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A GLOBAL FOULING FACTOR METHODOLOGY FOR ANALYZING STEAM GENERATOR THERMAL PERFORMANCE DEGRADATION

M. A. Kreider G. A. White R. D. Varrin, Jr.

ABSTRACT

Over the past few years, steam generator (SG) thermal performance degradation has led to decreased plant efficiency and power output at numerous PWR nuclear power plants with recirculating-type SGs. The authors have developed and implemented methodologies for quantitatively evaluating the various sources of SG performance degradation, both internal and external to the SG pressure boundary. These methodologies include computation of the global fouling factor history, evaluation of secondary deposit thermal resistance using deposit characterization data, and consideration of pressure loss causes unrelated to the tube bundle, such as hot-leg temperature streaming and SG moisture separator performance.

In order to evaluate the utility of the global fouling factor methodology, the authors performed case studies for a number of PWR SG designs. Key results from two of these studies are presented here. Uncertainty analyses were performed to determine whether the calculated fouling factor for each plant represented significant fouling or whether uncertainty in key variables (e.g., steam pressure or feedwater flow rate) could be responsible for calculated fouling. The methodology was validated using two methods: by predicting the SG pressure following chemical cleaning at San Onofre 2 and also by performing a sensitivity study with the industry-standard thermal-hydraulics code ATHOS to investigate the effects of spatially varying tube scale distributions. This study indicated that the average scale thickness has a greater impact on fouling than the spatial distribution, showing that the assumption of uniform resistance inherent to the global fouling factor is reasonable.

In tandem with the fouling-factor analyses, a study evaluated for each plant the potential causes of pressure loss. The combined results of the global fouling factor calculations and the pressure-loss evaluations demonstrated two key points: 1) that the available thermal margin against fouling, which can vary substantially from plant to plant, has an important bearing on whether a given plant exhibits losses in electrical generating capacity, and 2) that a wide variety of causes can result in SG thermal performance degradation. These include changes in primary control temperature, tube plugging, and measurement errors, as well as secondary tube scale. The analyses of San Onofre 2 and Callaway, as well as similar analyses performed at other plants, suggest a broad categorization of tube scale effects on heat transfer. Specifically, scale thinner than 100 microns (0.004 inches) was found to have little effect on heat transfer, while scale thicker than 225 microns (0.009 inches) was found to be highly thermally resistive, consistent with the presence of a consolidated inner scale layer adjacent to the tube interface.

DOMINION ENGINEERING, INC.

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INTRODUCTION

Since the early 1990s, an increasing number of PWR plants have observed decreases in secondary-side steam generator (SG) steam pressure. In some cases, the pressure decreases have been sufficient to cause reduced high-pressure turbine inlet pressure and hence reduced electrical generating capacity. These reductions in capacity have been as large as 4–5% at some plants. Because a 1% reduction in the electrical generating capacity of a typical PWR is equivalent to roughly $2 million U.S. per year in terms of the cost of replacement power, this phenomenon can have a significant impact on utility revenue.

In order to investigate the reasons for such thermal performance decreases, the authors have performed the following tasks:

- Applied the global fouling factor methodology to several U.S. PWR SGs representing a variety of designs.
- Evaluated the various possible root causes that can be responsible for steam pressure decreases for these same SGs, including changes in primary control temperature, tube plugging, measurement errors, and secondary tube scale.
- Validated the fouling factor and root-cause methodology by: 1) predicting the pressure increase following chemical cleaning at San Onofre 2, and 2) completing a sensitivity study using the thermal-hydraulics code ATHOS to determine the dependence of SG thermal performance on the spatial distribution of secondary scale.

The first task, global fouling factor analysis, facilitates determination of how much the thermal performance of the SGs has degraded. Because it accounts for changes in thermal power, primary temperatures, and heat-transfer area (e.g., plugging), it allows more insight into potential fouling due to secondary deposits than SG steam pressure or other simple thermal performance assessment techniques. Inputs to this analysis are thermal-hydraulic design data as well as plant instrument measurements recorded over the operating life of the SGs, including steam pressure, primary temperatures, feedwater flow rate, and the number of plugged and sleeved tubes for each outage. Summaries of such analyses completed for the SGs at two U.S. PWRs—San Onofre Unit 2 and Callaway—are included in this paper. Similar analyses completed for 10 other plants support the conclusions. Detailed results for several of these other plants are presented in EPRI Report TR-110018, expected to be issued in 1998.

The second task, evaluating sources of pressure loss, requires going beyond the global fouling factor. Although valuable, it cannot distinguish among some of the conditions which can degrade steam pressure, including measurement errors (e.g., those caused by hot-leg temperature streaming or feedwater venturi fouling), moisture separator and dryer fouling, and tube support blockages, as well as secondary tube scale. A key part of this effort comprises independent evaluations of the impact of tube scale on heat transfer using the physical and chemical property data collected from each plant.

Two means were used to provide validation of the global fouling factor and root-cause methodology. The first consisted of predicting the pressure increase upon chemical cleaning of the SGs at San Onofre Unit 2. Excellent agreement between the predicted and actual pressure increases represented a successful test on actual SGs. The second test, comprising a sensitivity study using the thermal-hydraulics code ATHOS to determine the impact of corrosion-product distribution on steam pressure, confirmed that the average scale thickness has a much greater impact on steam pressure than the spatial distribution in the SGs. This result is significant because the global fouling factor methodology inherently assumes a spatially uniform level of thermal resistance from the primary to secondary fluids.

The remainder of this paper discusses the analyses performed for San Onofre 2 and Callaway and the subsequent validations of the fouling factor and root-cause methodology.

GLOBAL FOULING FACTOR METHODOLOGY

As discussed in References (1) through (3), a decline in SG thermal performance generally refers to a decrease in SG outlet steam pressure and/or thermal power due to one or a combination of three types of causes: 1) a decrease in the tube bundle heat-transfer coefficient, 2) other sources within the SG shell (e.g., tube plugging), and 3) external sources (e.g., feedwater venturi fouling). A single global fouling factor was chosen to characterize SG fouling behavior since it is calculated using data typically recorded by utilities, allows fair comparisons of different SG designs, and facilitates comparisons to the experimentally measured or analytically predicted thermal resistance of tube scale.

