CONTRIBUTION OF SG DEGRADATION MECHANISMS TO RIHT BEHAVIOUR

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ABSTRACT

Degradation of steam generators has a significant effect on CANDU heat transport system effectiveness and the overall efficiency of a nuclear power plant. Steam generator degradation results in an increase in the reactor inlet header temperature (RIHT), which has to be kept below an upper limit to avoid dryout of the fuel. Therefore an understanding of steam generator degradation mechanisms is needed to avoid plant deratings.

In this paper, various steam generator degradation mechanisms are identified and their effect on the RIHT quantified using field data and numerical modelling. Thermal performance of CANDU steam generators has been mostly affected by a combination of divider plate leakage and tube-bundle fouling. An analysis of plant data indicates that CANDU 6 steam generators are fouling at the rate of $2.05*10^{-6}$ $m^2{}^\circ C/W$ per EFPY, of which the majority of this is attributed to primary-side fouling.

1. INTRODUCTION

Increased reactor inlet header temperatures (RIHT) can cause power deratings in CANDU power plants because of a limit imposed by the reactor trip margin. An increase in RIHT signifies degradation of one of the components of the heat transport system (HTS). Previous work has identified divider plate leakage ((Brissette and Lafreniere, 1996) and tube-bundle fouling (Burrill and Turner, 1994) as making significant contributions to the rise in RIHT. In this paper we present a methodology to quantify the contributions of various degradation mechanisms and operating parameters to the rise in RIHT at a CANDU 6 plant. The methodology is then applied to the analysis of field RIHT data from various CANDU 6 plants to determine the rate of DP degradation and tube-bundle fouling.

2. MODELLING OF RIHT: EFFECT OF OPERATING PARAMETERS AND HTS DEGRADATION

RIHT is affected by the heat transfer efficiency of the steam generators, the primary-coolant mass flow rate and SG operating parameters.

Whereas SG degradation mechanisms affect the heat transfer efficiency, degradation mechanisms in other parts of the HTS, such as diametral creep of pressure tubes and increased surface roughness of the primary-side piping, affect the primary-side mass flow rate. SG-related operating parameters that affect RIHT include reactor power, steam pressure, and feedwater temperature. Degradation mechanisms that are specific to the SG include:

- Primary-side Fouling
- Secondary-side Fouling
- Separator Fouling
- Divider Plate (DP) Leakage
- Preheater Thermal Plate Leakage
- Feedwater Distribution Box Leakage
- Tube Plugging

A parametric THIRST analysis was conducted to quantify the effects of all degradation mechanisms and operating parameters affecting RIHT. The results show that for CANDU 6 steam generators, the most significant effects are captured in the RIHT equation below:

$$\begin{aligned}\mathrm{RIHT} = \; & 266.6 - 0.026*(523.6 - \mathrm{Power})^{0.85} \\ & -12.5*(4.74 - P_{secondary}) \\ & -0.10*(186.7 - T_{secondary_{IN}}) \\ & -0.0066*(1925 - m_{primary}) \\ & -1.5*10^{5}*(3.52*10^{-5} - R_{foul}) \\ & +0.5*\%DP\_Leakage\end{aligned} \qquad (1)$$

where:

Power is the SG thermal power in MW,

$P_{secondary}$ is the secondary-side saturation pressure in MPa,
$T_{secondary_{IN}}$ is the feedwater inlet temperature in °C,

$m_{primary}$ is the primary-side mass flow rate in kg/sec,
R_{foul} is the fouling factor in m²K/W, and
% DP_Leakage is the percent primary-side flow leakage across the DP.

This equation includes the effects of the two major SG degradation mechanisms, DP leakage and tube bundle fouling, and the effects of operating parameters, such as SG secondary-side pressure, power level and feedwater inlet temperature. It also includes the effect of primary-coolant flow rate, which in turn includes the effects of pressure tube creep and increased roughness of HTS piping.

In the following section, the RIHT equation will be used to infer the rate of DP degradation and the rate of tube bundle fouling in CANDU 6 steam generators.

3. INFERRED STEAM GENERATOR DEGRADATION RATES: CANDU 6 RIHT FIELD DATA

RIHT trends are monitored at all CANDU 6 stations. Available field data are shown in Figure 1(a) to (d) for Wolsong 1, Embalse, PLGS and Gentilly-2 CANDU plants. Also shown in these figures are the predicted RIHT trends calculated using Equation 1 taking into account the change in operational parameters such as SG secondary-side pressure, the reduction in primary mass flow rate and DP replacement.

