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Heat Exchanger Maintenance
(Can We Afford to Wait?)

Introduction

Managing of a power plant today requires many decisions that can have a major impact on the bottom line. Making the correct one can make the management team a hero. The wrong one could mean disaster. Today's fuel costs have increased dramatically. Natural gas in the United States has gone from US$2.00 per decatherm to over US$14.00 at recent peak times (Figure 1).[1] Today's contract prices for coal including transportation costs are approximately double from a few years ago. Any change in operation, such as fouled or plugged tubes, can result in a costly heat rate increase. A major condenser, feedwater heater, or boiler tube leak can cause 1 to 3 days of lost power that can result on over US$1,000,000 of lost income. Derates during peak periods due to inefficient heat exchangers or copper deposits on the turbine blades can turn a very profitable year into a loser.
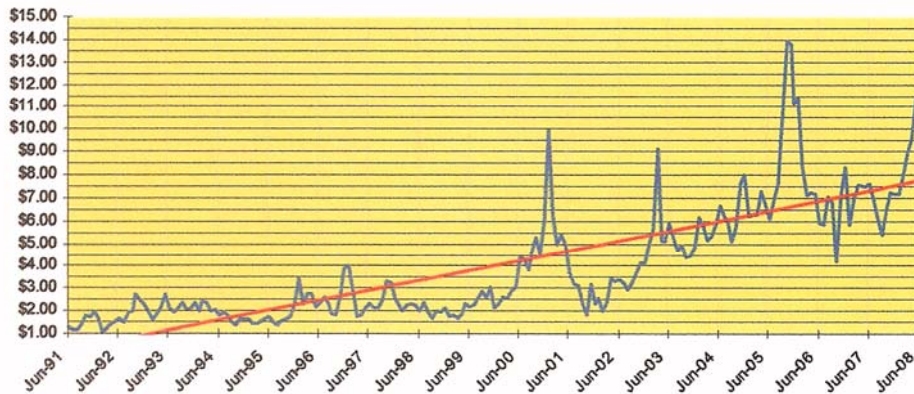

Figure 1 - Natural gas prices over the last 6 years in the United States [1]

1. Tube Failures

A number of potential failure mechanisms are possible in power plant heat exchanger tubing. The mechanisms common in copper alloys are quite different than those for stainless steels and high performance alloys. They are described separately below.

A. Copper Alloy Problems

- Steam Side Attack

The most common damage mechanisms for copper alloys from the steam side are ammonia grooving and stress corrosion cracking. Oxygen scavenging chemicals produce ammonia that combine with the condensate, and this mixture dissolves the tubing next to support plates. This solution, combined with high residual stresses can also cause cracking. Both mechanisms are common in the same condenser.

- Cooling Water Side Attack

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High water velocity, particularly near inlets or obstacles can erode the soft patina on copper alloys causing erosion-corrosion. For Admiralty and Aluminum Brass, velocity exceeding 1.8 m/sec can do this. Tube perforations due to turbulence around tube obstructions, such as clam shells, can result within a few days of inlet screening problems.[2]

Both H_2S and sulfuric acid can strip the protective patina and prevent reformation. The most common sources for these are decaying vegetation, sulfate reducing bacteria (MIC corrosion), or the use of treated wastewater.[3]   When existing cooling water sources are switched from fresh to treated wastewater, 90-10 copper-nickel tubing failures often start within 6 months of the change.