The global fouling factor methodology is described in detail in References (1) through (3) and is not repeated here. However, the basis for the method may be summarized with the equation used to describe heat exchangers with a phase change in one of the fluids,

$$Q = UA\Delta T_m = UA\frac{T_{hot} - T_{cold}}{\ln\left(\frac{T_{hot}-T_{sat}}{T_{cold}-T_{sat}}\right)} \qquad (1)$$

where Q is thermal power, U is the overall heat-transfer coefficient, A is the effective heat-transfer area, T_{hot} and T_{cold} are the primary temperatures, and T_{sat} is the secondary saturation temperature representing the average temperature within the boiling region. The two key assumptions necessary for applying the global fouling factor methodology are 1) the heat-transfer coefficient is spatially uniform (or can be approximated as such), and 2) the subcooling of the downcomer flow can be neglected.

An important consideration associated with the fouling factor is its uncertainty. Because the inputs used to calculate it may themselves be subject to random errors or systematic errors (e.g., instrument drift, hot-leg streaming, venturi fouling), any calculated fouling factor should be reported with an uncertainty band. Fouling factor uncertainties are calculated using the standard engineering approximation for computing uncertainty,

$$\Delta_{statistical} = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial R_f''}{\partial x_i} \right)^2 \Delta^2(x_i)} \tag{2}$$

where R_f'' is the fouling factor and the x_i are the input variables used to calculate it (temperatures, flow rates, etc.). Calculated uncertainties for the plants examined by the authors were typically in the range from ±25 10^{-6} to ±50 10^{-6} h-ft^2-°F/BTU (±0.0044 to ±0.0088 m^2-K/kW). Key input uncertainties in each case were steam pressure, primary temperatures, and feedwater mass flow rate.

EVALUATING STEAM PRESSURE LOSS

While the global fouling factor lends considerable insight into the nature of SG fouling, it cannot distinguish all of the distinct causes that can degrade steam pressure. Such causes can be divided into several broad categories:

1. CHANGES IN THE FOULING FACTOR VARIABLES. As indicated earlier, changes in primary temperature, heat-transfer area, and thermal power can affect steam pressure although to first order they do not affect the true global fouling factor. Thus, decreases in steam pressure that are not coincident with increases in the calculated global fouling factor suggest changes in one or more of these parameters are responsible for the pressure decrease. Such changes can be intentional (e.g., tube plugging required by defects or a planned decrease in primary temperature to lower the rate of tube corrosion mechanisms) or unintentional (e.g., lower-than-intended primary temperatures due to loop asymmetries and a high-loop T_{ave}, or maximum auctioneer, control system). If, on the other hand, a decline in steam pressure is accompanied by an increase in fouling factor, then one or more of the causes described below is responsible.
2. SECONDARY DEPOSITS. A buildup of corrosion layers on the secondary side of the SG which is either thermally resistive or blocks the flow through tube supports (reducing the recirculation ratio*) will lower steam pressure. However, not all secondary deposit layers are thermally resistive or cause blockages. Thus, increases in the fouling factor may also be the result of other plant conditions.
3. OTHER CAUSES. A number of other problems can mimic the effects of resistive secondary tube deposits by increasing the calculated fouling factor. These include uncertainty in the steam pressure measurement itself, additional pressure drop across the moisture separators and dryers due to fouling or clogging, and errors in applied primary

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* Note that thermal-hydraulic sensitivity analyses performed by the authors showed that the effect of recirculation ratio on steam pressure is small.

temperature due to simple measurement error, hot-leg temperature streaming, or divider plate leakage. References (2) and (3) contain further detail.

In order to fully evaluate the thermal performance of the SGs at a particular plant, all of these causes must be considered.

RESULTS FOR TWO U.S. PLANTS

The authors have performed fouling factor and root-cause analyses for the SGs at more than 10 plants over the past several years. These analyses have all supported the conclusions that: a) SG thermal performance losses can be caused by various factors, and b) secondary deposits can cause a range of effects on heat transfer from slight enhancement to significant thermal resistance. Of the plants examined, the two that are most illustrative of these conclusions are San Onofre Unit 2 and Callaway. While many of the following results have been previously published (see References (1) and (2)), they are included again here for the convenience of the reader.

San Onofre 2

A two-loop PWR with Combustion Engineering Model 3410 SGs, San Onofre Unit 2 experienced cumulative decreases in steam pressure of more than 50 psi (0.34 MPa) by the mid-1990s. These decreases were severe enough to reduce electrical generating capacity temporarily until and a feedwater heater bypass could be implemented. The historical steam pressure and fouling factor are shown in Figures 1 and 2. Note the following:

- The steam pressure exhibited an initial increase of 10–20 psi (0.07–0.14 MPa) during the first operating cycle followed by a gradual drop of about 85 psi (0.59 MPa) during subsequent operation prior to chemical cleaning, for a net decrease of nearly 70 psi (0.48 MPa).
- The global fouling factor followed an opposite, complementary trend, decreasing slightly during Cycle 1 and then increasing up to +190 10^{-6} (+0.033 m^2-K/kW), for a net increase of about 170 10^{-6} (0.030 m^2-K/kW). This relatively high increase in fouling factor was not caused by tube plugging or changes in primary temperature, but rather suggested that secondary tube scale was the primary cause of the steam pressure decrease.
- Between 1989, when consistent primary-temperature measurements became available, and the chemical cleaning in 1996–97, the fouling factor exhibited an unmistakable rapid rate of increase.

PRESSURE LOSS EVALUATION. An evaluation of the possible sources of pressure loss at San Onofre 2 resulted in an estimated loss due to non-deposit causes of about 11 psi (0.08 MPa), most of which was due to tube plugging since startup. As a result, the remaining 59 psi (0.41 MPa) of the decrease observed since startup was attributed to secondary deposits. As discussed later in this paper, the effects of tube scale were confirmed by the pressure recovery recorded after chemical cleaning.