Figure 1 shows that, early in plant life, all plants but Wolsong 1 showed similar trends in RIHT. This similarity disappeared in the later years during which period the plants, faced with reduced ROP margins and possible power deratings, started to take remedial actions. Among the actions taken, reduction of the secondary side pressure of SGs, replacement of SG primary-side divider plates, and cleaning the primary-side of the SG tubes, all had marked effects on the RIHT. Figure 1 shows (solid lines) the predicted RIHT trends using Equation 1, taking into account the changes in operating conditions. Values for the fouling rate, reduction in primary-coolant mass flow rate and DP leakage rate were adjusted to give a good fit of Equation (1) to the field data. The results are tabulated in Table 1. Other information such as the separate effects of primary and secondary side fouling, start-up DP leakage rates, leakage and degradation rates of the new floating DPs are also inferred from the RIHT data by relating a specific event to an observed change in RIHT, e.g., mechanical cleaning and DP replacement of Gentilly-2.

3.1 Inferred Tube Bundle Fouling Rate

Wolsong 1 SGs have fully welded primary-side DPs and no thermal plates. Hence, the change in RIHT can be attributed mainly to tube bundle fouling and, to a smaller extent, to reduced primary-side mass flow rate. Figure 1(a) shows the field data of Wolsong 1 RIHT. Assuming an average 0.5% reduction in primary flow rate per year and fitting the RIHT equation (Equation 1) to field data, the tube bundle fouling rate is found to be 2.05×10^{-6} °C m²/W per EFPY. From the slope of the RIHT data, the degradation rate appears to be fairly constant throughout the life of the station.

Note that the RIHT equation overpredicts the start-up temperature for Wolsong 1. A likely cause for this is the under-prediction of the SG heat transfer rate, either because of negative fouling at the start-up or because of the particular correlation used for the boiling heat transfer coefficient. The effect is to shift the RIHT prediction up by ~1°C in Figure 1(a) to 2(d). This shift, however, does not affect the slope of the RIHT lines and the conclusion regarding fouling rates remain valid.

The slopes of the Embalse, Pt. Lepreau and Gentilly-2 RIHT data are more than twice that of Wolsong 1. This is because these plants have also experienced DP degradation, another major contributor to RIHT increase. After the DP replacement, the rate of increase in RIHT at Pt. Lepreau and Gentilly-2 reduced to the Wolsong 1 level. This result indicates that the tube bundle fouling rate inferred for Wolsong 1 SGs is also valid for other CANDU SGs. The replaced DPs are not expected to degrade due to the use of corrosion resistant material at the leak paths. As a result, degradation following DP replacement can be attributed primarily to tube-bundle fouling.

