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TUBE MICRO-FOULING, BOILING AND STEAM PRESSURE AFTER CHEMICAL CLEANING

M. H. Hu

ABSTRACT

This paper presents steam pressure trends after chemical cleaning of steam generator tubes at four plants. The paper also presents tube fouling factor that serves as an objective parameter to assess tubing boiling conditions for understanding the steam pressure trend. Available water chemistry data helps substantiate the concept of tube micro-fouling, its effect on tubing boiling, and its impact on steam pressure. All four plants experienced a first mode of decreasing steam pressure in the post-cleaning operation. After 3 to 4 months of operation, the decreasing trend stopped for three plants and then restored to a pre-cleaning value or better. The fourth plant is still in decreasing trend after 12 months of operation.

Dissolved chemicals, such as silica, titanium can precipitate on tube surface. The precipitate micro-fouling can deactivate or eliminate boiling nucleation sites. Therefore, the first phase of the post-cleaning operation suffered a decrease in steam pressure or an increase in fouling factor. It appears that micro-fouling by magnetite deposit can activate or create more bubble nucleation sites. Therefore, the magnetite deposit micro-fouling results in a decrease in fouling factor, and a recovery in steam pressure.

Fully understanding the boiling characteristics of the tubing at brand new, fouled and cleaned conditions requires further study of tubing surface conditions. Such study should include boiling heat transfer tests and scanning electronic microscope examination.

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1. INTRODUCTION

The steam generator industry has been implementing chemical cleaning for steam generators. The purpose of cleaning is to maintain normal plant operation, recovering steam pressure or increasing tube corrosion resistance. After many years of operation, tubes become fouled with significant deposit of particulate and dissolved chemical. Chemical cleaning did remove several thousand kilograms of scale from each steam generator. Visual and eddy current inspection showed that the cleaned tubing is free of scale. One plant implemented chemical cleaning for removing scale from tube support plate broached holes to restore stable plant operation. Some plants entered the chemical cleaning for dual goal; increasing tubing corrosion margin and restoring steam pressure. Some performed the chemical cleaning with the main purpose being enhancing tube corrosion resistance. Apparently, removal of the tube scale increases the corrosion resistance margin since the cleaned tube is free of chemical concentration sites, such as open span tube deposit pores.

Regardless of the main purpose of implementing chemical cleaning, it has become apparent that cleaning can change the conditions of the tube micro-surface. The micro-surface conditions of the tube can alter the effectiveness of boiling nucleation. The micro-surface conditions of the cleaned tube is not necessarily identical to those of the brand new tube. This paper presents tube fouling factors from four plants having implemented chemical cleaning. The purpose is to attempt to understand the post-cleaning boiling effectiveness and its steam pressure characteristics. The ultimate goal is to help develop a procedure to mitigate potential detrimental impact of changes in micro-surface on boiling effectiveness.

2. PLANTS WITH CHEMICAL CLEANING

This paper covers four plants with chemical cleaning. Plant A experienced water level oscillations at full power setting. Subsequently, it was necessary to reduce power level for maintaining stable plant operation. Plant A has Westinghouse Model 51F steam generators. The cause to the water level oscillations was due to excessive pressure drop in the upper bundle that triggered a hydrodynamic density wave instability. Thus, the broached hole blockage led to excessive pressure drop through the upper tube support plates. The blockage is due to formation of scale at the inlet to the holes (Ref. 1). After 14 years of operation, chemical cleaning implemented in April 1994, and the broached holes were free of scale. The post-cleaning has enjoyed a stable plant operation without any water level oscillation at the designed full power and even at an up-rated power level. Cleaning removed about 2450 kilograms (kg) of scale from each steam generator. Tubes were free of scale according to visual inspection. The cleanliness of the cleaned tube was confirmed by eddy current tests. The eddy current signals are capable of providing deposit profiles of magnetite along tube. The post-cleaning deposit profile showed no scale deposit.

Plant B installed Westinghouse Model F steam generators. After 10 years of operation, it received chemical cleaning implemented in May 1995; the purpose was to increase tube corrosion resistance and to restore steam pressure. Each generator removed about 1950 kilograms of scale that is about 0.0076 centimeters (cm) thick without porosity (Ref. 2). After 6 years of operation, Plant C implemented chemical cleaning in Fall 1996. Plant C uses Westinghouse Model D4 steam generators. The purpose was to increase tube corrosion resistance. It removed about 500 kilograms per generator. After 12 years of operation, Plant D conducted chemical cleaning for widening margin to tubing corrosion. Plant D installed Westinghouse Series 51 steam generators. It took out 2180 kilograms of sludge from each generator.

3. REVIEW OF EFFECT OF PRECIPITATE AND DEPOSIT ON BOILING

Boiling tests (Ref. 3 & 4) have shown that dissolved chemicals (calcium sulfate) can precipitate due to micro-layer dryout under boiling bubble from a nucleation site. Precipitation of dissolved calcium sulfate reduces boiling heat transfer (Ref. 4). The precipitate of calcium sulfate grew and merged with other nucleation sites until surface was completely covered by precipitate. Jamialamadi and Muller-Steinhagen (Ref. 5) examined the conditions of precipitate of calcium sulfate.

Reference 5 observed two types of scale: ring-shaped, dense precipitate beneath the bubbles, and porous deposit outside the bubble nucleation sites. The different kinds of scale grow and merge with one another until the surface was completely covered. The porous deposit outside the bubbling area created additional nucleation sites and therefore, developed higher boiling heat transfer coefficient. Turbulence is a mechanism for scale formation without boiling. If the solution of calcium sulfate is not saturated, the porous type of scale by dissolved calcium sulfate did not always form. Then the dense type of calcium sulfate dominated and boiling heat transfer coefficient decreased (Ref. 5), or the tube fouling factor increased.