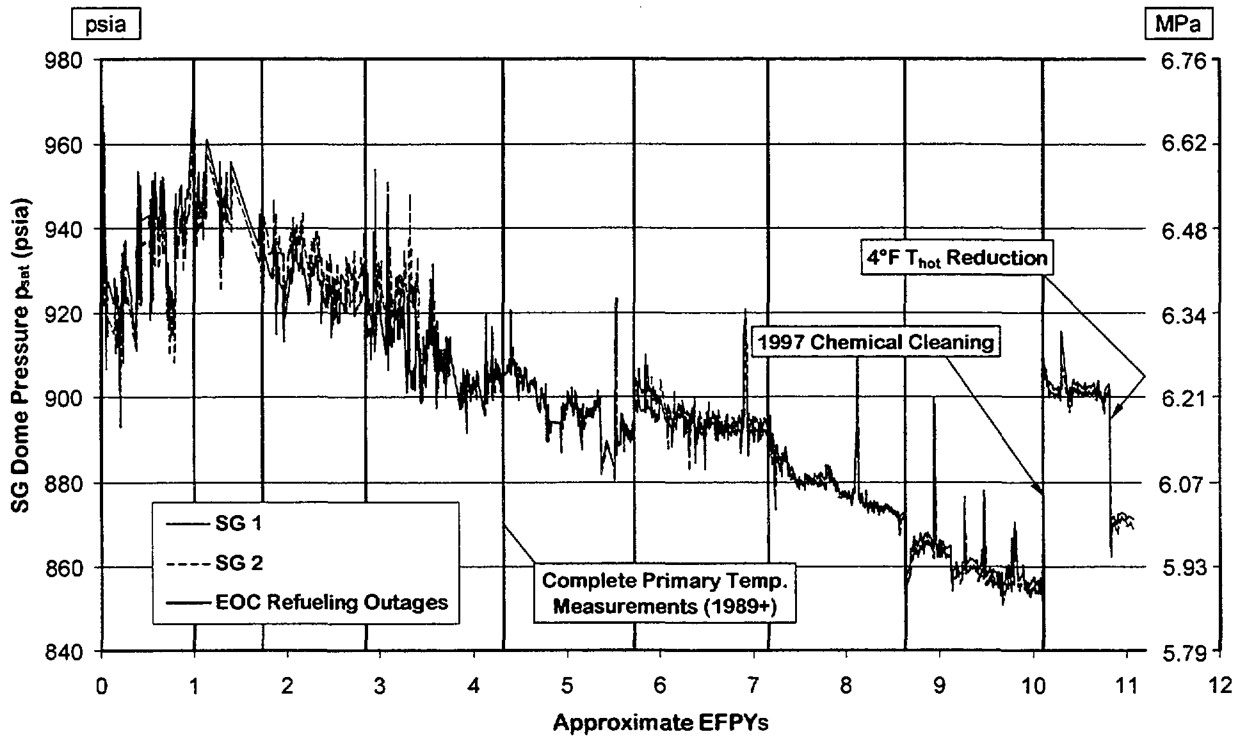

Figure 1. San Onofre 2 Historical Steam Generator Pressure

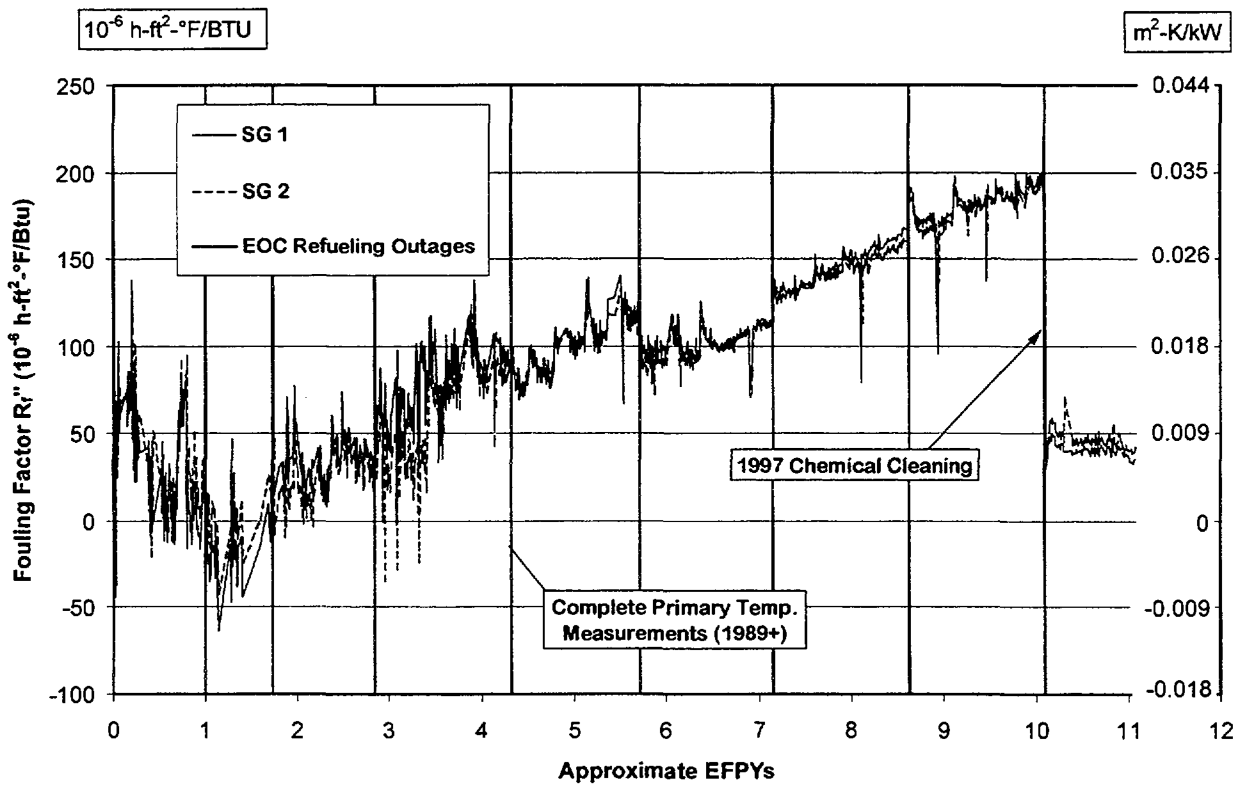

Figure 2. San Onofre 2 Historical Global Fouling Factor

Callaway

A four-loop PWR with Westinghouse Model F SGs, Callaway observed during the early 1990s a gradual decrease in steam pressure of nearly 50 psi (0.34 MPa) from peak pressures recorded during the second operating cycle, prompting speculation that secondary deposits were responsible for decreased performance. However, a chemical cleaning of the SGs in 1995 failed to increase the steam pressure—in fact, it *declined* slightly after the cleaning. Figures 3 and 4, which show the steam pressure and global fouling factor histories, respectively, help provide an explanation.