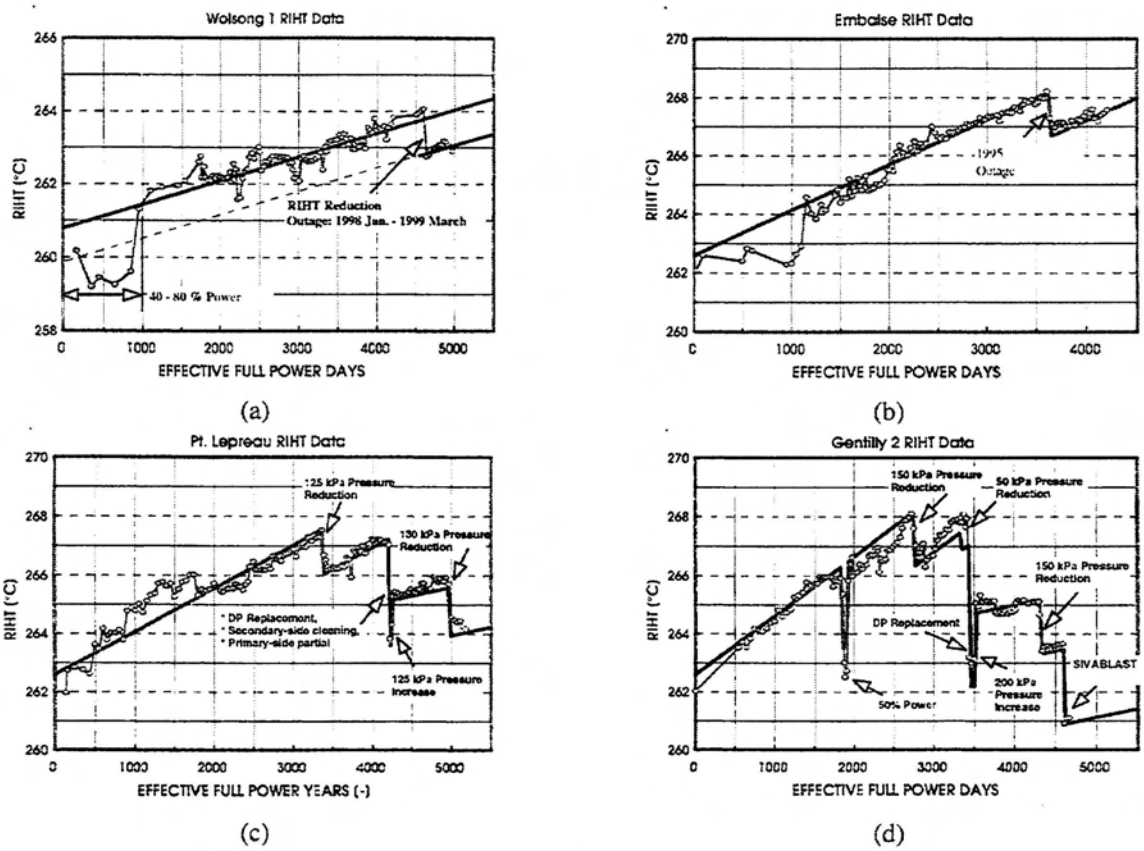

Figure 1: RIHT Trends for Various CANDU 6 Stations

Table 1: Assumed and Calculated Values Used in Estimating RIHT in Figure 1(a) to (d).

	Wolsong 1	Embalse	Pt. Lepreau	G2
TUBE BUNDLE FOULING				
Start-up fouling value[1], $m^2 \cdot °C/W$	$-12.0 \cdot 10^{-6}$	$-12.0 \cdot 10^{-6}$	$-12.0 \cdot 10^{-6}$	$-12.0 \cdot 10^{-6}$
% Mass flow rate decrease/year	0.50	0.50	0.50	0.50
Rate of Fouling per year, $m^2 \cdot °C/W$	$2.05 \cdot 10^{-6}$	$2.05 \cdot 10^{-6}$	$2.05 \cdot 10^{-6}$	$2.05 \cdot 10^{-6}$
DP REPLACEMENT EXPERIENCE				
%DP leakage at start-up[2] (0 EFPD)	-	3	3	3
% DP Leakage Increase per year	-	0.75	0.65	1.1
%DP Leakage at the time of DP replacement[2]	-	-	10.5	13.3
%DP leakage recovery at replacement	-	-	8.5	11.3
% Primary mass flow recovery after DP replacement	-	-	4	4
% DP leakage after DP replacement[2]	-	-	2	2
% DP Leakage Increase per year after DP replacement	-	-	0	0
VERIFICATION				
RIHT Recovery at DP replacement (prediction)			3.65	5.0
RIHT Recovery at DP replacement (actual)			3.6	5.1

[1] This value is adjusted to match the estimated start-up RIHT to the field data. It shifted the estimations down by ~1°C
[2] The thermal plate leakage effect is ignored. This assumption results in over-estimation of the DP leakage rate.

Tube-bundle fouling factors, after eliminating the DP leakage effect and taking into consideration the change in primary mass flow rate and change in SG secondary-side pressure, are obtained from the RIHT data as shown in Figure 2. As seen in this figure, the data from Wolsong 1, Pt. Lepreau and Gentilly-2 all fit to a straight line with a slope of $2.05\text{x}10^{-6}$ °C m^2/W per EFPY. Since the Embalse plant did not have any DP replacement or tube bundle cleaning experience, it was not possible to separate the combined effects of DP leakage and tube bundle fouling. However, because of the consistency of the Wolsong 1, Pt. Lepreau and Gentilly-2 data, the same tube bundle fouling factor is assumed to apply to Embalse as well. The figure shows the reduction in Gentilly-2 tube bundle fouling as a result of the 1999 mechanical cleaning. The amount of reduction is consistent with the claimed cleaning efficiency. On the other hand, the Pt. Lepreau tube bundle fouling shows almost no reduction in tube bundle fouling after a concurrent primary- and secondary-side cleaning. This may be because the thermally-beneficial primary-side cleaning effect was cancelled by the removal of secondary-side deposit, which was enhancing the heat transfer prior to the secondary-side cleaning. Another explanation is that a possible increase in thermal plate leakage after the secondary-side cleaning masked a small, and beneficial, effect of primary-side cleaning.