From these tests (Ref. 3, 4 & 5), we can conclude that number of boiling nucleation sites can be reduced by the dense precipitate of the dissolved chemicals. A concept of micro-fouling by precipitate of dissolved chemicals (Ref. 2) contends that the dissolved chemical precipitate decreases bubble nucleation site density. This concept is supported by the conclusion drawn from the above mentioned tests (Ref. 3, 4 & 5).

The particulate deposit of the magnetite improves boiling heat transfer of steam generator tubes (Ref. 6). Particulate such as magnetite can deposit on heating surface by turbulence (e.g., Ref. 7) and boiling (Ref. 8). Similar to precipitation of dissolved chemicals by boiling, particulate can deposit underneath the boiling micro-layer (Ref. 3 & 8). Unlike the dissolved chemical precipitate being smooth and dense, the particulate deposit by turbulent convection or boiling is rough and porous. As discussed above, porous deposit can be formed from dissolved chemicals by turbulence deposit outside the bubbling micro-layer (Ref. 5). This porous deposit of dissolved calcium sulfate created more bubble nucleation sites (Ref. 5). Thus, the particulate deposit can activate or create more boiling nucleation sites, as postulated by Hu (Ref. 2).

After many months operation, tubes would have received deposit of magnetite, which can improve boiling heat transfer (e.g., Ref. 6). In 1960s, steam generator designers did not know this phenomenon, and they treated the newly "fouled" tube as new and assigned a zero tube fouling factor for the fouled tube. With this assumption, it was argued that the wall superheat calculated by the boiling correlations was too high. The correlation developed from brand new tubes, such as that by Jen and Lottes (Ref. 9), was modified by reducing its coefficient to half. The modified correlation unfortunately underpredicts the wall superheat and thus results in an apparent tube fouling factor with positive value for the brand new tubing. Such a practice sticks with the existing design code for steam generator sizing and performance evaluation.

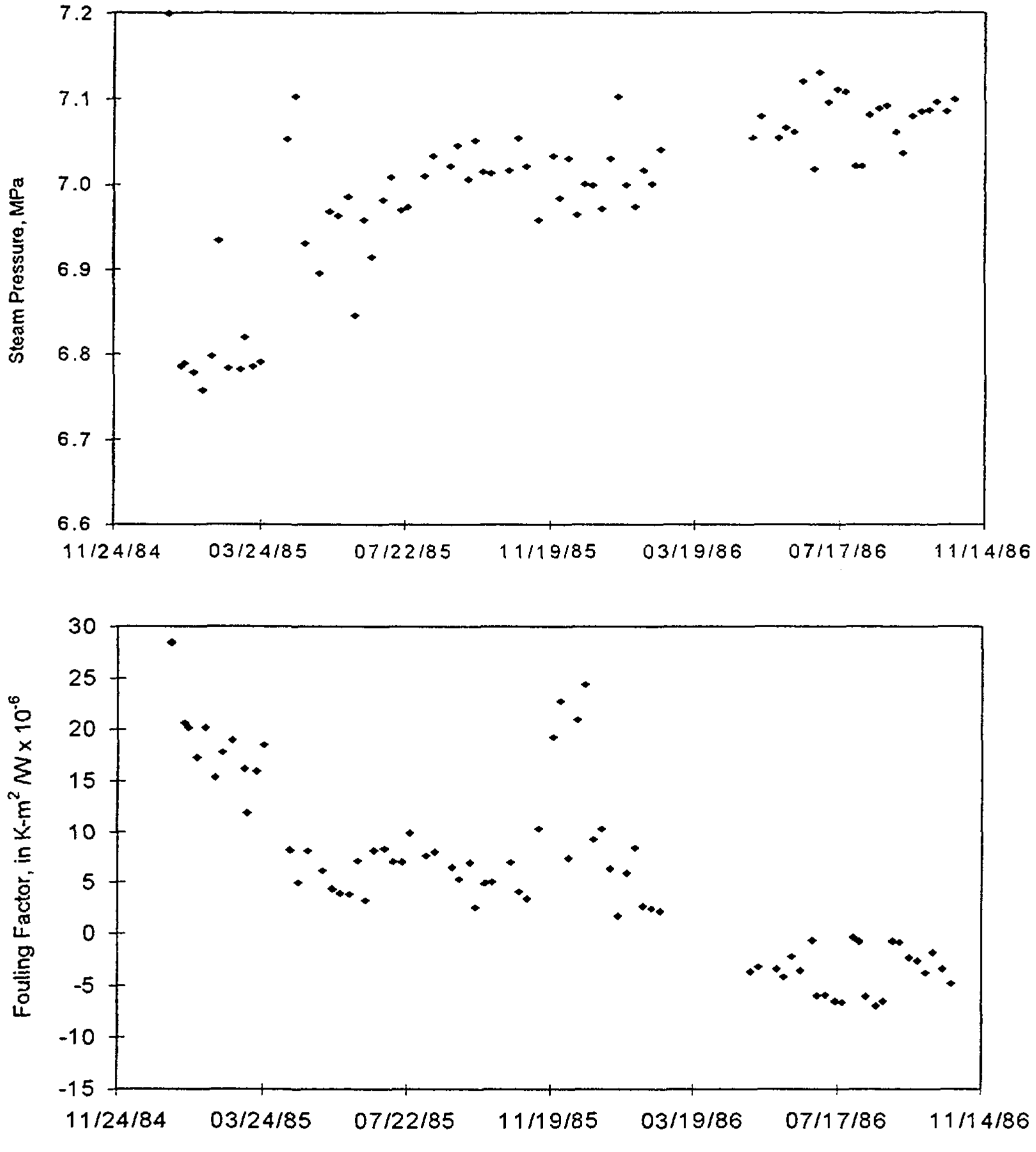

Figure 1 Rapid reduction in tube fouling factor and rapid increase in steam pressure right after commercial operation (From brand new tube to fouled tube of Plant B)

