends.

One constraint of the modular condenser upgrade requires that the existing tube length not be adjusted. In addition, the hydraulic aspect of the modular tubing design must follow the existing CW pump characteristics. After determining the thermal performance of the condenser with the 7/8 inch (22.2 mm.) OD tubing; the added generation of this conceptual power station will be quantified using the incremental turbine characteristic curve. Thus, both the turbine response curve and CW pump capacity curve have an important influence on the study results.

Since the tube length of 40 ft (12.19 m.) was fixed, the cost optimization process included first varying the number of tubes within the available cross-section of the bundle space with a check that they did not exceed any practical limit. This tube count was the basis for subsequently computing the surface area, cooling water velocity, the cooling water flow rate and the condenser backpressure. From that followed estimates of the incremental generation loss and the incremental present worth of revenue loss for the next 20 years of operation, the module manufacturing and installation cost, and finally all costs are summed to the total evaluated cost.

The condenser performance related costs are computed as an incremental present worth of future revenue requirements (PWRR). PWRR is an engineering cost variable that accounts for an annual future cost over the life of the plant by accruing the equivalent of those costs back to the present day so that they can be included in a capital cost evaluation. The computation requires the discount rate, annual escalation, life of the project along with the expected annual relative cost. The PWRR herein is used to describe the cost of the relative annual generation of the station that would result from installing the different condenser modules. For the sake of simplification, it incorporates the approximation that the station operates at only the design conditions for 70% of the year and will do so for the next 20 years. The PWRR for this study was computed on the basis of the modular replacement project economics using an article in Power Engineering [7]. Other construction aspect costs can be obtained from RS Means[8].

The HEI Standard [5] method was used to calculate the heat transfer coefficient and the backpressure. The process to determine the final module characteristics began with 22 BWG 6% Mo austenitic SS, 27-29% Cr ferritic SS and titanium tubes until the optimal number of tubes with the lowest PWRRs were identified. The process was repeated with 25 BWG 6% Mo austenitic stainless steel, 27-29% Cr ferritic stainless steel and titanium tubes.

Based on past estimates, a rough approximation of all the costs are developed in order to determine the range of selections. Then, the range of condenser module sizes with their associated performance was further winnowed down.

The average current tubing cost for each gauge and material was obtained from the tubing manufacturers shown in Table 4 and the titanium tube manufacturer. Two other newer stainless steels are also shown in Table 4 to provide some further cost comparisons. The 7%Mo austenitic alloy gives excellent performance in high temperature seawater but is expensive. Key selected modular condenser sizes were sent to a condenser manufacturer for pricing with both solid and clad tubesheets, and rolled and welded tube joints. In this instance, a major condenser manufacturer provided approximate current fabricated and shipped modular bundle costs. Installation costs were estimated from the past cost data files of the authors. The final cost for each material and gauge included the salvage value of the old bundle.

Table 4 -Tubing Cost Per Foot

Tube Material	**27-29% Cr Ferritic**	**6% Mo Austenitic**	**7% Mo Austenitic**	**22% Cr Duplex**	**Titanium**
22 BWG - $/ft (.028 in./ .71 mm.)	**1.32**	**1.74**	**2.62**	**.96**	**1.72**
25 BWG - $/ft (.020 in./ .51 mm.)	**.99**	**1.31**	**2.08**	**.74**	**1.20**