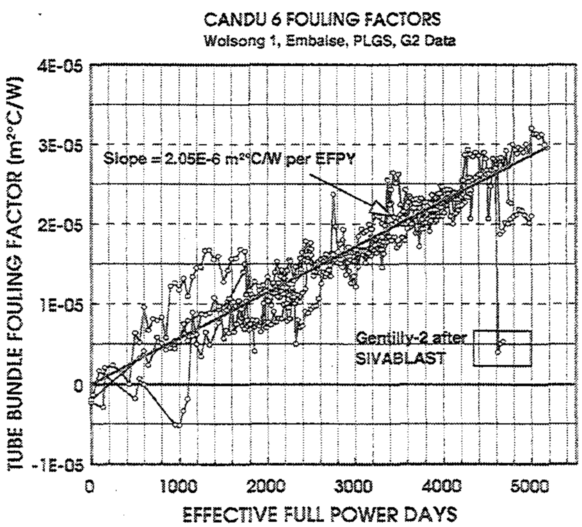

Figure 2: CANDU 6 Steam Generator Fouling Factors Inferred from the RIHT Data. The plot includes Wolsong 1, Embalse, PLGS and Gentilly-2 data

3.2 Separate Effects of Primary and Secondary Side Fouling

As a result of a mechanical mechanical cleaning on the primary side in 1999, at 12.6 EFPY, Gentilly-2 recovered ~2.7°C RIHT and 5% primary flow. Since a 5% increase in primary flow results in ~0.65°C increase in RIHT (see the 4th term of Equation 1), we can attribute a 2.7°C +0.65°C = ~3.3°C RIHT recovery to the removal of primary-side fouling deposits. Assuming a cleaning efficiency of 80% at Gentilly-2 (90% cleaning efficiency times 92% tubes cleaned), and using Equation 1, we can infer an equivalent fouling value of $27.5\text{x}10^{-6}$ °C m^2/W for the primary side before cleaning.

In section 4.1, it was concluded that the rate of tube bundle (primary+secondary) fouling for CANDU 6 plants is ~$2.05\text{x}10^{-6}$ C m^2/W per year. At 12.6 EFPY this value translates to a total fouling value of $25.8\text{x}10^{-6}$ Cm^2/W, which is less than the equivalent primary side fouling determined above. This implies that the contribution from secondary-side fouling was still negative with a value of $-1.7\text{x}10^{-6}$ Cm^2/W at the time of Gentilly-2 cleaning. Note that these inferred values are somewhat dependent on the assumed value of cleaning efficiency. A sensitivity analysis showed that a 10% error in cleaning efficiency would result in a 10% error in the estimated primary-side fouling value.

3.3 Inferred Divider Plate Leakage: Degradation Rate and Start-up Leakage

CANDU 6 field data indicate lower start-up RIHT for Wolsong 1, compared with other CANDU 6 stations. The lower Wolsong 1 RIHT at start-up was attributed to a lack of DP leakage. As a result of the continuously increasing RIHT, Gentilly-2 and Point Lepreau stations replaced all SG divider plates with newly-designed, welded floating DPs (Forest et al. 1995). After the DP replacement, both the Gentilly-2 and Point Lepreau plants have recorded a significant reduction in both RIHT and in the rate of RIHT rise, indicating that DP degradation was responsible for the major portion of the RIHT increase. This effect is evident when Wolsong 1 RIHT increase (0.2°C/year) as compared with the RIHT increase in other CANDU 6 stations (0.4°C/year).