Copper alloy tubing gradually thins due to general corrosion. The patina is porous, allowing copper ions to dissolve into the water. In non-aggressive water, dissolution rates are slow and 25 year tube life is not unusual.   It's not unusual for a copper tube to be 50% of the original wall thickness when it is replaced.
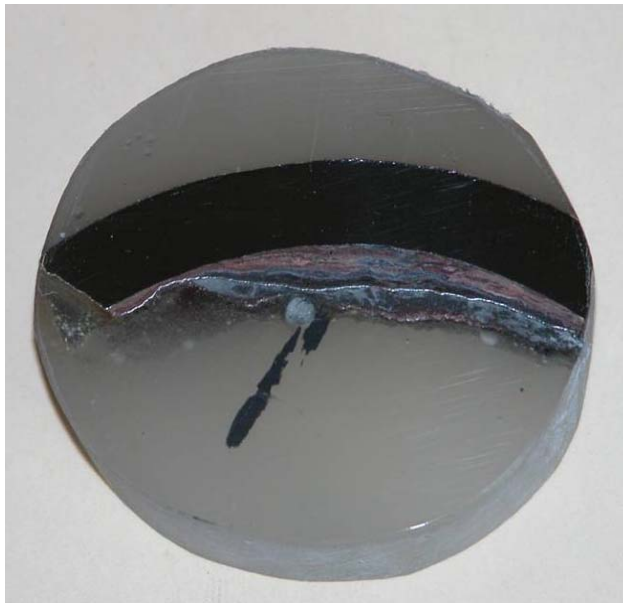

Figure 2 - Alternating copper metal and iron oxide layers on boiler tube. Courtesy Hoffman [4]

For a 300 MW Admiralty condenser, as much as 200,000 lbs of copper alloy can be dissolved. When the copper plates on boiler tubing (Figure 2), it can initiate catastrophic liquid metal embrittlement. Copper can also plate on HP tubing blades, dropping overall efficiency and plant output. More on this will be discussed later.

Traditional US discharge limits is 1 ppm, a relatively easy limit to comply. However, limits of 40 PPB or less are now being imposed. This target is significantly tougher and may require expensive treatments to reducing the corrosion rate. High discharge levels can raise local water concentrations. For example, figure 3 shows measured daily copper discharge levels in the Arabian Gulf[5].
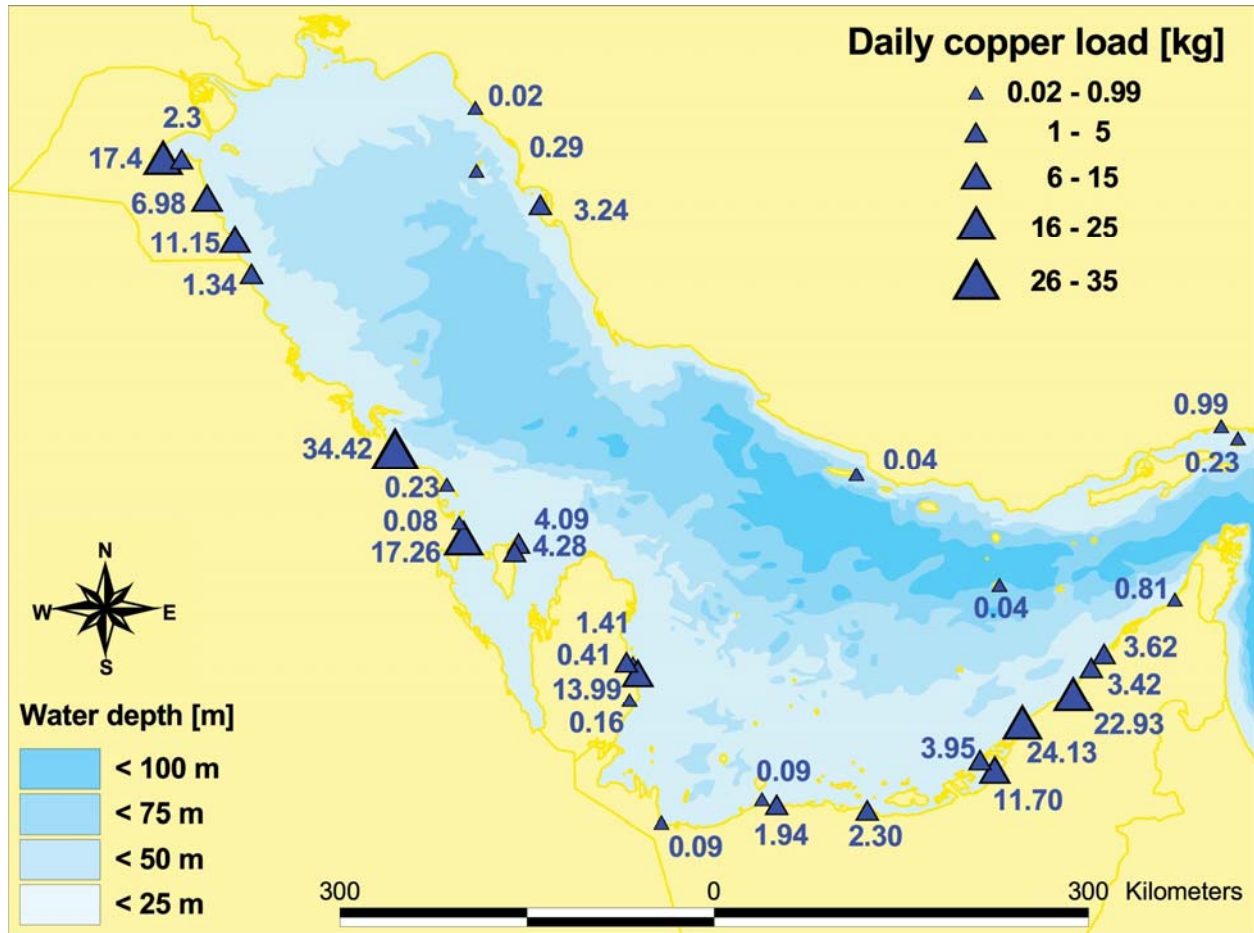
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Figure 3 - Daily copper discharge levels from power plants and desalination units in the Arabian Gulf [5]