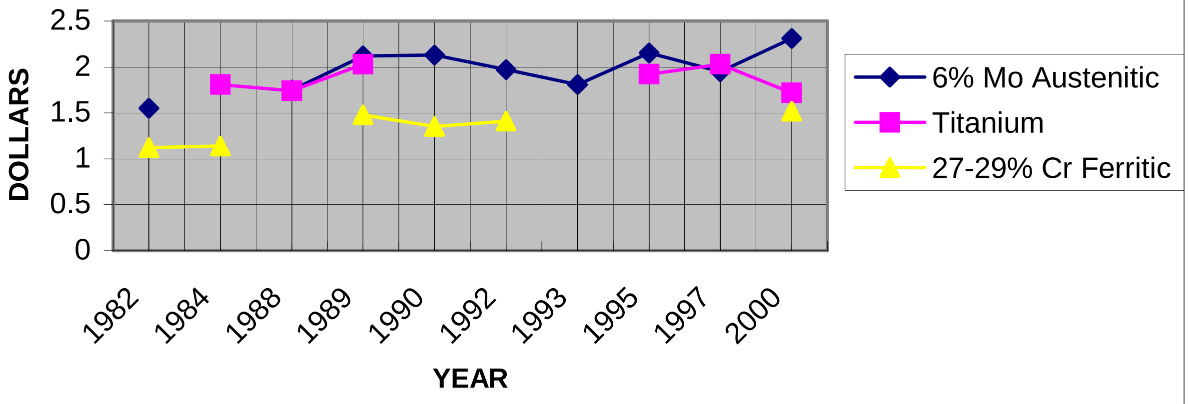

Figure 1 - Historical Pricing ($/ft) for 22 BWG Condenser Tubing

Historical Tubing Costs

Tubing costs constitute a major element of the final modular bundle evaluation. Base tube metal prices fluctuate considerably with the market conditions [9]. Besides the purely commercial aspects of supply and demand for the tubing, international events and trading in the metals can have a large, rapid and unpredictable influence on the price. The historical prices of the three major tube materials used in this study are shown in Figure 1.

Note that there was not sufficient data to accurately forecast & trend pricing between the materials. As a result, the past pricing indicates that the capital cost rankings of the optimized selections from this study may be drastically different if the analysis had been performed in a different time frame. With a realization that the expected tube pricing used in the modular study may have changed appreciably in any given year, the final optimized selection could be modified as well. It is strongly recommended that a short-term projection be made of the tubing candidate costs and a corresponding sensitivity analysis of the replacement bundle optimization selection be used to determine the effect of any price fluctuations.

Performance and Generation Comparison

After the cost and sizing algorithms are developed and all the computer runs are generated, the output is carefully examined to determine the economic optimal selection for each tube material and gauge. The optimum module size results for the specific conditions, design descriptions, plant and economic data related to this study are:

Table 5– Optimized Design Parameters

Optimized Module Size Selection	1	2	3	4	5	6
Tube Material	6% Mo Austenitic	27-29%Cr Ferritic	Titanium	6% Mo Austenitic	27-29% CR Ferritic	Titanium
Tubesheet Material	Solid 6%Mo	Solid 6%Mo	Solid Titanium	Solid 6%Mo	Solid 6%Mo	Solid Titanium
Tube Wall BWG – In. (mm.)	22 - .028 (.71)	22 - .028 (.71)	22 - .028 (.71)	25 - .020 (.51)	25 - .020 (.51)	25 - .020 (.51)
No. Tubes	24570	24570	24570	24570	24,570	24570
Number of Tube Support Plates/Bundle	11	11	13	12	12	14
GPM (m^3/min)	284000 (1075.1)	284000 (1075.1)	284000 (1075.1)	287000 (1086.4)	287000 (1086.4)	287000 (1086.4)
Cleanliness	0.9	0.9	0.9	0.9	.9	0.9
Tube Velocity, FPS(m/s)	7.0(2.13)	7.0(2.13)	7.0(2.13)	6.8(2.07)	6.8(2.07)	6.8(2.07)
CW Temp., °F(C)	70(21.1)	70(21.1)	70(21.1)	70(21.1)	70(21.1)	70(21.1)
CW Temp. Rise, °F(C)	14.6(8.1)	14.6(8.1)	14.6(8.1)	14.4(8.0)	14.4(8.0)	14.4(8.0)
Backpressure, In Hga(kPa)	1.67 (5.66)	1.64 (5.55)	1.62 (5.49)	1.63 (5.52)	1.61 (5.45)	1.59 (5.38)
Increased Design Backpressure Basis Original Cond.- In. Hga(kPa)	0.07 (.24)	0.04 (.14)	0.01 (.03)	0.03 (.10)	0.0 (0.0)	-0.02 (-.03)
Incremental Lost MW	0.26	0.15	0.05	0.11	0.01	-0.05
PWRR of Lost MW-Thousands	$522	$306	$108	$217	$26	$-93

The bottom line of Table 5 demonstrates the present day cost effects of the different thermal performances to be expected from the tubing options represented by the listed optimum replacement modules. It indicates that comparatively, the most adverse impact on station generation would occur if 22 BWG 6% Mo tubing modules were installed and lesser performance effects would occur when either a thinner tubing, 27-29% Cr ferritic or titanium were used. The relative magnitude of the performance related PWRR costs in the case of this study, it should be noted, is about 10% or less of the installed cost.

