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AECL-12118

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CONSÉQUENCES DE LA DÉGRADATION DES GV SUR LA TCER

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RÉSUMÉ

La dégradation des générateurs de vapeur (GV) a un effet considérable sur l'efficacité du circuit primaire des réacteurs CANDU[MD] ainsi que sur le rendement des centrales nucléaires en général. Cette dégradation entraîne l'augmentation de la température du collecteur d'entrée du réacteur (TCER), qui doit rester au-dessous d'une limite supérieure si l'on veut éviter l'assèchement du combustible. Il s'ensuit qu'une meilleure compréhension des mécanismes de dégradation des GV est nécessaire si l'on souhaite éviter des réductions de la puissance des centrales.

Ce rapport donne plusieurs mécanismes de dégradation des GV. Les conséquences de la dégradation sur la TCER sont quantifiées en utilisant les données d'exploitation et de modèles numériques. L'analyse révèle que les deux principaux facteurs de dégradation qui nuisent aux performances thermiques des GV CANDU sont les fuites au niveau des plaques de partition et l'encrassement des faisceaux tubulaires. Les résultats indiquent également que le taux d'encrassement des faisceaux dans les générateurs CANDU 6 est de $2{,}05 \times 10^{-6}$ $m^2 \cdot °C/W$ par année équivalente à pleine puissance (AEPP). La plus grande partie de cet encrassement a lieu du côté primaire.

Le présent rapport a été présenté lors de la 5^e Conférence internationale de la SNC sur l'entretien des installations CANDU, qui s'est déroulée du 19 au 21 novembre 2000 à Toronto, au Canada.

Technologie des échanges thermiques
Laboratoires de Chalk River
Chalk River (Ontario)

Mars 2001

AECL-12118

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ABSTRACT

Degradation of steam generators (SGs) has a significant effect on CANDU® heat transport system effectiveness and the overall efficiency of a nuclear power plant. SG 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, a better understanding of SG degradation mechanisms is needed to avoid plant deratings.

In this report, various SG degradation mechanisms are identified and their effect on the RIHT is quantified using field data and numerical modelling. Analysis shows that thermal performance of CANDU SGs has been mostly affected by a combination of divider plate leakage and tube-bundle fouling. The results also indicate that the rate of tube-bundle fouling in CANDU 6 steam generators is equal to 2.05×10^{-6} $m^2 \cdot °C/W$ per effective full power year (EFPY), of which the majority of this is attributed to primary-side fouling.

Presented at the 5th CNS International Conference on CANDU Maintenance, 2000 November 19 – 21, Toronto, Canada.

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AECL-12118

FIGURES

1. INTRODUCTION

Increased reactor inlet header temperatures (RIHT) can cause power derating 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 (DP) leakage (Brissette and Lafreniere, 1996) and tube-bundle fouling (Burrill and Turner, 1994) as contributing significantly 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 steam generator (SG) operating parameters.

Whereas SG degradation mechanisms affect the heat transfer efficiency, degradation mechanisms in other parts of the HTS, e.g., 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 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 SGs, the most significant effects are captured in the RIHT equation below:

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

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 m^2C/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. This equation also accounts for the effect of primary-coolant flow rate, which in turn takes account of the effects of pressure tube creep and increased roughness of HTS piping.

As shown in the following section, the RIHT equation is 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 FOR 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, Point Lepreau Generating Station (PLGS) and Gentilly-2 CANDU plants, respectively. 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 except Wolsong 1 show 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, the reduction of SG secondary-side pressure, replacement of SG primary-side divider plates, and cleaning the primary-side of the SG tubes, all had marked effects on the RIHT. The solid lines in Figure 1 show 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 provide a good fit of Equation (1) to the field data. The results are tabulated in Table 1. The effects of primary and secondary side fouling, start-up DP leakage rates, and 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 at 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 a reduced primary-side mass flow rate. Figure 1(a) shows the field data for Wolsong 1 RIHT. Fitting Equation (1) to field data with the assumption of an average 0.5% reduction in primary fluid flow rate per year results in a tube-bundle fouling rate of 2.05×10^{-6} °C m^2/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 over-predicts the start-up temperature for Wolsong 1. A likely cause for this discrepancy 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 of this under-prediction is the shifting of the RIHT prediction up by ~1°C in Figure 1(a) to 1(d). This shift, however, does not affect the slope of the RIHT lines and the conclusion regarding fouling rates remains valid.