Figure 1 depicts the trend of apparent fouling factor and steam pressure of Plant B after commercial operation. Concentration of magnetite in the feedwater was usually very high after commercial operation, and had an average value of 20 ppb during first fuel cycle. After about one year operation, steam pressure increased from 6.75 million pascals (MPa) to 7.05 MPa, and the tube fouling factor decreased from

0.0000280 K-m^2/W to zero value, and designers happened to take this zero value as the boiling conditions of the brand new tube. Therefore, the brand new tube without any fouling shows a positive fouling factor. The design fouling factor was established against this zero fouling factor.

4. RESULTS AND DISCUSSION

4.1 Discussion on Plant A

Figure 2 depicts trends of steam pressure and fouling factor before and after chemical cleaning. Based on the Westinghouse thermal-hydraulic code (a one-dimensional code for calculating steam generator performance), fouling factor was calculated using plant operating parameters including simulation of tube plugging and sleeving. The post-cleaning began with a fouling factor, which was about equal to that before the cleaning. Note that pre-cleaning tube had a scale about 0.0102 centimeters (Ref. 2) over the entire bundle, and the post-cleaning tube was essentially no scale. The tube fouling factor then began to increase for about three months before it turned around to decrease toward the pre-cleaning value.

Table 1 lists silica concentration in steam generator bulk water. As seen, during the first three months, it had a high silica concentration and then decreased. The decreasing mode in steam pressure during the first three months was hypothesized to be a result of precipitate of dissolved chemicals, such as silica. The precipitate micro-fouling of silica and/or other dissolved chemicals could cover some nucleation sites.

Table 1 Steam Generator Silica and Feedwater Iron and Copper Concentration (Plant A)

Months Post Cleaning	Iron Concentration, ppb	Copper Concentration, ppb	Silica Concentration, ppb
1	7.4	1.1	350
2	3.8	0.4	150
3	2.9	0.4	130
4	3.4	0.7	100
5	3.3	0.8	70
6	2.7	0.7	50

After three months of the post-cleaning operation, Plant A started to decrease in the tube fouling factor. After the first three months, concentration of silica also reduced (see Table 1). It is considered that, after three months, there was an increase in bubble nucleation site density. Such an increase was due to the magnetite deposit micro-fouling. The magnetite micro-fouling created bubble nucleation sites more than the precipitate micro-fouling destroyed. Note that feedwater iron concentration is about 3 ppb or higher (see Table 1) which activates or creates more bubble nucleation sites. In other words, micro-fouling by magnetite is positive in enhancing boiling.

Micro-conditions of the cleaned tube is better in activating bubble nucleation sites than those of the brand new tube. This can be inferred from tube fouling factor. The brand new tube of Plant A had an apparent fouling factor of 0.0000282 K-m^2/W, and the cleaned tube had an initial value of 0.0000035 K-m^2/W. The cleaned tube was initially 8 times better than the brand new tube. This is important to know. In addition, the design tube fouling factor was 0.0000352 K-m^2/W. Note that design fouling factor is provided to accommodate the heavy tube fouling that can take place after many years of plant operation. It was a measure against to the best boiling conditions after light deposit of magnetite, not a measure against to the brand new tubing. So the cleaned tube was initially 10 times better than the design value. Even at the peak fouling factor of 0.0000123 K-m^2/W, the cleaned tube is still better than both the brand new tube and design fouling factor. Of course, the cleaned tube apparently had a fouling factor higher than the lowest possible value under porous deposit, as to be discussed in Plant B.