To further put these results into perspective, it should be appreciated that although the selections above are a result of a wide variety of costs and data, they represent a balance and are chosen from the minimums of shallow total cost curves that are very sensitive to the inputs. Hence, if the future revenues from the sale of station generation are projected to maintain uniformly high unit values (as for example, the recent reported costs of power in the Western US), the optimum should reflect this by moving toward the tubing that creates a larger surface area and provides better performance. Conversely, if the objective is to minimize capital costs due to a project budget situation, then the optimum would shift toward a higher backpressure, lower surface area condenser module.

Based on the thermal conductivity listed in Table 1, one can draw a conclusion that the performance will be very similar between 6% Mo Austenitic, and 7% Mo Austenitic. The 27-29% Cr Ferritic has a slightly higher conductivity than this grouping. Note that for reference, the performance of 25% Cr Duplex will be somewhere in between these two groups of materials.

The relatively large performance cost impact on the study results strongly indicates that during operation, the condenser must perform as well as had been assumed in order to realize that backpressure benefit. That in turn underscores the importance of maintaining a maximum level of condenser performance and it requires that the condenser performance be monitored to ensure it is performing at the minimum backpressure for the specific operating conditions.

Further, it should also be recalled that although the original design of this copper alloy condenser 30 years ago produced a target turbine exhaust pressure of 1.61 in. Hga (5.45 kPa), it is certain that the design condition exhaust pressure now, 30 years later during the present operation is higher than any of the backpressures listed above. That is, all the module selections would provide the station a gain in generation. In addition, the condenser operation will be reliable and tube failures should not be expected with any of the stainless steels listed in Table 1.

Note that at other times of the year, the turbine exhaust will be at a different pressure level and so the station will produce a different incremental generation that corresponds to the particular turbine response curve. This seasonal effect, based on duration and the expected average monthly inlet CW temperatures to the condenser from either a wet cooling tower or the local water body would be included in more complete or site specific studies.

Capital and Total Cost Comparisons

Repeating the same optimized module selections in the same sequence as the last section, the minimum evaluated costs of the candidate replacement tube bundles that reflect the economic conditions for the project are tabulated in Table 6 below. The selections shown are the lowest cost choices from a large spreadsheet that comprised an original group of 36 different modular condenser options which would feasibly fit inside the original shell size. Within each material and tube wall thickness grouping, the bottom line costs varied by about +$300,000 from those shown.

The tube support plate span within a condenser is selected to avoid the damaging tube vibration. This occurs when the steam passing through the condenser tube bundle reaches a critically high velocity and produces a high amplitude, whirling fluid-elastic reaction on the local tubing. The maximum span for each module in this case was determined by the HEI [5] method and the results are shown in Table 5. Though there a number of variables which influence the outcome of these estimates, the tube material Young’s Modulus and the moment of inertia of the tubing cross section are significant. The listing of Table 5 mirrors these vibration estimates with longer support spans being permitted for the 22 BWG tubing while the lower Young’s Modulus (i.e., higher flexibility) of the titanium modules requires shorter spans. The cost of the modules however does not reflect the cost of added support because usually the support plate tube holes are drilled in stacks. That is, the extra drilled support plates are incorporated into existing stacks at little manufacturing cost increase.

Except for the costs of the tube material, the module costs of Table 6 are estimates of the complete costs to the condenser manufacturer to provide the replacement module at the site. That includes design and engineering, module materials, fabrication, installation of the tubes in the shop, module shipment preparation & bracing and shipping to a domestic site. (The module size was selected to be able to fit on a low-boy truck.). Since the existing waterboxes are to be reused, no costs for that element are included.

The major activities within the installation cost category include contractor mobilization, providing access for the new bundles and a work path to the original condenser, removal of interferences, removal and ready storage of the waterboxes, removal of the original tube bundles and its tubing, temporarily bracing the remaining condenser shell and supporting existing heaters in the condenser steam dome. Then the work entails off-loading the new modules and their installation under the turbine, providing the new heater and hotwell supports, replacement of the waterboxes and gaskets, replacement of the interferences, leak testing and finally demobilization.