B. *Stainless Steels*

- Steam Side

All stainless steels, both the commodity grades (TP 304, TP 316, and derivatives), and the higher performance versions are resistant to the majority of boiler chemicals including all of the hydrazine derivatives. At higher temperature, one mechanism does cause premature failure, chloride stress corrosion cracking (SCC), which can occur in feedwater heaters.

Those containing 8% nickel (TP 304) are most sensitive to SCC as shown in Figure 4. The failure mechanism has also become more common in plants that have switched from base load to cycling modes. The chlorides concentrate in regions that alternate between wet and dry, primarily in the desuperheating zone.

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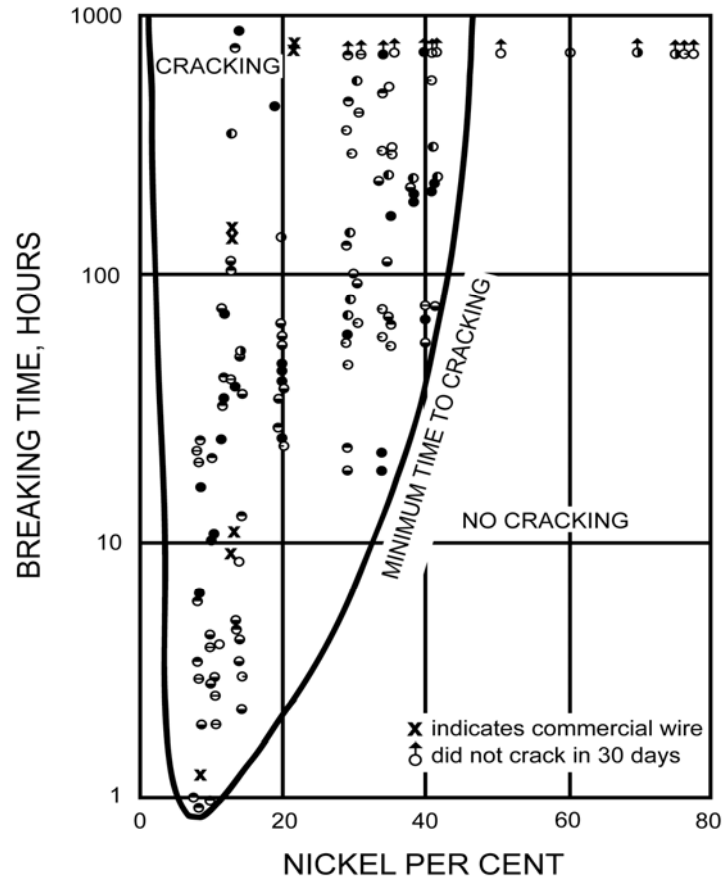Senior Account Executive – Plymouth Tube Co.
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Figure 4 - Time to failure of Fe, Cr, & Ni wires in boiling magnesium chloride vs. nickel content