The slopes of the Embalse, PLGS and Gentilly-2 RIHT data are more than twice that of Wolsong 1. This is attributed to the absence of DP degradation at the latter plant. Following DP replacement, the rate of increase in RIHT at PLGS and Gentilly-2 was equal to the rate at Wolsong 1. 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.

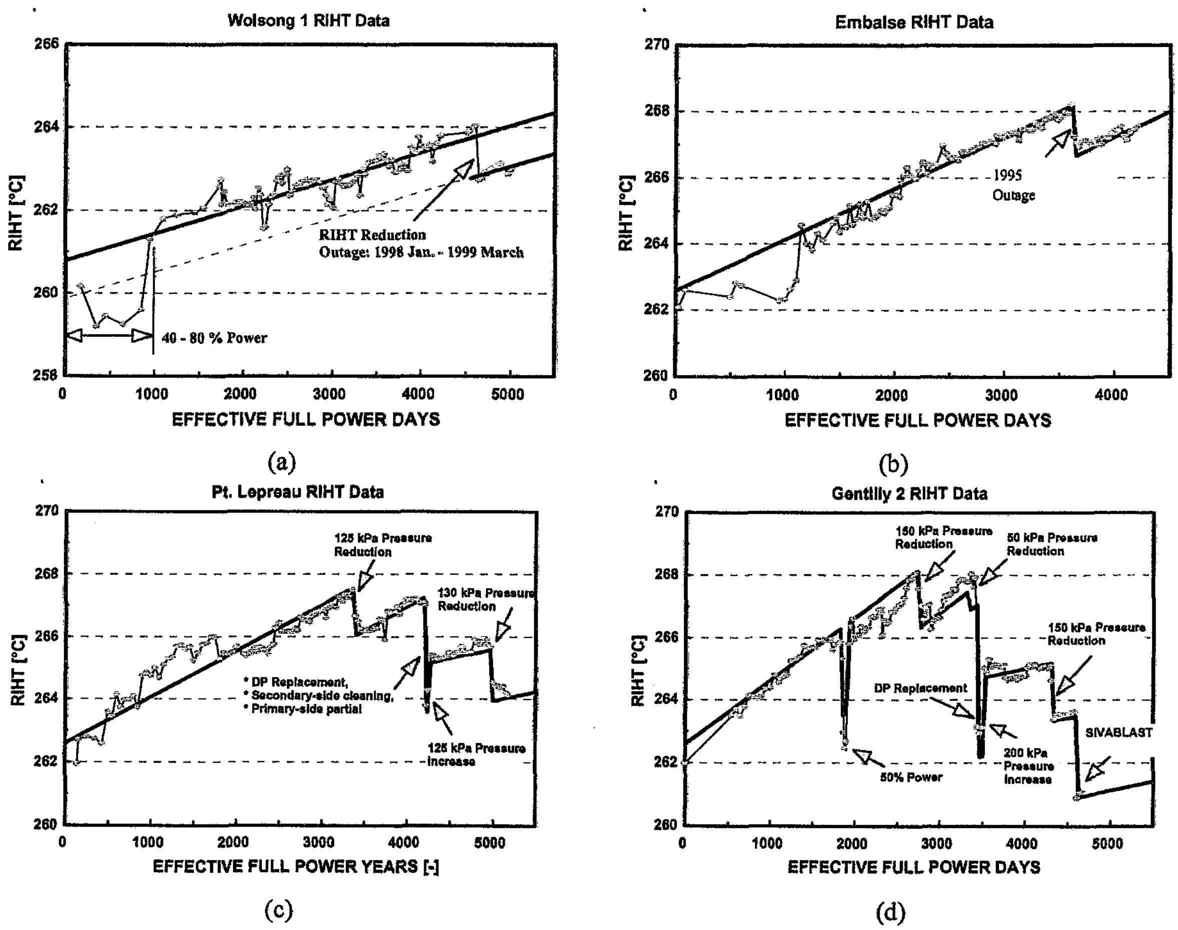

Figure 1 RIHT Trends for Various CANDU 6 Station.