It was mentioned in Section 4.1 that all CANDU 6 stations appear to be fouling at a similar rate: i.e., ~$2.05\text{x}10^{-6}$ °C m^2/W per year. Using this value, fitting Equation 1 to field data, and assuming a 0.5% per EFPY reduction in primary flow rate, the annual DP degradation rates of 0.75%, 0.65% and 1.1% were inferred for Embalse, PLGS and Gentilly-2, respectively. Note that the latter two values are in line with the DP replacement experience of Gentilly-2 and PLGS, but the Embalse leakage rate is obtained by assigning Embalse the same tube bundle fouling rate as Wolsong-1, PLGS and Gentilly-2. Differences in DP degradation rate of various plants might be because of varying manufacturing tolerances, bolt tightness or material properties. A 1.1%/EFPY and 0.65%/EFPY increase in leakage rates result in a total degradation of 10.4% (at 9.5 EFPY) and 7.7% leakage (at 11.5 EFPY) for Gentilly-2 and Pt. Lepreau, respectively. Equation 1, after taking into account the primary-flow recovery, indicates that the RIHT recovery for these plants would be 5.0°C and 3.65°C because of the DP replacement. These values are very close to those of field measurements (5.1°C and 3.6°C, for Gentilly-2 and PLGS, respectively).

It was noted earlier that the start-up temperature is ~1.5°C lower in Wolsong 1 (~261°C) than that of other CANDU 6 plants (~262.5°C). Using the last term of Equation 1 and attributing the start-up difference to DP leakage, we can conclude that the start-up DP leakage rate was ~3% of the primary flow. If thermal plate leakage is taken into account (estimated to be responsible for 0.5°C higher RIHT for the Wolsong 2, 3, 4 SGs), the DP leakage at the start-up can be estimated to be somewhat lower. Hence we can conclude that the average CANDU 6 DP leakage at start-up was 2 to 3% of primary-side flow rate.

Another observation regarding DP degradation is related to the degradation rate after DP replacement. The slope of the RIHT data after DP replacement is very close to that of the Wolsong 1 data. This indicates that further degradation of floating-type DPs has been negligible. This is not surprising because of the corrosion resistant material used in the leak-paths.

4. PREDICTING SG TUBE-BUNDLE FOULING FACTOR

The work presented in Section 3 identified a tube-bundle fouling factor rate that was common to the 4 CANDU 6 plants analysed. In this section we present a methodology to predict the tube-bundle fouling factor rate from estimates of tube-bundle deposit inventory, deposit distribution and measured heat-transfer properties of the deposit, and compare with the results of the previous section.

Factors that influence the effect of deposit on the rate of heat transfer include the deposit loading, the deposit distribution on the tube bundle, the mode of heat transfer, and the thermal resistance of the deposit per unit deposit mass or deposit thickness. For this analysis, the deposit loading on the tube-bundle was estimated from plant chemical cleaning data. From single-tube chemical cleanings performed at both Gentilly-2 and Point Lepreau Nuclear Generating Stations (NGS), a deposit loading of 0.185 kg magnetite/m^2 was estimated to build up on the inside surface of the tube bundle over a period of 10 EFPY of operation. The corresponding estimate for the outside surface of the tube bundle, based on results from the chemical cleaning of the secondary-side of the SGs at Point Lepreau (NGS) (Verma and Walsh, 1996) is 0.085 kg magnetite/m^2 over 10 EFPY of operation. In both cases, the deposit inventory was assumed to increase at a linear rate throughout the operating period of the plant.

The deposit distribution on the inside surface of the tube-bundle was derived from an analysis of eddy current inspection data. Details of the deposit distribution, i.e., light deposit on the hot-leg near the tube sheet, heavier deposit over the U-bend region and on the cold leg, and very heavy deposit in the region of the integral pre-heater, are consistent with predictions by a model of precipitation fouling of magnetite under primary heat transport system conditions (Burrill and Turner, 1994). In the absence of field data, the deposit distribution on the outside surface of the tube bundle was simulated using the SLUDGE[1] code.

The thermal resistance of tube-bundle deposit was determined by a series of measurements made under both single-phase forced-convective and flow-boiling conditions (Turner et al, 2000). For single-phase forced convection (applicable to the inside surface of the tube-bundle which is exposed to the primary coolant), the thermal resistance could be correlated with deposit loading using the following expression:

$$R_d = -7.3\text{x}10^{-6} + 1.4\text{x}10^{-5} m^{0.69} \ (m^2 . ^\circ C/W) \quad (2)$$

where m is deposit loading in kg/m^2.

[1] A three-dimensional computer code developed by AECL to predict secondary-side fouling in steam generators.