- Cooling water side

Pitting and crevice corrosion – TP 304 and TP 316 are susceptible to pitting, crevice corrosion, and MIC related crevice corrosion and should not be considered if the cooling water has chlorides that exceed 150 ppm and 500 ppm respectively. Like copper alloys, TP 304 and TP 316 should not be considered candidates if treated wastewater is the cooling water source.   A detailed discussion this topic and SCC can be found in the paper by Janikowski, et al[6].

C. Titanium

Titanium grade 2 is considered immune to any corrosion mechanisms common in the power generation cooling circuits. One exception may be the crystallization equipment used in zero discharge plants. In this equipment grades 7 or 12 may need to be considered. However, because of its low modulus of elasticity, it is susceptible to vibration damage. This can be prevented by proper design.

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2. The Value Comparison   NOTE: IDEA TO BOX???

Justification for your cleaning and/or retubing starts with a defendable Value Comparison summary. It should be based upon a "life cycle" basis. The analysis should be developed for the remaining life time of the plant.

The individual components that can be used for building the analysis include:
- Initial tube cost
- Installation costs
- Fuel savings based on higher thermal performance
- Lower cooling water chemical treatment costs
- Reduction of lost generation due to turbine efficiency losses
- Reduction or elimination of boiler tube and high pressure turbine cleaning costs
- Elimination of emergency outages / derates to plug leaking tubes.

Following is the condenser model example criteria to help determine the true cost of running with existing tubing versus comparing the cost of replacing with new tubing:
- Condenser for a 300 MW coal fired plant
- Currently installed with 16,400, 90-10 copper nickel tubes sized 25.4 mm OD x 18 BWG (1.24 mm average wall thickness) x 12.86 meters long
- Steam load is 671,506 kg per hour with an enthalpy of 109 kcal / kg
- Turbine exhaust area is 34.8 square meters
- Circulating pumps provide a design flow of 25,878 m^3/ hr that result in a design head loss through the tubes of 5.97 meters
- 6% of the existing tubes are plugged
- Scaling is minimized through aggressive water chemistry controls providing an HEI[8] cleanliness factor of 85%
- Designed for a common (early Summer & early Fall) inlet water temperature of 29°C, however it can be higher in Mid-Summer.

In our model, Cu-Ni tube leaks are now occurring approximately twice per year. Every 4-5 years the high pressure steam turbine needs to be cleaned due to copper plating on the turbine blades. During this time frame, the overall drop in plant capacity is 21 megawatts. As this is a closed cooling tower plant, the service water has been chemically treated with ferric sulfate to assist repassivation of the copper nickel after excursions of cooling water chemistry due to efforts to keep the tubes and cooling tower clean. The alternative candidates considered are all proven to have a good track record in similar water. As the chloride levels commonly climb over 700 ppm, and Mn and Fe levels are high[7], TP 304 and TP 316 are not considered candidates.

The HEI Standards for Steam Surface Condensers[8] are an excellent basis for comparing the thermal and mechanical performance of the various tube materials. In addition to determining back pressure, the potential for vibration damage, and changes in uplift should also be evaluated. The initial results of the analysis are included in Table 1.