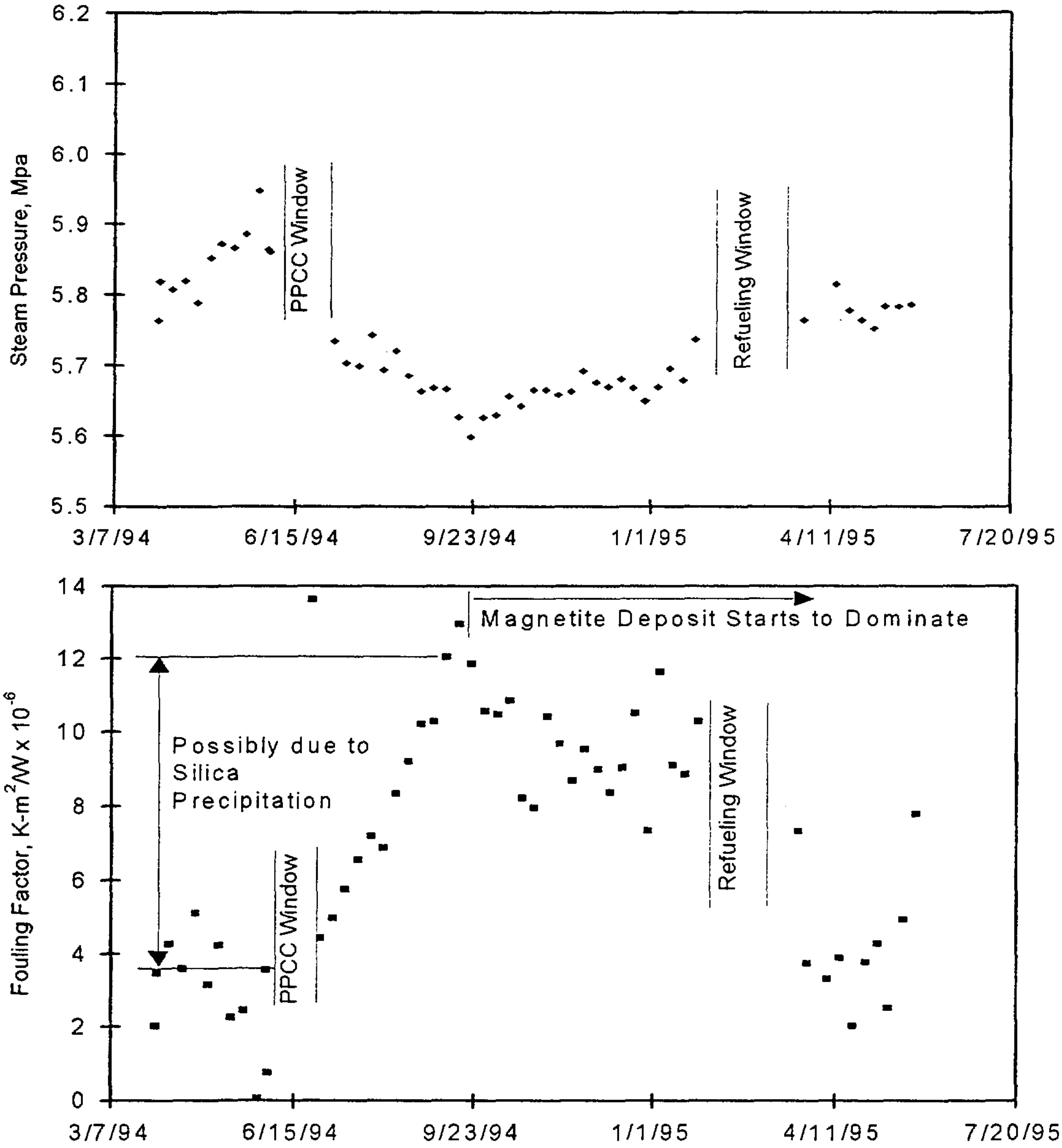

Figure 2 Steam Pressure and Fouling Factor before and after Chemical Cleaning (Plant A)

4.2 Discussion on Plant B Results

Figure 3 shows steam pressure and tube fouling factor. After the cleaning, steam pressure dropped about 69 kilo-pascals (or 10 pounds per square inch); tube fouling factor jumped to 0.0000106 K-m^2/W from 0.0000053 K-m^2/W. Tube scale was obtained at one and half years before the chemical cleaning. Thickness of the scale ranged from 0.0061 to 0.0102 centimeters with double layer. The inner layer and outer layer had a porosity of 11% and 32%, respectively.

As discussed for Plant A, the porous deposit of magnetite can enhance boiling heat transfer coefficient. However, amount of the enhancement depends on porosity of the deposit. According to Uhle (Ref. 6), an effective range of porosity appears to be from 30% to 80% with optimum being from 40% to 60%. The porosity of 11% to 32% for the Plant B at the time of chemical cleaning was outside the optimal porosity range. But it could still increase some bubble nucleation sites.

Table 2. Steam Generator Silica and Feedwater Iron and Copper Concentration (Plant B)

Months Post-Cleaning	Iron Concentration, ppb	Copper Concentration, ppb	Silica Concentration, ppb
1	25	-----	450
2	5.0	0.04	315
3	6.2	0.05	245
4	----	-----	245
5	4.6	0.02	162
6	4.2	0.02	180

The post-cleaning fouling factor jumped to 0.0000106 K-m^2/W from 0.0000053 K-m^2/W. It then continued increasing for about four months to a value of 0.0000132 K-m^2/W. After the cleaning, each steam generator received 1.4 to 1.8 kilograms of titanium during wet layup, and another 1.4 to 1.8 kilograms before startup. It continues receiving 4 grams per day.

Table 2 lists the post-cleaning feedwater iron, copper and steam generator bulk water silica concentration. Silica concentration started at 450 part per billion (ppb) and decreased toward 180 ppb at the end of six months. Precipitate of dissolved chemicals, such as silica, titanium probably dominated during the first 4 months. As discussed above for Plant A, the boiling induced chemical precipitate can reduce bubble nucleation sites, and thus an increase in fouling factor appeared. This could explain the fouling factor jump and increase during the first 4 months of the post-cleaning operation.

As shown in Table 2, the feedwater iron concentration was about 4 to 6 ppb. The accumulated effect of the magnetite micro-fouling began to dominate, after the first 4 month operation. Therefore, the fouling factor began to decrease. After two years of the post-cleaning operation, tube fouling factor dropped from 0.0000132 K-m^2/Wto 0.0000040 K-m^2/W.