In particular, note the following in Figures 3 and 4:

- The net change in the global fouling factor between early operation and the time of the chemical cleaning in 1995 was –28 10^{-6} (–0.005 m^2-K/kW), suggesting that the heat-transfer capability of the SGs had been enhanced rather than degraded over that time period.
- Although the average steam pressure decreased by nearly 50 psi (0.34 MPa) between Cycle 2 and the cleaning after Cycle 7, the net pressure decrease since the start of operation was a more modest 17 psi. Steam pressure actually increased by about 30 psi (0.21 MPa) during the interval between initial startup and the middle of Cycle 2.
- The fouling factor increased slightly following the chemical cleaning.

PRESSURE LOSS EVALUATION. A breakdown of the pressure loss at Callaway reveals that the bulk of the net pressure decrease (15 psi or 0.1 MPa) was caused by a power uprate instituted in 1988. Note on Figures 3 and 4 that, as expected, the steam pressure decreased at the time of the uprate while the fouling factor remained essentially unchanged. Other non-deposit causes, including tube plugging, additional separator/dryer pressure drop, and hot-leg temperature streaming were judged to have decreased steam pressure by a combined 6 psi (0.04 MPa). As a result, secondary deposits are believed to have *increased* steam pressure by about 4 psi (0.03 MPa). This conclusion is consistent with the negative net fouling factor at the time of cleaning (–28 10^{-6} h-ft^2-°F/BTU or –0.005 m^2-K/kW), the 30-psi (0.21 MPa) increase in steam pressure over the first two cycles, and the slight increase in fouling factor following chemical cleaning. It is consequently not surprising in retrospect that removal of such scale decreased steam pressure slightly.