Commonly, 22 BWG is chosen for stainless steel or Ti tube wall replacements. Stainless steels have a higher modulus of elasticity than copper alloys and are stiffer. This minimizes the impact

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of vibration. Titanium's modulus of elasticity is lower requiring staking to prevent vibration change. Copper's thicker ID and OD patinas result in lower cleanliness factors (typically 85%) than the stainless steels or titanium, which can be 95%.

Although the original design flow was 25,878 m^3/ hr, flow will vary as the head loss changes. The low head / high volume pumps used for circulation water purposes have mass flow rates that are highly sensitive to head loss. For example, the 0.457 meter head increase caused by plugging 6% of the tubes may result in a typical 2% decrease in cooling water mass flow. A lower head from the thinner wall tubing results in a 3% increase in mass flow. If available, the specific pump curve(s) for the plant should be used.

In this analysis, we've used the design inlet water temperature for the basis. When the plant has an undersized condenser and this condenser is limited during peak summer conditions, we may consider using the maximum inlet water temperature for our analysis.

Alloy		90/10	90/10 - 6% plugged	Ti Gr 2	N08367	S44660
Wall	Mm	1.24	1.24	0.71	0.71	0.71
Cleanliness		0.85	0.85	0.95	0.95	0.95
Cooling Water	M^3/hr.	25,878	25,360	26,654	26,654	26,654
Velocity	M/sec	2.13	2.22	2.00	2.00	2.00
Inlet Temp	^{o}C	29	29	29	29	29
Back Pressure	mm Hg	74.68	76.20	70.61	72.64	70.87
HEI Calc. Span	Mm	936	936	797	921	954
Vibration?		Original	Original	Much More likely	More likely	Less likely
Uplift	Kg	0	0	(92,675)	(51,624)	(55,557)
Est. Fuel Cost	$/MBTU	$2.50				
Est. US$ saved /year from 90/10 based on 2.5 mm Hg = 15 BTU/KWHr			($58,968)	$157,248	$78,624	$147,420

Table 1- Comparison of thermal and mechanical of various condenser tube candidates for a 300 MW unit using HEI Standards for Steam Surface Condensers

A lower back pressure, or better vacuum, is desired, which increases turbine efficiency. For this condenser, the 6% plugged tubes created a back pressure increase of 1.52 mm Hg. HEI predicts a very significant back pressure drop of 4.07 mm for titanium and slightly lower 3.81 mm for the super-ferritic S 44660. With lower metal thermal conductivity, the drop in pressure for the super-austenitic N 08367 is approximately half at 2.04 mm.

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Over the years, many different vibration methodologies have been developed to calculate a "safe span" that results in no tube damage. The HEI span reported in Table 1 assumes that the condenser tube will vibrate and that the support plates shall spaced to keep the vibration amplitude equal to or less than 1/3 of the ligament spacing. This design was developed to preventing tube-to-tube collisions.   In this analysis, HEI predicts a span of 936 mm for the Cu-Ni. The calculated span for titanium is almost 140 mm shorter which suggests that the risk of vibration damage is high. N08367 has a slightly shorter span than Cu-Ni. Only the S44660 has an HEI calculated span longer than the Cu-Ni. The most common solution to preventing vibration problems is the installation of "stakes" mid-span between the support plates. A qualified expert should be consulted to ensure that proper staking is used with any tube option.

The change in back pressure will have an impact on heat rate and the total fuel cost. This coal fired plant has an estimated 20 year period will average US$2.50 per million BTU (or per 252,000 kcal) fuel cost. For this plant, we've determined that for each 2.50 mm of Hg change in back pressure, the plant will save or require 15 BTU (3.75 kcal) for each kWHr. The 6% plugged tubes is costing us about US$59,000 per year in additional fuel costs. The model shows an additional fuel savings of US$157,000 per year if titanium is chosen, US$79,000 per year additional if the super austenitic N08367 is selected, or US$147,000 additional per year if the super-ferritic S44660 is final choice.