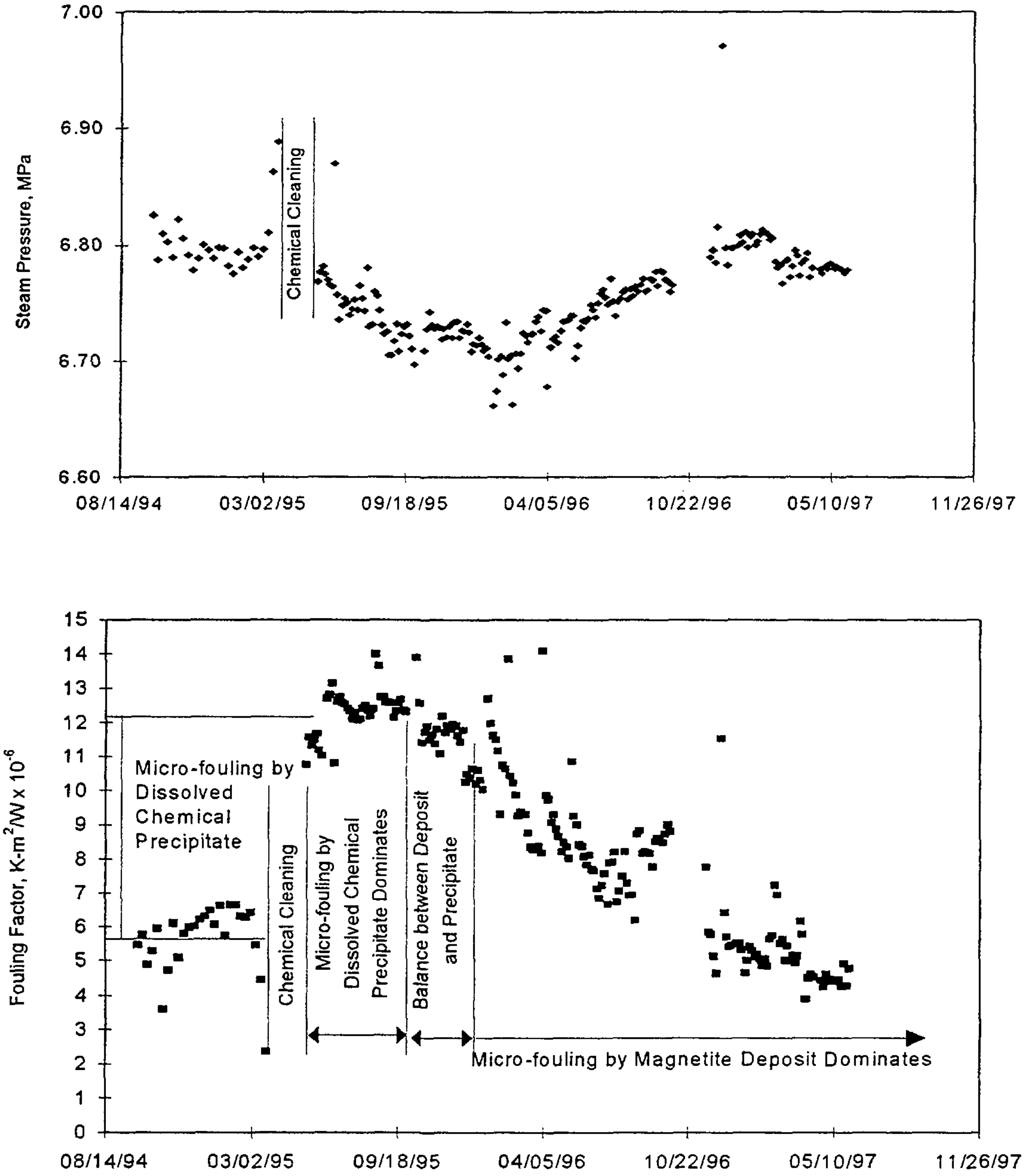

Figure 3 Steam Pressure and Fouling Factor before and after Chemical Cleaning (Plant B)

Fouling factor just before the cleaning was about 0.0000056 K-m^2/W. Plant B has a design fouling factor of 0.0000088 K-m^2/W. Figure 1 depicts the rapid decrease in the tube fouling factor once it began commercial operation; it decreased from 0.0000264 K-m^2/W (for the brand new tubing) to about zero (for a fouled conditions) within one year. The initial value of 0.0000106 K-m^2/W for the post-cleaning tube is slightly higher than the design value, but much lower than the brand new tube. It arrived at 0.0000040 K-m^2/W two years later, which is better than the new tube, design value and the pre-cleaning value. However, this 0.0000035 K-m^2/W is still higher than the optimal value of -0.0000050 K-m^2/W (Ref. 2).

A correlation of fouling factor with feedwater iron concentration was developed (Ref. 2) using the micro-fouling of magnetite and dissolved chemicals. Application of the correlation for Plant B with 20 ppb iron in the feedwater indicated a time period of 2 EFPY to reach the optimal value of -0.0000049 K-m^2/W. According to Ref. 2, we have the following expression:

$$R = R_\infty + \frac{R_o - R_\infty}{1 + \frac{2}{3} C (R_o - R_\infty) \left[\sqrt{\beta W_{fw} C_{fwp}} - \sqrt{\beta W_{fw} C_{fws}} \right] t^{3/2}}$$

where we have used R is the fouling factor, R_o the initial fouling factor, and R_∞ an asymptote fouling factor, C the correlation coefficient, b the fraction of iron or chemical deposit on tube wall, W_{fw} the feedwater flow rate, C_{fwp} the feedwater iron concentration, C_{fws} the feedwater dissolved chemical concentration, and t the time. Figure 4 depicts the prediction of fouling by the correlation for the field fouling data starting 4 months after the chemical cleaning. The post-cleaning has an iron concentration of about 4 ppb in the feedwater, we consider that titaninum is about 0.1 ppb in the feedwater, and the initial fouling factor is that at 4 months after the cleaning (i.e., 0.0000132 K-m^2/W). The asymptote of -0.0000050 K-m^2/W is taken from Ref. 2.