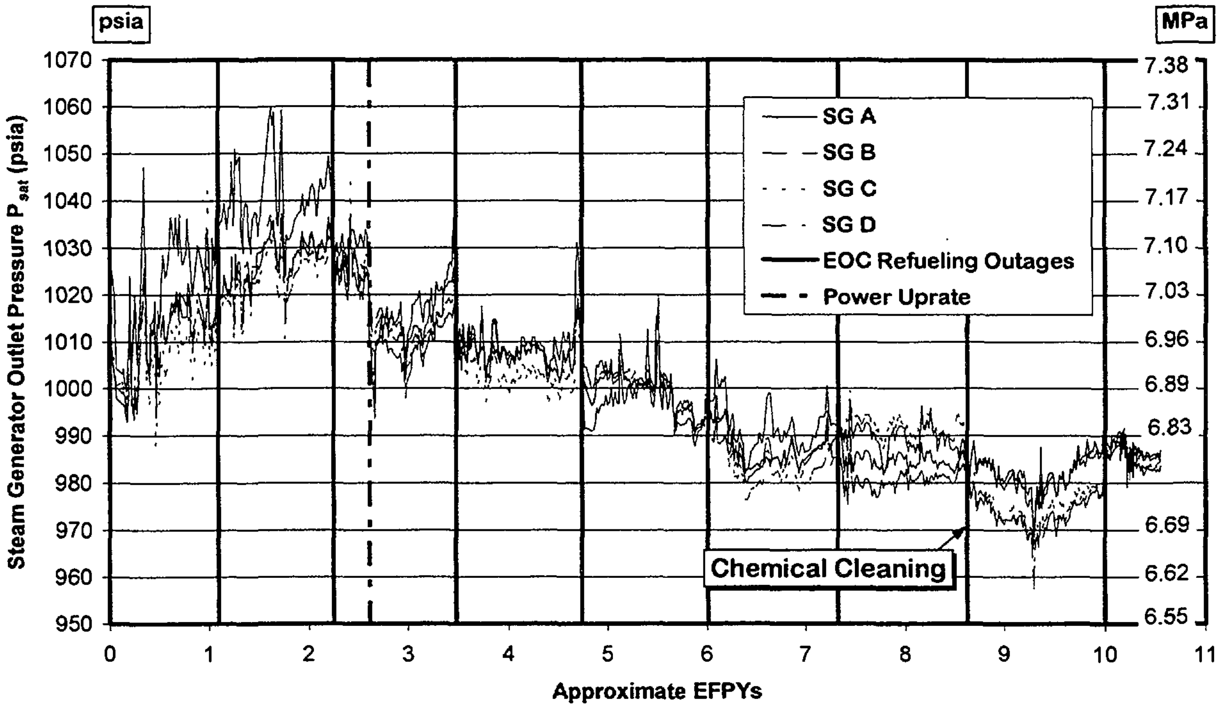

Figure 3. Callaway Historical Steam Generator Pressure

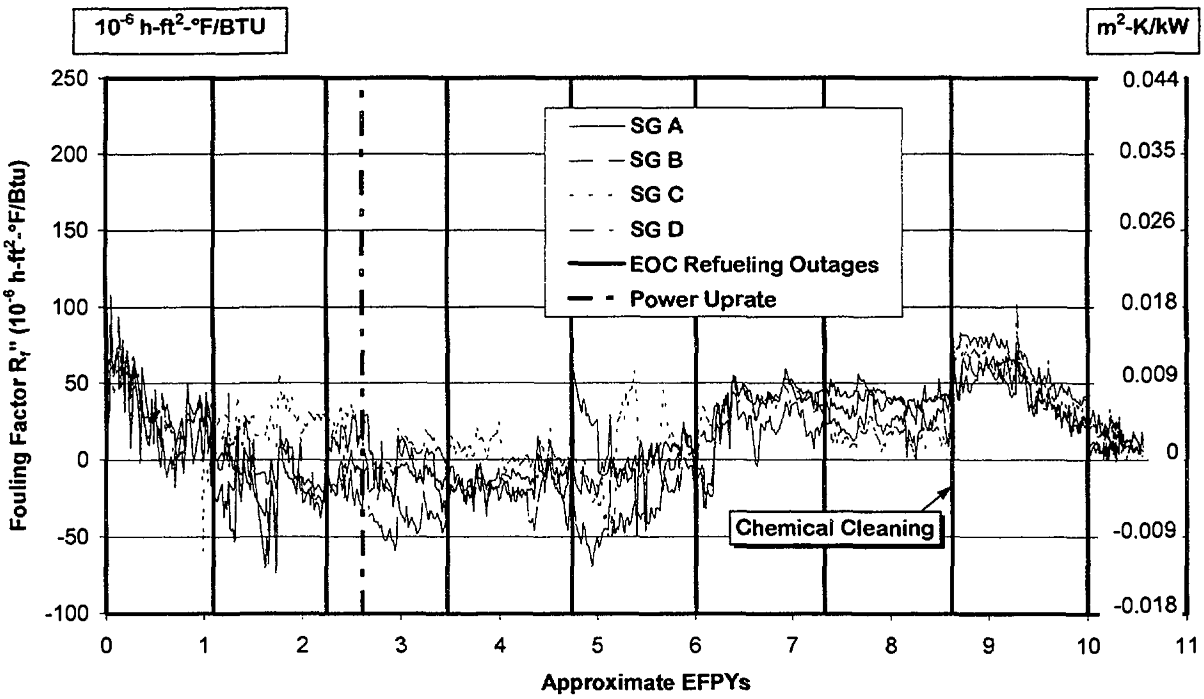

Figure 4. Callaway Historical Global Fouling Factor

EFFECTS OF SECONDARY DEPOSITS

San Onofre 2

As demonstrated by these two cases, secondary tube deposits can have a wide range of effects. At San Onofre 2, samples of the resistive deposits responsible for a steam pressure loss of more than 50 psi were taken from the SGs in 1995 and tested both physically and chemically. (The types of tests available for characterizing secondary tube scale are discussed in detail in EPRI Report TR-106048, *Characterization of PWR Steam Generator Deposits* (4).) The results indicated the following properties:

- Average scale thickness of 9–11 mils.
- A three-layer structure consisting of: a) a consolidated magnetite/copper inner layer (about 40% of the total thickness), b) a void-filled middle layer (10–15% of the total thickness), and c) a porous magnetite outer layer (45–50% of the total thickness).
- An overall porosity of 20–25%.

Based on these and other characterization data, the thermal resistance of the San Onofre 2 scale (as of 1995) was estimated to be approximately +185 10^{-6} h-ft^2-°F/BTU (0.032 m^2-K/kW). This value was based on analytical modeling and experience with flow- and pool-boiling heat-transfer experiments as described in References (1) and (3). Note that this estimate agrees reasonably well with the observed decrease in calculated fouling factor following the removal of deposits via chemical cleaning (about 150 10^{-6} h-ft^2-°F/BTU or 0.026 m^2-K/kW).

Further evidence that tube scale can be thermally resistive is described in Reference (5), which documents heat-transfer testing performed on a U-bend tube section removed from one of the Ginna SGs in 1991. The experiments suggested that the Ginna scale, with an average thickness of about 9 mils and a very low porosity of about 10%, had a thermal resistance of more than 200 10^{-6} h-ft^2-°F/BTU (0.035 m^2-K/kW).

Callaway

On the other hand, the Callaway results presented earlier demonstrate that secondary scale is not always highly thermally resistive. Tests on Callaway scale prior to chemical cleaning indicated that, in contrast to the San Onofre 2 scale, Callaway samples exhibited:

- An average thickness of about 4 mils.
- A predominantly porous structure of nearly 100% magnetite.

These tube scale properties correlated with a slight enhancement of heat transfer at Callaway according to the global fouling factor calculations presented earlier. Heat-transfer enhancement can occur in deposits with a structure marked by numerous interconnected pores and capillaries. Such a structure provides an increased number of boiling nucleation sites and increases boiling efficiency through wick boiling (capillary force enhancement) and changes in bubble nucleation and growth dynamics.

Based on analyses of more than 10 plants performed by the authors (including San Onofre 2 and Callaway), a rough categorization of secondary deposits emerges:

1. Thin deposits between zero and 4 mils (100 μm) tend to have little thermal resistance and may enhance heat transfer, as at Callaway.
2. Deposits of intermediate thickness—between 4 and 9 mils (100 to 225 μm)—exhibit a range of behavior from little effect on heat transfer to moderate thermal resistance.
3. Deposits thicker than about 9 mils (225 μm) tend to have a large thermal resistance.

It should be noted that the boundaries between these categories are based on a sample of plants and should not be considered sharp demarcations. It is possible that exceptions exist in the SGs at other plants.

VALIDATION OF GLOBAL FOULING FACTOR AND ROOT-CAUSE METHODOLOGY

In addition to the independent evaluation of deposit properties, two additional means were used to validate the global fouling factor and root-cause pressure-loss methodology. The first involves the pressure recovery at San Onofre 2 after the recent chemical cleaning, while the second consists of a sensitivity study performed to determine the impact of the spatial distribution of tube scale thickness on SG thermal performance.

San Onofre 2 Pressure Recovery

As described in Reference (6), the authors used the results of a global fouling factor analysis and root-cause pressure loss evaluation to generate best-estimate and statistical lower-bound predictions of the steam pressure expected at San Onofre 2 after the 1996–97 chemical cleaning. The key steps in making these predictions included:

- Determining accurately the clean thermal resistance characteristic of the SGs. Because the initial data set analyzed did not include primary temperature measurements prior to 1989, the calculated fouling factor during early Cycle 1 operation was based on values typical of operation in 1989. Consequently, a search for additional Cycle 1 data (including primary temperatures) was performed, resulting in 25 data points reflecting operation between December 1983 and March 1984. The startup thermal resistance computed using these additional data was slightly higher (by 19 10^{-6} h-ft^2-°F/BTU or 0.003 m^2-K/kW) than would have been expected from the design thermal-hydraulic values and design fouling factor (i.e., the design clean thermal resistance).
- Adjusting the steam pressure calculated from the global heat-transfer equation (Eq. (1)) to account for other sources of pressure loss applicable to San Onofre 2. These included estimates for losses due to tube plugging (12 psi or 0.08 MPa), added separator/dryer pressure drop (3 psi or 0.02 MPa), primary-side fouling (1 psi or 0.01 MPa), and an increase in primary temperature (a 5-psi or 0.03 MPa gain).

- Calculating statistical lower-bound estimates of the pressure increase by considering the uncertainty associated with the inputs in Eq. (1) used to calculate steam pressure (e.g., cold-leg temperature, thermal power, overall bundle thermal resistance, OD tube surface area). The 95% and 99% statistical lower bounds on pressure, computed with Eq. (2), were found to be 22 psi (0.15 MPa) and 31 psi (0.21 MPa) lower, respectively, than the best estimate.
- Considering the effect of newly plugged tubes on steam pressure. Because a significant number of tubes was expected to be plugged during the same outage as the chemical cleaning, a parametric study evaluating the effect of the number of newly plugged tubes, up to an estimated upper bound of 300 per SG, was completed.