Provided that our chemists have enough control over the cooling water, we expect to see this plant commercially viable for approximately 20 years without an additional retube. The other candidates have an excellent track record for doing the same, even if we have water chemistry excursions. Our tube suppliers have provided budgetary estimates included in our summary, which is detailed in Table 2. During discussions with potential tube installers, we've found that the cost to simply install the various alloys is not significantly different, at approximately US$250,000.   However, our consultant has recommended some staking due to the lower stiffness of the titanium and the N08367 tubing. Based upon the consultant's recommendations, our installers have quoted an average of US$200,000 for the titanium and US$50,000 for the austenitic.   The consultant is also concerned about the additional uplift if titanium is chosen. We've included US$50,000 in the budget for reinforcement of anchor points.

We can estimate our operational and maintenance costs are for the various candidates. Based on the fuel costs that we calculated in Table 1, we expect a savings of US$3.1 million over 20 years for titanium, US$1.55 million for N08367, and almost US$3.0 million for S44660, compared with 1.24 mm copper nickel. Our experience with the CU-Ni is that we will get occasional tube leaks, predominately from erosion corrosion from entrapped debris. We estimate that this will

Alloy Option	90/10 18 BWG	Titanium 22 BWG	N08367 22 BWG	S44660 22 BWG
Estimated Tube Purchase Cost	$2,200,000	$2,900,000	$3,300,000	$2,000,000
Installation Charges	$250,000	$250,000	$250,000	$250,000
Staking Cost	$0	$200,000	$50,000	$0
Anchoring Improvement	$0	$50,000	$0	$0

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Fuel savings - 20 years	$0	-$3,144,960	-$1,572,480	-$2,948,400
Derate to fix tube leaks - 1/ yr for 5 years, 2 / year after	$4,875,000	$0	$0	$0
Chemical treatment $100,000 /yr	$2,000,000	$0	$0	$0
Turbine cleaning every 4 years	$1,000,000	$0	$0	$0
20 year total cost basis	$10,325,000	$255,040	$2,027,520	-$698,400
20 year savings	$0	$10,069,960	$8,297,480	$11,023,400
Approx. years for payback vs. Cu-Ni	$0	6.8	8.7	4.1
Optional: Lost MW from Copper on HP Turbine -Avg 5 MW/yr loss @ $55 / MW, 85% operation time	$40,953,000	$0	$0	$0

Table 2 Value Comparison Summary - Estimated 20 year installation and operating costs (USD) of various tube candidates for 300 MW power plant condenser

occur per year during the first 5 years and twice per year after 5 years. Fortunately this condenser was designed as a divided flow design so that we do not completely need to shut the plant down to fix the leak. To locate the leaks and plug the tubes, it normally takes us 2 days. During a derate of that time frame, we typically loose US$225,000 of income. No cost was assigned to the other alloys as they are not susceptible.

Our traditional cost for chemical treatment (pH adjustment, ferrous sulfate treatments, others) to protect the copper tubing has been costing about US$100,000 per year. These will not be required with the other alternatives.

On our plant, we see a significant drop in plant output due to copper buildup on the HP turbine blades as shown in the example in Figure 6 [9]. These deposits significantly lower the turbine efficiency, restricting the overall plant output. Approximately every four to five years, the derate is significant enough to justify cleaning the turbine, at a cost of approximately US$250,000. An example of the cleaning recover is shown in Figure 7 [10]. If we choose titanium or the high performance stainless options for Cu-Ni replacement, this cleaning cost disappears.