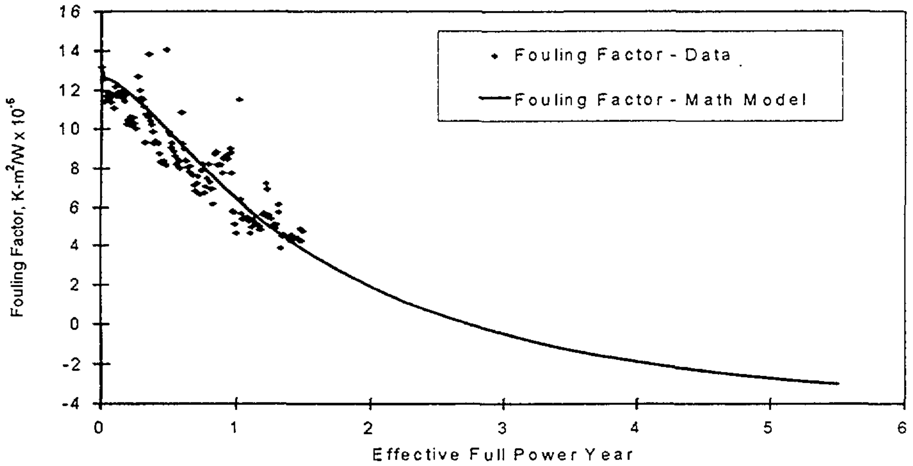

Figure 4 Fouling Factor Data and Mathematical Prediction for Plant B
(Effective Full Power Year beginning 4 Months after Chemical Cleaning)

During the early life of the plant operation, Plant B reached the asymptote of -0.0000050 K-m^2/W under a higher feedwater iron concentration (~20 ppb) in 2 EFPY. Figure 4 suggests that the cleaned tube with a feedwater iron concentration of 4 ppb could approach the asymptote of -0.0000050 K-m^2/W within about 5 EFPY, if water chemistry maintains the same as current conditions.

4.3 Discussion on Plant C Results

Figure 5 depicts steam pressure and fouling factor before and after chemical cleaning. Restart from the cleaning outage began at a pressure higher than before the cleaning. Tube fouling factor reflects these characteristics beginning at a lower fouling factor than the pre-cleaning value. This plant used EDTA, like Plants A and B. In addition, it implemented soaking with DMA.

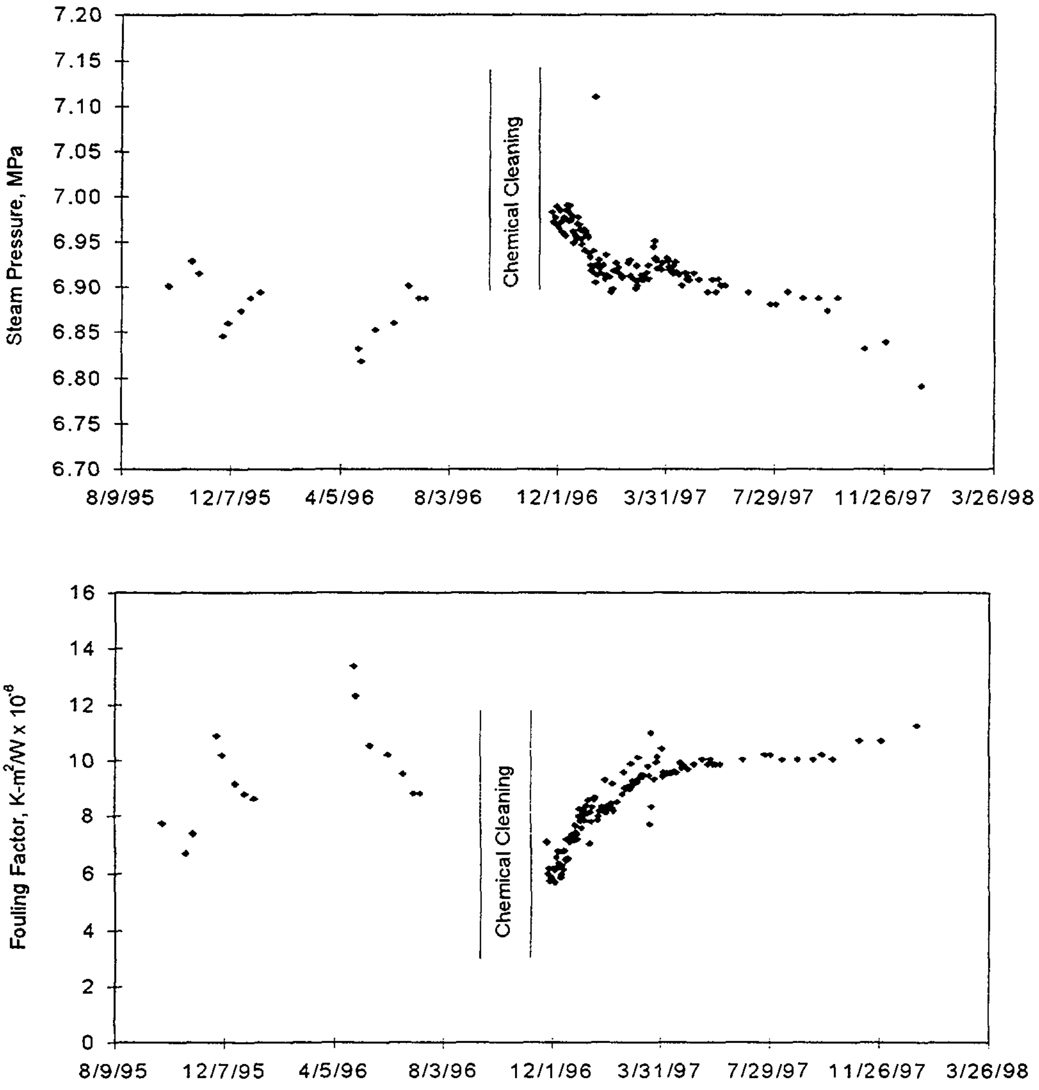

Figure 5 Steam Pressure and Fouling Factor before and after Chemical Cleaning (Plant C)