The parametric steam pressure predictions and the actual observed steam pressure are shown in Figure 7. The predicted and actual pressure differ by about 1 psi (0.01 MPa), quite good agreement considering the total increase of 51 psi (0.35 MPa). This test provides confirmation for the global fouling factor and root-cause methodology for evaluating thermal performance of actual SGs.

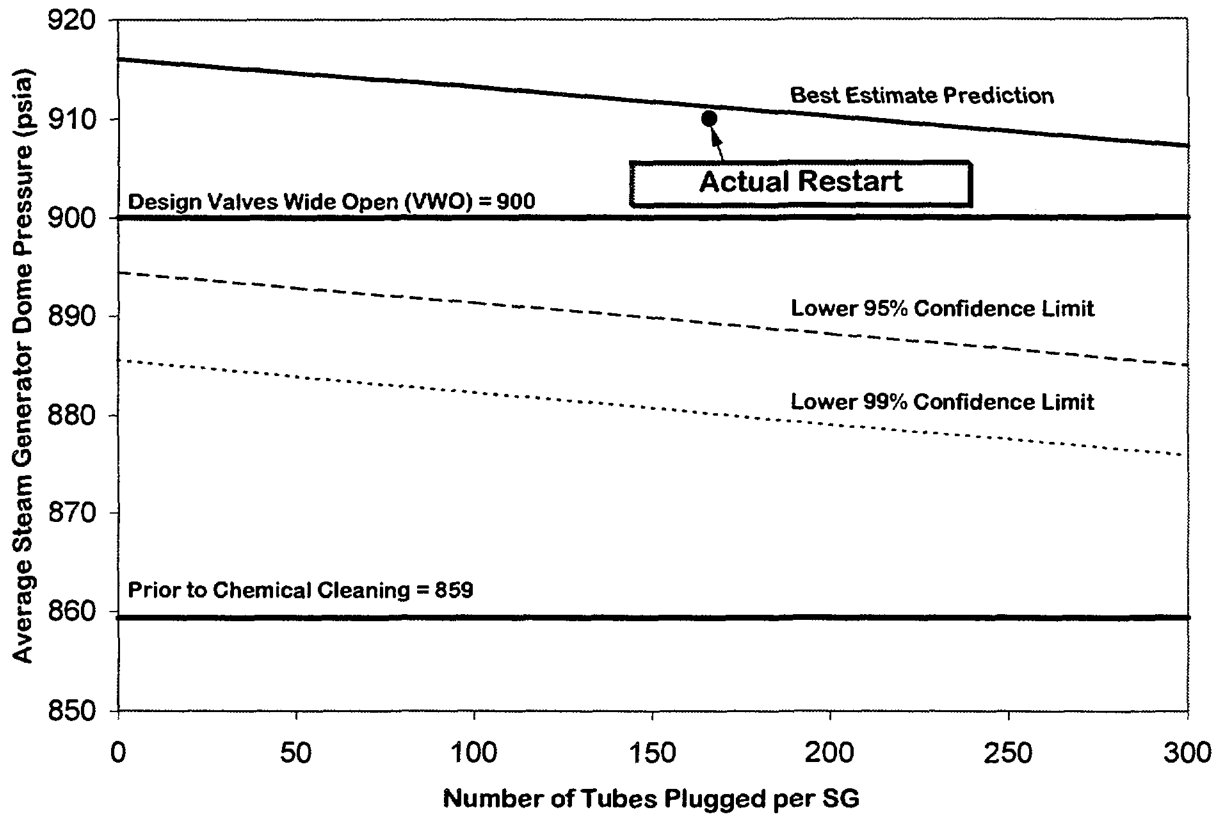

Figure 7. Predicted Steam Pressure After Chemical Cleaning at San Onofre 2

Sensitivity of SG Thermal Performance to Tube Scale Spatial Distribution

As we have seen, the global fouling factor, coupled with the root-cause evaluation of steam pressure loss, led to the correct conclusion that secondary deposits were the chief cause of pressure decreases at San Onofre 2 prior to chemical cleaning. However, it is not clear to what extent the observed steam pressure decrease depended on the spatial distribution of tube scale thermal resistance within the bundle, an effect not considered by the global fouling factor.

To address this issue, the authors performed a limited sensitivity study by 1) modifying the ATHOS code to allow input of a spatially varying thermal resistance, 2) calculating the resultant steam pressures for different thermal resistance distributions applied to the San Onofre geometry (with thermal-hydraulic inputs typical of recent operation), and 3) comparing these steam pressures with those calculated by ATHOS assuming no secondary fouling. In particular, scale thickness distributions for which the thermal resistance (i.e., the local fouling factor) varies linearly from the tube sheet to the U-bend area—while the area-averaged fouling factor in each case remains constant—were investigated. Separate sensitivity studies were performed for average fouling factors of 60 10^{-6} and 200 10^{-6} h-ft^2-°F/BTU (0.011 and 0.035 m^2-K/kW). As is clear from Figure 8, the test cases included distributions with significant nonuniformities.

To investigate each case, the ATHOS geometry was divided into 10 regions: five axial slices with roughly equal heat-transfer areas (four plus the U-bend area) and two halves (hot leg and cold leg). Within each region, the applied thermal resistance remained constant. Each distribution is thus piecewise constant, approximating a linear variation, as shown in Figure 8 for one of the nine cases with an average fouling factor of 60 10^{-6} h-ft^2-°F/BTU (0.011 m^2-K/kW).

The results of the sensitivity study are summarized in Figure 9. The key conclusions are:

- Over the range of distributions examined, the average thermal resistance is predicted by ATHOS to have a significantly greater impact on steam pressure than thermal resistance distribution. This is reflected by the fact that the two curves are 45–55 psi (0.31–0.38 MPa) apart while variations from one end of each curve to the other are 10 psi (0.07 MPa) or less.
- For each curve, the uniform distribution results in the highest pressure loss. This occurs because the various regions of the SG transfer heat roughly in parallel. As a consequence, more heat is transferred through regions with smaller thermal resistances when the spatial distribution is nonuniform. (A second-order effect can also be discerned in Figure 9. The pressure loss for a high positive fouling factor slope is less severe than for a negative fouling factor slope of the same magnitude. This effect is due to the relatively high heat fluxes at the bottom of the hot leg.)