As had been indicated previously, PWRR is an engineering cost variable that accounts for annual future costs over the life of the plant by accruing the equivalent of those costs back to the present day so that they can be included in a capital cost evaluation. In the case of modular retubing, an estimate of the costs of the relative variation in station generation due to the different condenser performances that will be attained by the candidate module is estimated by the PWRR in Table 5 and repeated in Table 6. Note that cost parameter implicitly assumes the condenser and turbine will run at design conditions with the capacity factor of 70% as listed previously. While this is clearly a simplification, it is however indicative of the annual station operation.

The total evaluated costs for a particular optimized bundle selection of Table 6 are the aggregate cost today of the module, the installation, the tubing, the PWRR related to the daily future cost of condenser performance but less the salvage value of the original condenser's copper alloy tubing- assuming the latter had experienced and average 40% wall loss.

In this table, the remarks on sensitivity and the cost emphasis of the project stated in the last section are worthwhile reiterating at the outset: If it is required to minimize the project capital costs, then the optimum selected from the total cost curves would shift toward a higher backpressure, lower surface area condenser module. The optimum selection would be different than those shown because they would have been obtained from the minimums of total cost curves that were based on different economics. In the instance of minimizing the module cost, it is prudent to check the performance of the final selection to ensure there are adequate operating margins and that size selection does not encroach on the maximum operating backpressure turbine limits. Turbine limits can be set either by periods of maximum water temperature and unit full load bypass (particularly if the condenser serves a combined-cycle facility) or if it is known that a station power uprate may be a future consideration. In addition, the comments concerning the variation of tubing costs that may occur before the order is placed are relevant when reviewing any optimization. The manufacturer's module costs may also vary depending on the commercial conditions at the time of the project. A sensitivity study with an indication of this latter variation should be included in the optimization analysis before the size of the module is finally established and precisely specified.

Table 6– Capital & Evaluated Costs

Optimized Module Size Selection	1	2	3	4	5	6
Tube Material	6% Mo Austenitic	27-29% Cr Ferritic	Titanium	6% Mo Austenitic	27-29% Cr Ferritic	Titanium
Tubesheet Material	Solid 6%Mo	Solid 6%Mo	Solid Titanium	Solid 6%Mo	Solid 6%Mo	Solid Titanium
Tube Wall BWG In. (mm.)	22 - .028 (.71)	22 - .028 (.71)	22 - .028 (.71)	25 - .020 (.51)	25 - .020 (.51)	25 - .020 (.51)
Tubing Cost	$1,863,000	$1,305,000	$1,699,000	$1,378,000	$ 982,000	$1,181,000
Module Cost	$2,410,000	$2,410,000	$2,538,000	$2,410,000	$2,410,000	$2,544,000
Installation Cost	$1,621,000	$1,621,000	$1,621,000	$1,621,000	$1,621,000	$1,621,000
Salvage Value	$225,000	$225,000	$225,000	$225,000	$225,000	$225,000
PWRR of Lost MW (Repeated)	$522,000	$306,000	$108,000	$217,000	$26,000	-$93,000
Total Evaluated Costs	$6,191,000	$5,417,000	$5,741,000	$5,401,000	$4,814,000	$5,028,000

The capital costs listed above in Table 6 are for the specific, typical fabrication of welded tube joints and solid tubesheets. Considering the magnitude of the overall module costs, the cost decrease with other fabrication options frequently called for by specifications is relatively small. For rolled only tube joints instead of welded, the deduction for 22 BWG tubes is $65,000 and for 25 BWG tubes it is $69,000. For clad instead of solid tubesheets, the deduction is $55,000 for 22 BWG tubing and $58,000 for 25 BWG tubing, respectfully. These latter costs apply to both the stainless steel and the titanium module fabrications.

The total evaluated cost is shown on the bottom line of Table 6. It indicates the variation for modules of different tube materials and gage thickness. In terms of this specific study, the 27-29% Cr ferritic material appears to be of the lowest cost in either the 22 or 25 BWG. As had been indicated though that result is a consequence of the current price of the material compared to 6% Mo Austenitic, as well as titanium. If the cost study were conducted at a different time or the plant economics changed dramatically, this cost ranking would need to be reviewed.