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

	Wolsong 1	Embalse	PLGS	G2
TUBE BUNDLE FOULING				
Start-up fouling value[1], $m^2\cdot°C/W$	$-12.0\cdot10^{-6}$	$-12.0\cdot10^{-6}$	$-12.0\cdot10^{-6}$	$-12.0\cdot10^{-6}$
% Mass flow rate decrease/year	0.50	0.50	0.50	0.50
Rate of fouling per year, $m^2\cdot°C/W$	$2.05\cdot10^{-6}$	$2.05\cdot10^{-6}$	$2.05\cdot10^{-6}$	$2.05\cdot10^{-6}$
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. The estimates were shifted down by ~1°C
[2] The thermal plate leakage effect is ignored. This assumption results in over-estimation of the DP leakage rate.

After eliminating the DP leakage effect and taking into consideration the change in primary mass flow rate and SG secondary-side pressure, tube-bundle fouling factors can be deduced from the RIHT data, as shown in Figure 2. This figure shows that the data from Wolsong 1, PLGS and Gentilly-2 can all be fit to a straight line with a slope of 2.05×10^{-6} $m^2\cdot°C/W$ 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, PLGS 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. Conversely, the PLGS tube-bundle fouling shows almost no reduction in tube-bundle fouling after a concurrent primary- and secondary-side cleaning. This result suggests that the benefit of removing primary-side deposit was offset by the removal of the secondary-side deposit, which was still thin enough to be enhancing the rate of heat transfer. Another possibility is a possible increase in thermal plate leakage after the secondary-side cleaning masked a small, and beneficial, effect of primary-side cleaning.

3.2 Separate Effects of Primary and Secondary Side Fouling

As a result of a 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 (refer to the 4th term of Equation 1), one can attribute a 2.7°C +0.65°C = ~3.3°C RIHT recovery to the removal of primary-side fouling deposit. 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 27.5×10^{-6} $m^2\cdot°C/W$ for the primary side before cleaning.

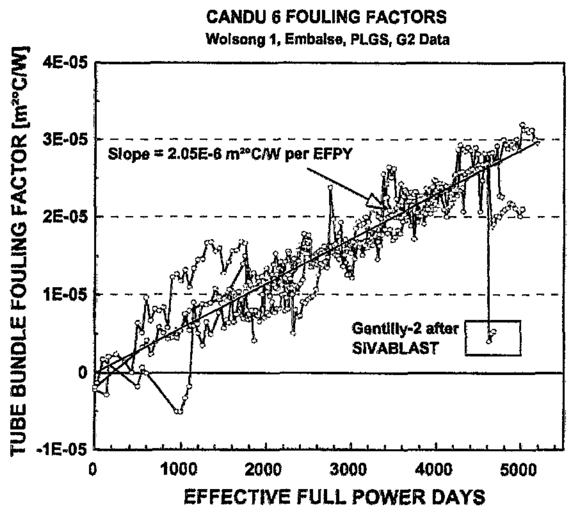

Figure 2 CANDU 6 steam generator fouling factors inferred from the RIHT data. The plot includes Wolsong 1, Embalse, PLGS and Gentilly-2 data.

In section 3.1, the rate of tube-bundle (primary+secondary) fouling for CANDU 6 plants was determined to be ~2.05×10^{-6} $m^2\cdot{}^\circ C/W$ per year. At 12.6 EFPY this value translates to a total fouling value of 25.8×10^{-6} $m^2\cdot{}^\circ C/W$, which is less than the equivalent primary side fouling determined from the RIHT reduction following mechanical cleaning at Gentilly-2. This result implies that the contribution from secondary-side fouling was still negative, with an approximate value of -1.7×10^{-6} $m^2\cdot{}^\circ C/W$ 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). Since 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 the Wolsong 1 RIHT increase (0.2°C/year) is compared with the RIHT increase in other CANDU 6 stations (0.4°C/year).