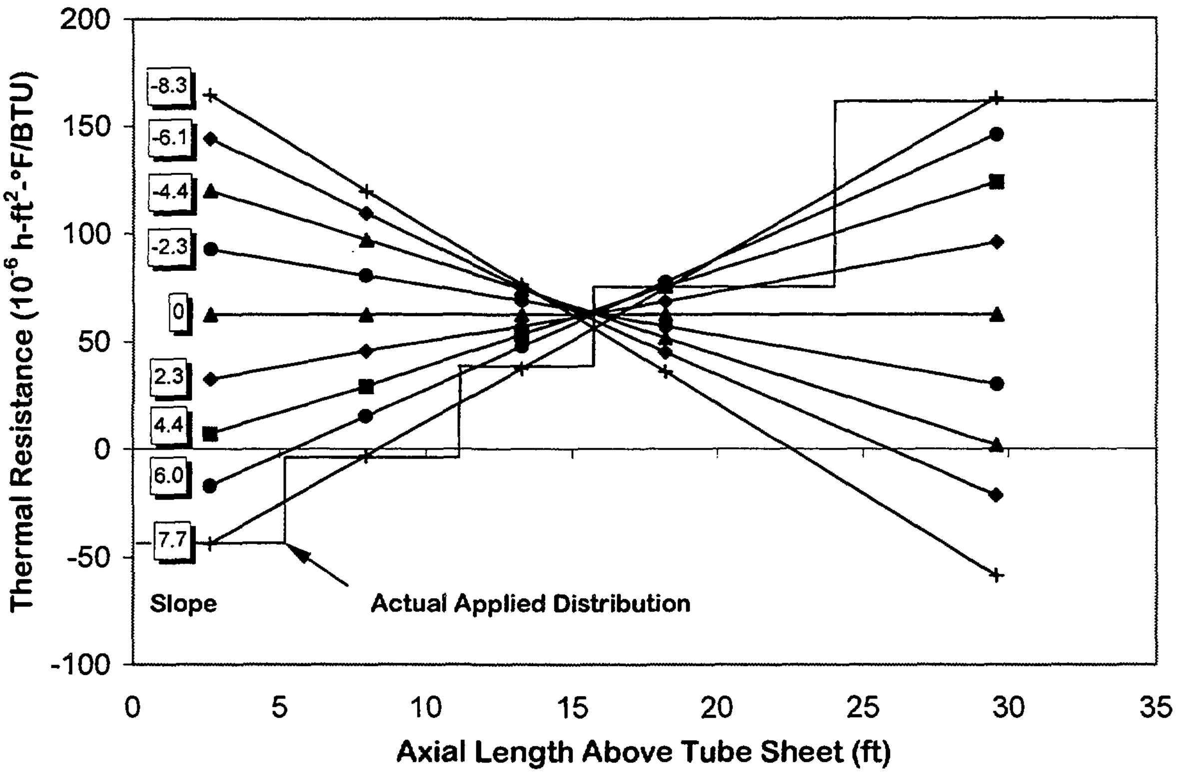

Figure 8. Linear Variations of Fouling Factor Applied to ATHOS Model (60 10^{-6} Avg)

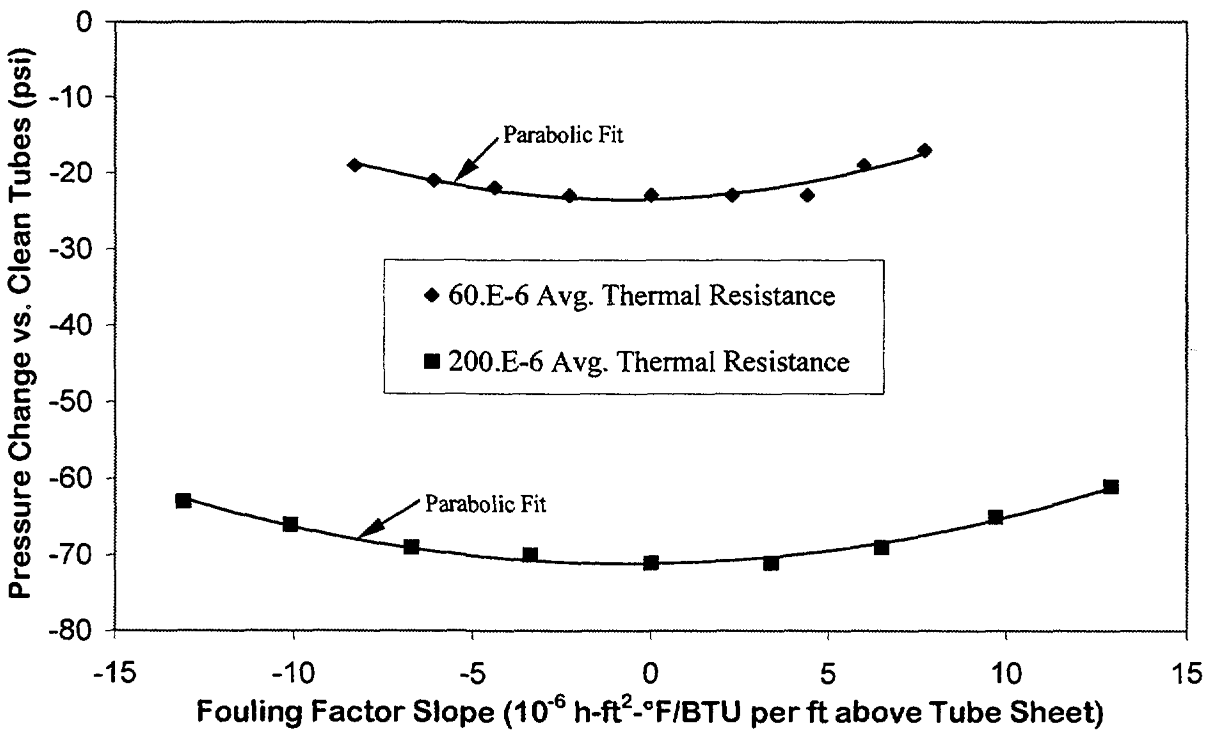

Figure 9. Results of Sensitivity Study

SUMMARY AND CONCLUSIONS

The primary conclusions from the efforts documented here (and also from similar analyses for other plants) include:

1. The principal causes of SG thermal performance degradation can vary greatly from plant to plant. For example, at San Onofre 2, resistive secondary deposits were chiefly responsible for an observed steam pressure decrease of more than 50 psi (0.34 MPa). On the other hand, tube deposits at Callaway were found to be slightly heat-transfer enhancing while a thermal power uprating was the primary source of a 17 psi (0.12 MPa) loss.
2. Small or moderate steam pressure losses (i.e., <30 psi) are often the product of several factors, such as tube plugging, primary temperature fluctuations or measurement error (e.g., hot-leg streaming), and power uprates. Such losses are of greatest concern to plants with small design margins. Larger pressure losses (i.e., 50 psi or more) may be due to thermally resistive secondary deposits, primary temperature decreases (usually 6–8 psi/°F or 0.07–0.1 MPa/°C), or high levels of tube plugging.
3. Field experience at Callaway and San Onofre 2 indicates that full-bundle chemical cleaning is effective at returning SG thermal performance approximately to start-up levels.
4. Agreement between the predicted and actual pressure recovery following chemical cleaning at San Onofre 2 provides some confirmation of the effectiveness of the fouling factor and root-cause methodology for evaluating SG thermal performance.
5. The ATHOS sensitivity study showed that the average thermal resistance of a deposit layer is much more significant than the spatial distribution of that thermal resistance within the SG. This result shows that the uniform thermal resistance assumption implicit to the global fouling factor methodology is reasonable.

ACKNOWLEDGMENTS

The authors would like to recognize Dr. Govinda Srikantiah of the Electric Power Research Institute for providing the thermal-hydraulics code ATHOS for use in this work. We would also like to thank plant personnel at Southern California Edison and Union Electric for supplying the voluminous instrument data used in the work documented here.

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DISCUSSION

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Paper: A Global Fouling Factor Methodology for Analyzing Steam Generator Thermal Performance Degradation

Questioner: J. Nickerson, AECL

Question/Comment:

For those plants who have reduced T_{hot} but just at 100% power, what is their strategy over the next 5 years; e.g., would they increase T_{hot} again to start at 100% power as fouling continues or maintain T_{hot} constant and take power reduction?

Response:

The answer depends on several factors, including the current state and expected progress of tube corrosion, the cost of replacement power for the individual utility, and whether or not the utility might replace the steam generators. For example SCE, which reduced temperature about 4°F and plans to reduce it a further 8°F at San Onofre 2 and 3, is unlikely to subsequently raise the primary temperature due to advancing tube corrosion. SCE would accept power reductions in the event of increased plugging and fouling in order to prolong the life of the current steam generators, which they likely will not replace. On the other hand, a utility that has already planned to replace the current steam generators in 3 cycles, for example, might decide to raise primary temperatures to maintain generating capacity.

Questioner: J. Nickerson, AECL

Question/Comment:

For the plants you have analyzed, was the initial period of enhanced heat-transfer performance seen at all of the plants on AVT?

Response:

Heat-transfer enhancement during early-life operation (i.e., Cycle 1 or immediately following chemical cleaning) was most pronounced at Callaway and San Onofre 2 and 3 among the plants we have examined. (All three plants started operating with AVT chemistry.) A few additional AVT units have exhibited fouling trends suggestive of slight enhancement while a number of other plants do not seem to have exhibited enhancing behavior. However, it should be emphasized that due to scatter, measurement uncertainty, and the difficulty of collecting substantial instrument data for Cycle 1 operation at most plants, it is hard to evaluate early-life trends conclusively in many cases.

Questioner: R. Staehle, University of Minnesota

Question/Comment:

Could you characterize the distribution of copper deposits with respect to location in the bundle, distribution through the thickness, variation among plants, and concentrations? Also, how does the presence of copper relate to the distribution of SCC? Also, when the steam generators are cleaned, does copper build up during the cycle?

Response:

Some evidence from tube pulls has suggested that copper concentrations in tube scale is often higher at higher elevations in the bundle, especially on the hot-leg side (e.g., higher copper at the 7th HL tube support than at the 1st). (Also note that scale copper concentrations tend to be higher than the copper concentrations in the corresponding tube sheet sludge powder.) However, the data on which this trend is based are fairly limited. Scale samples from numerous plants also indicate that it is common for copper concentrations to be higher close to the tube-to-tube-scale interface although a number of plants have scale which exhibits relatively uniform copper concentrations through the thickness. Variation of scale copper concentrations among plants is substantial, ranging from a few percent or less up to as high as about 30%. It should also be noted that ostensibly "copper-tree" plants may still exhibit measurable amounts of copper in their tube scale due to the presence of tramp elements in carbon steel or due to the presence of copper-bearing steels such as Cor-Ten in secondary components.

We are not aware of any reported correlations between free-span SCC and the presence of metallic copper in tube scale. There have been some occurrences of freespan IGA/SCC in low-copper plant such as Palo Verde (which exhibited several percent copper in scale samples analyzed). On the other hand, some plants with substantial amounts of copper in their secondary systems and in their tube deposits have not experienced significant freespan attack (e.g., Sequoyah 1, with 20% to 30% copper in the scale). Note, however, that there have been some reported correlations between IGA/SCC in TSP crevices and the presence of copper oxide, e.g., in Japanese units as reported in a 1985 IGA/SCC workshop.

Copper accumulation in tube scale can still take place following chemical cleaning. In fact, if changes in water chemistry are made concurrent with the cleaning (e.g., to a high pH), high concentrations of copper in the incipient tube scale can be observed due to copper release from corrosion products that have accumulated on carbon steel components in the balance of plant.

Questioner: E.G. Price, AECL

Question/Comment:

For the 2-layer and 3-layer deposits at a thickness of 10-11 mils as described, how adherent is the deposit? Is chemical cleaning necessary for removal of these deposits?

Response:

The adherence of thick scale layers can vary significantly from fairly friable to very tenacious depending on composition and morphology. Mechanical cleaning using water jets may be effective at removing friable layers or even somewhat tenacious layers although two cautions should be noted:

(1) It is difficult to remove deposit layers from a large percentage of the bundle surface area using available mechanical cleaning technology due to the tortuous nature of the bundle geometry. That is, the water jets cannot access significant portions of the deposit surfaces. Consequently, even after extensive cleaning, more than half of the deposit mass may remain. In contrast, currently used chemical cleaning techniques usually remove 95% or more of the deposit mass.

(2) Mechanical cleaning typically employs oxygenated water jets which may facilitate conversion of metallic copper to copper oxide and magnetite to hematite within the remaining tube scale material. These changes are thought to be detrimental to tube corrosion rates. Consequently, use of mechanical cleaning should be accompanied by subsequent efforts to restore reducing conditions (e.g., high levels of hydrazine at elevated temperature).

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