Similar to Plants A and B, fouling factor continues increase from the post-cleaning, initial value. Time duration with increasing mode varied among these three plants. Plants A and B took 3 and 6 months, respectively. Plant C is still increasing after 12 months; the increasing rate in fouling factor was high during the first 5 months, and it appeared to approach an asymptote after 12 months. However, a reactor trip in Fall 1997, led to a loss of steam pressure about 69 KPa (or 10 psi), and an increase in fouling factor. Plant

C was not yet shown a decreasing trend in fouling factor as Plants A and B. This may be due to an excellent control in limiting magnetite ingress. Plant C achieved a record low value of feedwater iron concentration being less than 0.5 ppb. This is extremely low when compared to a range of value from 3 to 8 ppb for Plants A and B (see Tables 1 and 2). It then appears that Plant C does not enjoy the positive impact of the micro-fouling by magnetite deposit in promoting more bubble nucleation sites.

For Plant C, the brand new tubing had a fouling factor of 0.0000150 K-m^2/W, and a designed fouling of 0.0000088 K-m^2/W. Note that Plant C has a lower value of the apparent fouling factor when compared to Plants A and B. Plants A and B are of design without preheater, and Plant C is of preheating design. Preheating yields a better heat transfer and thus a lower value of apparent fouling factor on the basis of one-dimensional modeling. The initial value of 0.0000056 K-m^2/W for the cleaned tubing is lower than those of both brand new and pre-cleaning fouled tubing. The current fouling factor asymptote at 0.0000106 K-m^2/W is slightly higher than the designed value and less the brand new tubing.

4.4 Discussion on Plant D Results

Figure 6 presents steam pressure and fouling factor. The post cleaning operation seemed to begin at a higher steam pressure or a lower fouling factor. It began to increase in the fouling factor for a duration of 3 months, and then turned around to a decreasing mode at a fast pace. This plant had a feedwater iron concentration about 2 to 3 ppb, which is about the same as Plants A and B. The micro-fouling by the magnetite deposit is again demonstrated in decreasing fouling factor and recovering steam pressure.

The pre- and post-cleaning fouling factor was about 0.0000062 K-m^2/W and 0.0000035 K-m^2/W, respectively. The brand new tubing had a fouling factor of 0.0000264 K-m^2/W. The designed fouling factor for Plant D is 0.0000352 K-m^2/W. The cleaned tubing peaked at about 0.0000088 K-m^2/W, and dropped down to 0.0000035 K-m^2/W after one year of post-cleaning operation. It is not known definitely why the cleaned tubing went through an early mode of high fouling factor. However, tube fouling factor of the cleaned tubing was always lower than the brand new tubing or the design fouling factor. Above all, the cleaned tube eventually arrived at a fouling factor being lower than the value before the cleaning.

As a comparison, Table 3 lists relevant parameters for all of four plants. All plants went through an increasing mode in tube fouling factor and a decreasing mode in steam pressure. After about one year, Plants A, B, and D recovered to a condition prior to the cleaning. And Plant B shows a continued decrease in tube fouling factor to a value lower than the pre-cleaning value.

Table 3 Summary of Tube Fouling Factors (FF: K-m^2/W x 10^{-6}) and Time to Recovery for All Four Plants

Plant	FF for New Tube	Minimum FF	Design FF	Pre-Cleaning FF	Post-Cleaning FF	Post Peak FF	Time to Post Peak, month	Recovery Time to Pre-Cleaning, year
A	28.2		35.2	3.5	3.5	12.0	3 - 4	~ 1
B	26.4	-5	8.80	5.3	10.6	13.2	3 - 4	~ 1.5
C	15.0		8.80	7.0	5.6	10.6	> 12	
D	26.4		35.2	6.2	3.5	9.0	3 - 4	~ 1