As shown in Section 4.1, all CANDU 6 stations appear to have a similar tube-bundle fouling rate of approximately 2.05×10^{-6} °C m^2/W per year. Using this value for the tube-bundle fouling rate and a 0.5% reduction per EFPY in primary flow rate, the best fit of Equation (1) to RIHT data from Embalse, PLGS and Gentilly-2 results in annual DP degradation rates of 0.75%, 0.65% and 1.1%, respectively. Note that the latter two values are in line with the DP replacement experience of Gentilly-2 and PLGS. Differences in DP degradation rates for various plants might be a result of varying manufacturing tolerances, bolt tightnesses or material properties. A 1.1%/EFPY and 0.65%/EFPY increase in leakage rates results in a total degradation of 10.4% (at 9.5 EFPY) and

7.7% leakage (at 11.5 EFPY) for Gentilly-2 and PLGS, respectively. Equation (1), after taking into account the primary-flow recovery, indicates that the RIHT recovery for these plants should be 5.0°C and 3.65°C following DP replacement. These predictions are very close to field measurements, i.e., 5.1°C and 3.6°C, for Gentilly-2 and PLGS, respectively, following DP replacement.

It was noted earlier that the start-up temperature is ~1.5°C lower in Wolsong 1 (~261°C) than for other CANDU 6 plants (~262.5°C). Using the last term of Equation (1) and attributing the start-up difference to DP leakage, one 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), DP leakage at start-up is estimated to be somewhat lower. Hence, we conclude that the average CANDU 6 DP leakage at start-up was 2 to 3% of the 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, due to the corrosion resistant material used in the leak-paths.

4. PREDICTING THE SG TUBE-BUNDLE FOULING FACTOR

The work presented in Section 3 identified a tube-bundle fouling factor rate that was common to the four CANDU 6 plants analysed. This section presents a methodology for predicting the tube-bundle fouling factor rate from estimates of tube-bundle deposit inventory, deposit distribution and measured heat-transfer properties of the deposit. This prediction methodology is then compared 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 PLGS 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 PLGS (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 are consistent with predictions made 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

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

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:

$$R_d = -7.3x10^{-6} + 1.4x10^{-4} m^{0.69} (m^2 \cdot °C/W) \tag{2}$$

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

The first term in Equation (2) takes into account the effect of deposit roughness on the fluid film resistance, whereas 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:

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

The terms in Equation (3) have the same interpretation as the corresponding terms 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.

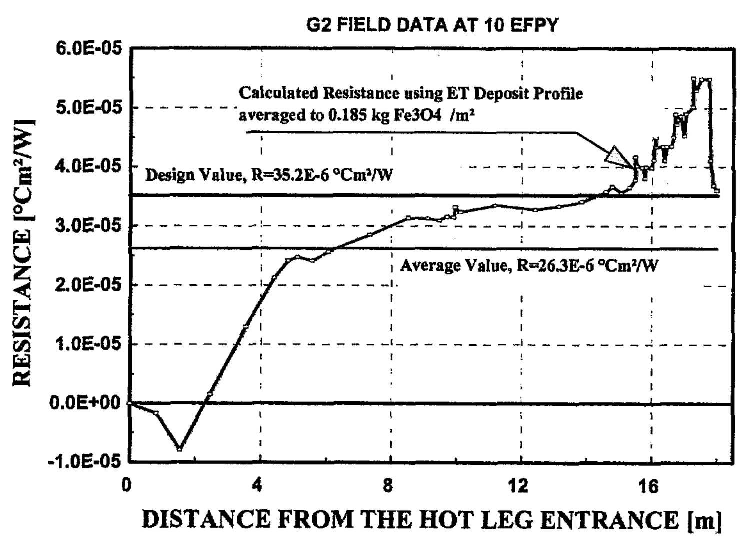

Figure 3 Predicted distribution of primary-side fouling resistance along the tube-bundle based on measurements of deposit loading, distribution, and thermal resistance.