The first term in Equation (2) takes account of the effect of deposit roughness on the fluid film resistance, whilst the second term accounts for the resistance to heat transfer through the deposit by conduction. Under flow-boiling conditions (applicable to the outside surface of the tube-bundle), the thermal resistance of the tube-bundle deposit could be correlated with deposit loading using the following expression:

$$R_d = -20x10^{-6} + 3.1x10^{-4} m\ m^2.°C/W) \qquad (3)$$

The terms in Equation (3) have the same interpretation as the corresponding ones in Equation (2). A comparison of the two equations reveals that both the thermal resistance per unit deposit mass and the effect of deposit roughness on film resistance is greater under flow-boiling conditions than under single-phase forced convection.

Combining the expressions for deposit thermal resistance with the appropriate deposit distribution results in a fouling factor distribution for the tube-bundle. Fouling factor distributions for the inside (primary-side conditions) and outside (secondary-side conditions) of the tube bundle after 10 EFPY of operation are shown in Figures 3 and 4, respectively. The predicted fouling factor trends for a linear rate of build up of fouling deposit on the tube bundle are shown in Figure 5.

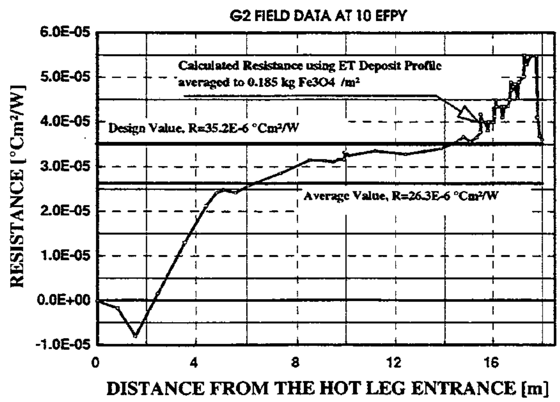

Figure 3: Predicted distribution of primary-side fouling resistance along the tube bundle based on measurements of deposit loading, distribution, and thermal resistance.

After an initial drop in fouling resistance during the first two years of operation, the predicted rate of loss of thermal performance from tube-bundle fouling at CANDU-6 plants averages $4.0x10^{-6} m^2.°C/W$ per EFPY. Of this total, 39% ($1.5x10^{-6} m^2.°C/W$ per EFPY) is attributed to secondary-side fouling and the remainder, $2.5x10^{-6} m^2.°C/W$ per EFPY, is attributed to fouling on the primary side. At 12.6 EFPY the predicted contributions from primary and secondary side fouling are $32x10^{-6}$ and $1.9x10^{-6}$ $m^2.°C/W$, respectively. The latter predictions compare well with the values inferred from the analysis of RIHT field data following the primary-side mechanical cleaning at Gentilly-2. The total tube-bundle fouling factor rate deduced from this analysis, however, is about twice that inferred from the analysis presented in Section 3.

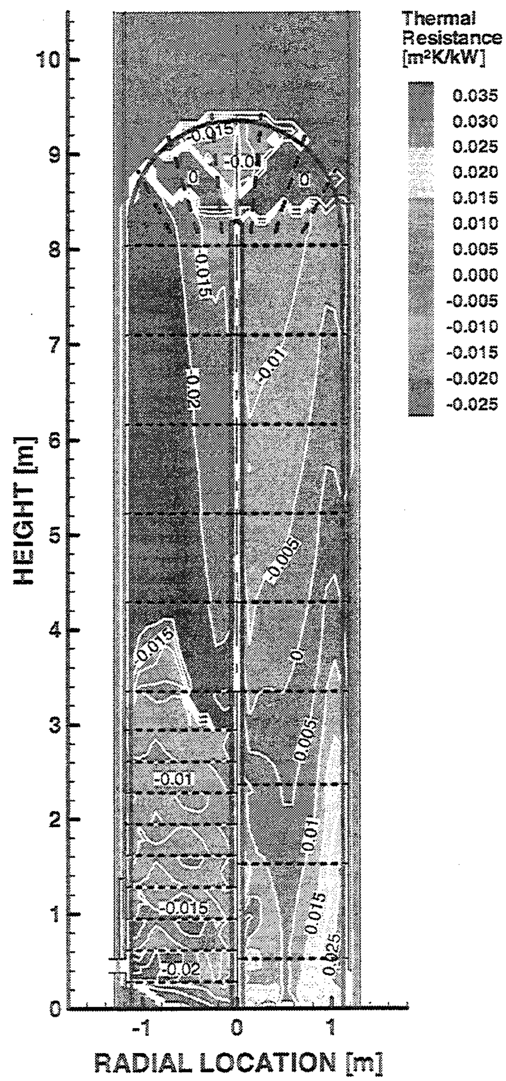

Figure 4: Predicted distribution of fouling resistance along the secondary-side of the tube bundle based on measurements of deposit loading and thermal resistance. Deposit distribution predicted by SLUDGE.