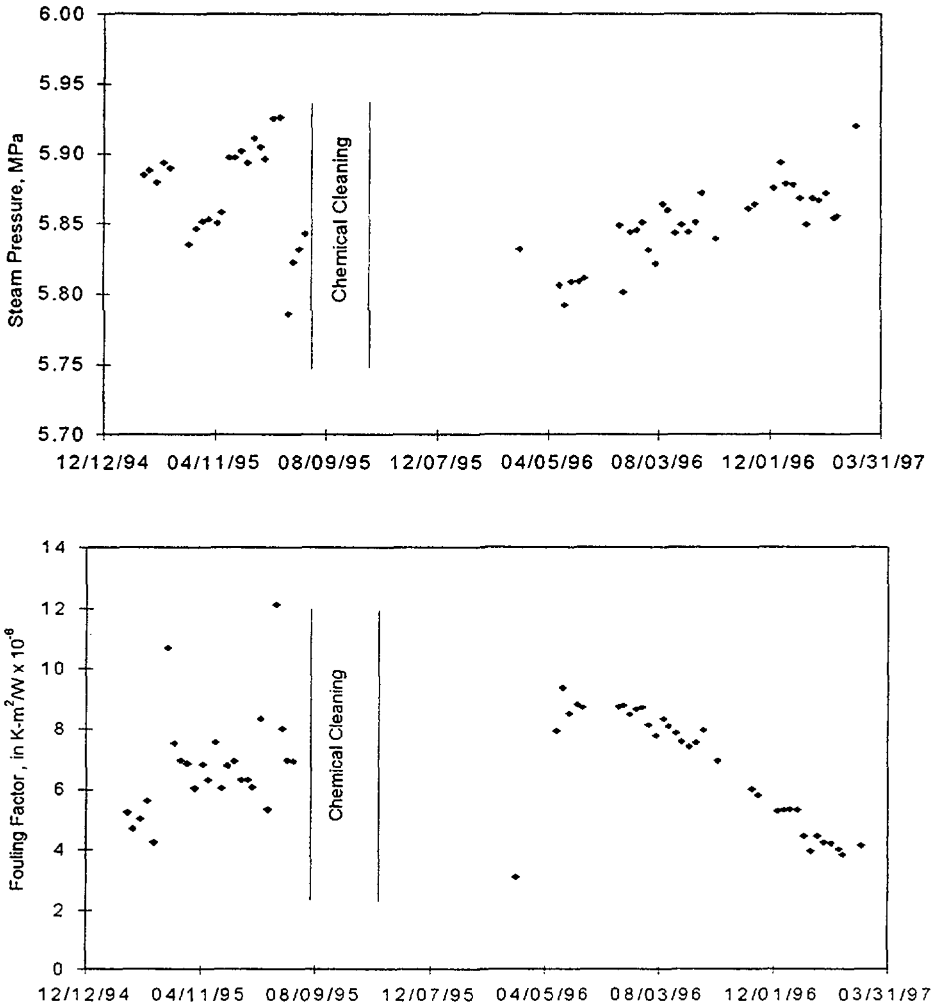

Figure 6 Steam Pressure and Fouling Factor before and after Chemical Cleaning (Plant D)

5. SUMMARY

We can draw the following conclusions:

1. Initial fouling factors of the cleaned tube vary among four plants. Plant A had an initial value equal to the pre-cleaning value. Plant B had an initial value higher than the pre-cleaning value. Plants C and D had their initial fouling factor lower than the pre-cleaning value.
2. All four plants immediately experienced a period of increasing trend in fouling factor or a decreasing trend in steam pressure.
3. The micro-fouling of boiling induced precipitate of dissolved chemicals seems to be responsible for the post-cleaning increase in tube fouling factor. As test demonstrated, boiling induced precipitate of dissolved

calcium sulfate was dense and reduced bubble nucleation sites. Both Plants A and B showed high silica, and Plant B had had titanium injection in the post-cleaning operation.

4. The micro-fouling of magnetite deposit seems to be responsible for the eventual decrease in the tube fouling factor. As test demonstrated, the porous deposit increased bubble nucleation sites. Plants A, B and D had had feedwater iron concentration in the range of 3 to 8 ppb in the post-cleaning operation. After one to two years, they all showed a decrease in the fouling factor to a value equal or lower than the value just before the cleaning. Plant C did not show a decrease in the fouling factor after one year operation. This may be due to the extremely low iron concentration (<0.5 ppb) in feedwater.

Continued study of the cleaned tube behavior is required to fully understand the tubing surface conditions in terms of boiling characteristics. This can be done by boiling heat transfer tests for brand new tube, fouled tube and cleaned tube. In addition, scanning electronic microscope can examine the micro-surface of the brand new, fouled and cleaned tube in terms of nucleation sites. Such an understanding would help develop a cleaning process for maintaining or creating bubble nucleation site density.

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DISCUSSION

Authors: M.H. Hu, CBS, Westinghouse Nuclear Services Division

Paper: Tube Micro-Fouling, Boiling and Steam Pressure after Chemical Cleaning

Questioner: J. Gorman, Dominion Engineering

Question/Comment:

Has the idea of microfouling by silica causing increases in fouling factor been quantified or checked by examination of pulled tubes or modelling considering thickness and conductivity of the silicon layer?

Response:

The idea of micro-fouling by silica is developed from a hypotheses that precipitates of dissolved chemical could reduce the density of bubble nucleation sites. Dissolved calcium sulfate can precipitate due to microlayer dryout under boiling from a nucleation site. Microlayer deposition mechanism has been reported in open literature, for examples, Ref. 4 cited in this paper, a poster paper in this conference entitled "Deposition of magnetite Particles Onto Alloy-800Steam Generator Tubes," by Basset, M., et. al. Precipitation of dissolved calcium sulfate reduces boiling heat transfer. A reduction in boiling heat transfer is considered to be a result of reduction of nucleation site density due to chemical precipitation, not due to thickness and additional conductive resistance of the silica layer. This idea of microfouling by dissolved chemical precipitation has yet to be verified by examination of pulled tubes.

Questioner: K. Bagli, Ontario Hydro

Question/Comment:

In your summary, you have indicated that the precipitates of dissolved chemicals result in an increase of fouling factor after chemical cleaning. Can you please elaborate on this hypothesis?

Response:

Boiling takes place at bubble nucleation sites. The bubble nucleation sites have been observed. For example, the bubble nucleation sites are clearly shown in a poster paper in this conference entitled "Deposition of Magnetite particles Onto Alloy-800 Steam Generator Tubes," by Basset, M., et. al. After chemical cleaning, dissolved chemicals, such as silica or titanium, were observed to be high in concentration. Dissolved chemical can precipitate due to microlayer dryout under boiling from a nucleation site. This precipitation can eventually cover the whole heating surface and reduce the number of bubble nucleation sites. A reduction in number of nucleation sites decreases boiling heat transfer and thus increases tube fouling factor. As discussed in the paper, dissolved chemical, such as silica, was high during the first few months after the chemical cleaning, and the fouling factor increased during this period. After the first few months, silica concentration decreased, while magnetite continued entering the steam generator. Porous deposits of magnetite can create additional nucleation sites and increase boiling heat transfer. Therefore, the fouling factor began to decrease after the first few months.