Based on an overview and comparisons of the optimized costs listed in Table 6:

1. With respect to the replacement scenario and economics associated with this study, the least expensive condenser module alternative is 27-29% Cr ferritic material with 25 BWG tubing. That is a reflection of lower capital costs of this tubing combined with a reasonably favorable impact on plant thermal performance.
2. The tube material represents a very significant component of the overall costs of modular bundle replacements.
3. Regardless of the tubing thickness or material, the module fabrication and installation costs are roughly the same.
4. Thinner tubing will obviously reduce the initial capital costs of condenser modules but it also has an influence on the future generation capability of the station.

After the final selection is made from the tabular results, including considerations of sensitivity and reasonable cost variations, the modules would be specified. The tubing would normally be incorporated into the module specification. Design standards such as HEI and ASTM would be referenced. It is also suggested that an ASME condenser performance test be included in the specification to be assured the condenser performance estimates would be realized in operation. A separate installation specification would also be written. Condenser manufacturers and installation contractors would be contacted for bid proposals.

In parallel to the purchasing, the actual bid costs received should be compared to the costs estimated within the optimization to be certain the simulation was reasonably accurate. If not, the effect of any cost adjustments on the optimization should be understood and accepted or some other action taken- for instance, the module purchased should be slightly modified in surface area.

Recommendations/Conclusions

Modular condenser cost estimates are subject to a variety of factors that can create uncertainty and inaccuracy in the future projection of the capital and performance costs. As a consequence, all optimizing results must be carefully weighed. Despite uncertainty in the estimated overall costs, clearly in every case, it was concluded that the resulting optimized stainless steel modules would provide the plant owner with a corrosion resistant, reliably operating condenser in salt or brackish water service. Stainless steel modules produce a lower turbine exhaust pressure with incrementally more generation for sale than would be currently experienced with the old condenser. Finally, the stainless steels have a bright future as the likelihood of the intersection of their performance and cost with industry trends will continue to cause their increased usage.

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Table 1

Properties of Seawater Corrosion Resistant Stainless Steel Condenser Tube Replacement Alloys and Comparison Materials

Alloy Type	Alloy[1]	UNS No.	Suppliers[1]	Density Lb/cu in	Conductivity Btu/hr-ft-F	Thermal Expansion in/in x10^{-6}/F	Young's Modulus 10^{+6} Psi	Yield Strength 10^{+3} Psi
27-29% Cr Ferritic	**Sea-Cure®**	**S44660**	T.T. Inc.	0.28	9.5	5.4	31	75
	AL 29-4C®	**S44735**	I.T.P. Inc.	0.28	9.5	5.2	30	80
	FS 10	**S44800**	S.M..I.	0.28	9.5	5.4	31	85
25% Cr Duplex	**SAF 2507®**	**S32750**	A. S.T. Inc. T.T. Inc.	0.28	8.2	7.2	29	78
6% Mo Austenitic	**AL6XN®**	**N08367**	I.T.P, Inc T.T. Inc.	0.29	7.9	8.5	27	55
	254SMO®	**S31254**	A.S.T. Inc.. T.T. Inc.	0.29	7.5	8.9	29	45
7% Mo Austenitic	**654 SMO®**	**S32654**	A. S.T. Inc.	0.29	7.5	8.5	29	56
Comparison Materials								
90-10 CuNi	**Alloy 706**	**C70600**	-	0.32	26	9.5	18	15
Titanium	**Grade 2**	**R50400**	-	0.16	12.5	4.8	16	50

1. See Appendix A for a List of Registered Trademarks, Trade Name and Suppliers.
2. Yield Strength Obtained from various Manufacturers' Data – Typical Values.

Appendix A List of Trademarks, Trade Names and Suppliers

SEA-CURE® - Crucible Materials Corporation, Trent Tube Division (T.T.)

AL 29-4C® - ATI Properties, Inc., International Tubular Products, Inc. (I.T.P.), Trent Tube Division (T.T.)

Sumitomo FS-10 - Sumitomo Metal Industries, LTD. (S.M.I.)

SAF 2507® - Avesta Sandvik Tube (A.S.T)

AL-6XN® - ATI Properties, Inc., International Tubular Products, Inc.

254 SMO® - AvestaPolarit Stainless, Avesta Sandvik Tube

654 SMO® - AvestaPolarit Stainless, Avesta Sandvik Tube