The fouling factor rate deduced for primary-side fouling alone agrees well with the total tube-bundle fouling rate inferred from the RIHT data. This suggests that the contribution from secondary-side fouling is being overestimated for CANDU 6 plants. The general features of the secondary-side fouling factor curve shown in Figure 5, i.e., a minimum value of -1.5×10^{-6} $m^2 \cdot °C/W$ at about 2 EFPY and a fouling factor rate thereafter of 1.5×10^{-6} $m^2 \cdot °C/W$ per EFPY of operation, are consistent with behaviour observed at many PWR plants, where performance degradation appears to be strongly affected by secondary side fouling (Lovett and Dow, 1991). Where secondary-side fouling has been an issue in PWR plants, however, the deposit inventory on the secondary side has been found to be at least five times greater than that used in the present analysis. This result suggests that the thermal resistance of secondary-side deposit is much smaller than that predicted by Equation (3).

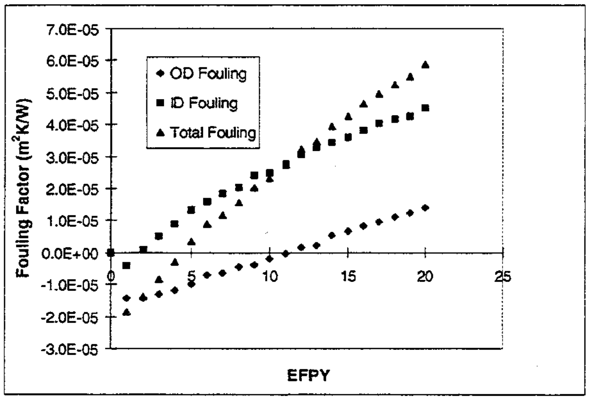

Figure 5: Predicted fouling factors for primary-side, secondary-side, and total tube-bundle fouling as a function of EFPY for a CANDU 6 SG. The prediction is based on the fouling factor distributions in Figures 3 and 4 and an assumed linear rate of deposit build-up with increasing EFPY.

5. CONCLUSIONS

The major mechanisms affecting the RIHT in CANDU systems appear to be primary-side tube fouling and DP leakage. From the analysis of RIHT data, the following values are obtained.

Tube-Bundle Fouling: All CANDU 6 plants appear to be fouling at a similar rate. The following are deduced by an analysis of the RIHT plant data:

- The station-averaged SG tube bundle fouling (primary+secondary) rate is $2.05*10^{-6}$ $m^2 °C/W$ per EFPY. This value is reasonably constant throughout the operating history of CANDU 6 SGs and accounts for 0.3°C/EFPY increase in the RIHT.
- Gentilly-2 SG primary-side cleaning indicates that the primary fouling rate has been $2.2*10^{-6}$ $m^2 °C/W$ per year.
- At about 13 EFPY, secondary fouling appears to be still negative, e.g. enhancing the heat transfer.

DP Leakage: CANDU 6 stations with segmented primary divider plates degraded faster than Wolsong 1 that has welded DPs. The following results were found:

- DP leakage rates increased by about 0.65% to 1.1% per year in stations with segmented divider plates. This accounts for 0.3 to 0.5°C/year increase in RIHT
- Segmented DPs leaked about 2 to 3% at the start-up.
- The replaced floating DPs appear to be leaking 2% of the primary fluid with no further degradation to date.

Other SG thermal degradation mechanisms, such as separator fouling and feedwater distribution box leakage do not appear to be making a significant contribution to performance degradation. Very few tubes have been plugged in CANDU 6 steam generators. Hence, this mechanism has also not contributed significantly to the rise of RIHT.

The fouling factor rate deduced for primary-side fouling from measurements of deposit inventory and thermal resistance is in good agreement with results from the RIHT analysis, whereas the rate deduced for secondary-side fouling appears to be overestimated. Comparison with performance degradation in PWR plants suggests that the discrepancy may arise from an over-estimate of the thermal resistance of secondary-side deposit

6. REFERENCES

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