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Figure 6 - Copper deposits on and HP turbine on a western US Power plant

The summary line shows some very significant differences for the condenser tube candidates. The combination of derate to fix tube leaks, water chemistry control, and additional cleaning required due to copper transport, has added over $10,000,000 to the cost directly related to the use of Cu-Ni tubing. Although the installation & tubing costs of the titanium option and N08367 option are significantly higher, this is mitigated by a significant fuel saving (vs. Cu-Ni) for titanium and to a lesser extent for
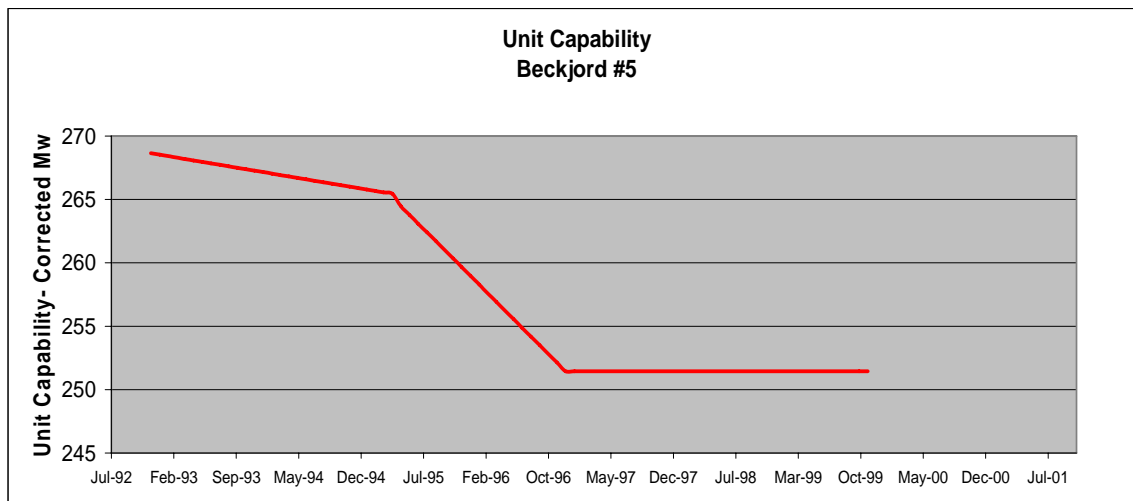

Figure 7 - Loss of MW capacity due to copper plating on the HP turbine blades for a 270 MW plant (Source Burck & Foster[10])

N08367.   The 20 year fuel savings pays for approximately 92% of the titanium installation costs and about 44% of the N08367 costs.   With S44660 lower initial cost and excellent thermal

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conductivity resulting in good fuel savings, the installation & tube costs are paid for by fuel savings alone in 14 years.

One very significant performance penalty was not included in the 20 year analysis, but is identified in the last row of Table 2. Copper deposits on the HP turbine blades can have an enormous financial impact. Derates of 20 MW or greater is possible on a plant of this size after a four year period. Using the following assumptions:

- The turbine is cleaned every 4-5 years,
- The average MW derate is 5 MW,
- The plant is in operation 85% of the time,
- The average selling price is US$55 per MWHr (based upon the average selling rate at the Cinergy hub)[1]

The total income lost over the 20 year period is US$40,953,000!   This emphasizes how important it is to keep the plant operating efficiently, particularly keeping the turbine free from copper deposits.

3. Summary:

Keeping our exchangers, particularly feedwater heaters and condensers, operating efficiently is critical to the bottom line. Not only are current operations and maintenance important, but materials selection for the performance of the exchanger and impact in the balance of the system is critical. Copper discharge levels are being controlled at more global locations and changes in regulation may force an expensive retube. Factors to consider and manage are:

- Tube cleanliness,
- Tube material and thickness,
- Installation costs including modifications,
- The selections impact on heat rate,
- The impact of copper transport,
- The cost of condenser tube repair including lost MW,
- The cost of emergency shutdowns due to boiler tube repair including lost MW,
- The cost of chemical treatments,
- Lost MW due to undersized condenser,
- And, the cost of lost MW due to lost efficiency.

Proper planning, maintenance, and materials selection can turn a borderline operation into a big winner. We cannot afford to wait.

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