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 4.0×10^{-6} $m^2\cdot°C/W$ per EFPY. Of this total, 39% (1.5×10^{-6} $m^2\cdot°C/W$ per EFPY) is attributed to secondary-side fouling and the remainder, 2.5×10^{-6} $m^2\cdot°C/W$ per EFPY, is attributed to fouling on the primary side. At 12.6 EFPY the predicted contributions from primary and secondary side fouling are 32×10^{-6} and 1.9×10^{-6} $m^2\cdot°C/W$, 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.

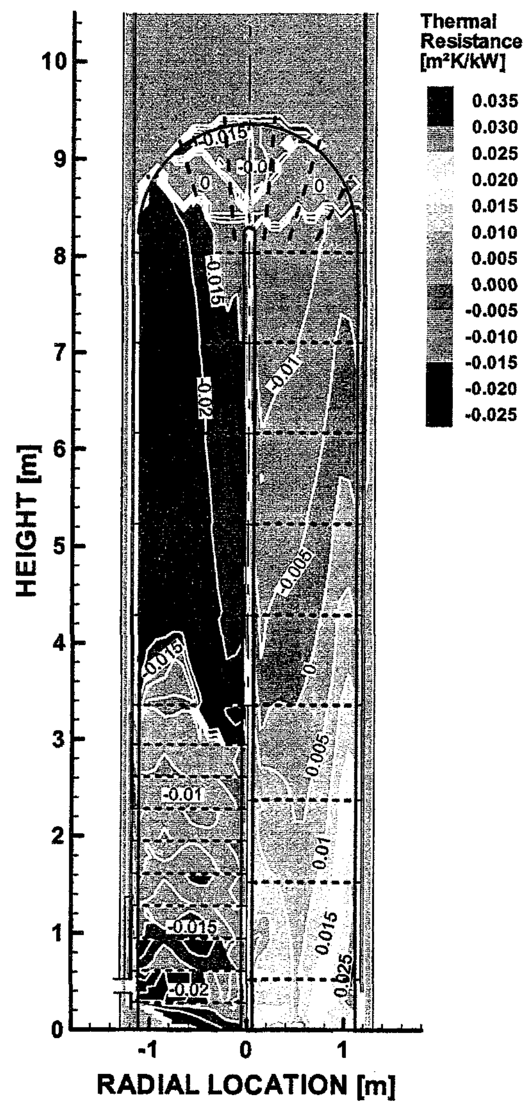

Figure 4 Predicted distribution of fouling resistance along the secondary-side of the tube-bundle based on measurements of deposit loading and thermal resistance. Deposit distribution predicted by SLUDGE.

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 agreement 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 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). In these 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 the secondary-side deposit is much smaller than that predicted by Equation (3).

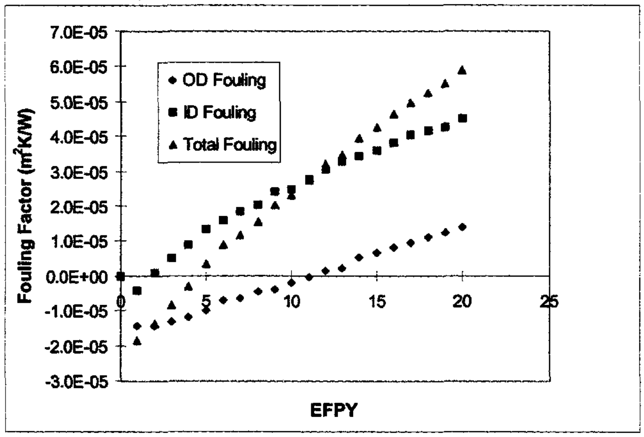

Figure 5 Predicted fouling factors for primary-side, secondary-side, and total tube-bundle fouling as a function of EFPY for a CANDU 6 SG. The prediction is based on the fouling factor distributions in Figures 3 and 4, and an assumed linear rate of deposit build-up with increasing EFPY.

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 $2.05*10^{-6}m^2\cdot°C/W$ °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 $2.2*10^{-6}$ $m^2\cdot°C/W$ per year.
- At about 13 EFPY, secondary fouling appears to be still negative, e.g. enhancing the rate of heat transfer.

DP Leakage: CANDU 6 stations with segmented primary divider plates degraded faster than Wolsong 1, which 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-estimation of the thermal resistance of the secondary-side deposit.

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AECL-12118

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