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THE DRYOUT-POWER IMPROVEMENT OF CANFLEX SEU BUNDLES IN CANDU REACTORS

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ABSTRACT

An assessment of the impact on dryout power has been completed for a string of CANFLEX bundles containing 0.9% slightly enriched uranium (SEU) fuel with either a 2-bundle-shift or 4-bundle-shift fuelling scheme. The effect of radial heat-flux distribution on dryout power for the CANFLEX bundles has been shown to be small (about a 0.5% difference) between natural uranium (NU) and 0.9% SEU fuel with the same axial heat-flux distribution (AFD). On the other hand, the variation in AFD for the SEU fuel has a large impact on the dryout power, compared to the NU fuel. Based on the calculated results, the introduction of CANFLEX 0.9% SEU fuel bundles and a 2-bundle-shift fuelling scheme in a CANDU fuel channel would lead to a dryout-power enhancement of 8% to 27% over the complete range of pressure-tube creep (having the downstream-skewed profile), compared to the current 37-element NU fuel bundles using the 8-bundle-shift fuelling scheme. The enhancement is slightly higher (10% to 29%) for a 4-bundle-shift fuelling scheme.

1. INTRODUCTION

The CANFLEX® fuel-bundle design allows the use of various levels of enrichment in a CANDU® reactor. AECL is currently assessing all aspects associated with the use of slightly enriched uranium (SEU) of enrichment around 0.9% in the CANFLEX bundle. Recycled uranium (RU) from the reprocessing of spent pressurized-water reactor fuel is a potential source of enrichment. The use of SEU fuel would lead to a change in the radial heat-flux distribution (RFD) from the natural uranium (NU) fuel bundle, while the fuelling scheme would result in a change in the axial heat-flux distribution (AFD) from that currently encountered in CANDU reactors. Both changes would have a beneficial impact on the critical channel power (CCP), and hence raise the reactor operating power. This study examined the potential improvement in dryout power for a CANFLEX bundle string using 0.9% SEU fuel with either a 2-bundle-shift or a 4-bundle-shift fuelling scheme.

The current carrier of NU fuel in CANDU reactors is the 37-element bundle. It has a center-depressed RFD that does not vary significantly over the resident period inside the reactor. Previous studies have shown that the variation in RFD due to burnup has little impact on critical beat flux (CHF) (or dryout power and CCP) for NU fuel, but that the variation can be significant for SEU fuel (Yin et al. 1991). The fuelling scheme changes the AFD of the bundle string inside the fuel channel; this in turn has a strong impact on the dryout power (and CCP). Groeneveld et al. (1992) showed that the dryout power of a bundle string with a non-uniform AFD is generally higher if its peak heat-flux point is located at the upstream end rather than the downstream end in a channel. Leung et al. (1998) recommended using the boiling-length-average (BLA) approach to account for the AFD effect.

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2. EVALUATION OF FUEL-STRING DRYOUT POWER

The fuel-string dryout power is calculated by subdividing the channel into nodes, and comparing the BLA heat fluxes against the predicted CHF values based on the correlation at each node until a tangent point is reached. As suggested by Leung et al. (1998), the BLA heat flux is calculated by averaging the power introduced to the coolant over the axial distance from the boiling initiation point to the location of interest. The CHF at each node is expressed as

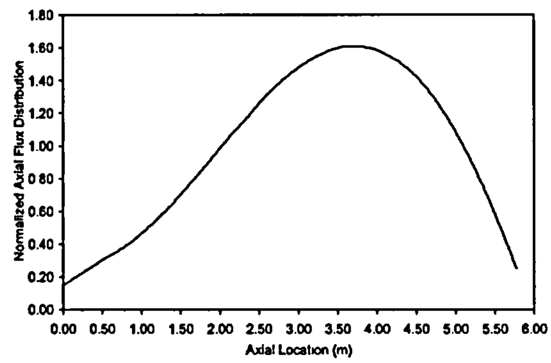

Figure 1: Axial Heat-Flux Profile of the Full-Scale Bundle Simulators.

$$CHF_{BLA} = CHF_{ref.BLA}\, K_{rfd} \qquad (1)$$

where $CHF_{ref.BLA}$ is the reference CHF value and K_{rfd} is the modification factor for the RFD effect. The reference CHF correlations were derived from experimental data obtained with full-scale 6-m simulators of 12 fully aligned 37-element and CANFLEX bundles equipped with appendages and end-plates. Each bundle string was electrically heated; each had a non-uniform AFD, corresponding to the downstream-skewed cosine profile, and RFD, corresponding to NU fuel of mid-burnup level. Figure 1 shows the AFD of the simulators in the full-scale bundle tests, and Figure 2 shows the RFD of the simulators in the 37-element and CANFLEX bundle tests. Both the AFD and RFD have been normalised to a bundle average surface heat flux of 1 (the average surface heat flux for a CANFLEX bundle is 5% lower than a 37-element bundle for the same bundle power). The tests covered uniform and non-uniform variations in pressure-tube diameter to simulate various levels of diametral creep. Figure 3 illustrates the representative variations in pressure-tube diameter for various channels in a CANDU 6 reactor.

The modification factor, K_{rfd}, for the 37-element bundles was proposed by Yin et al. (1991). It is expressed as:

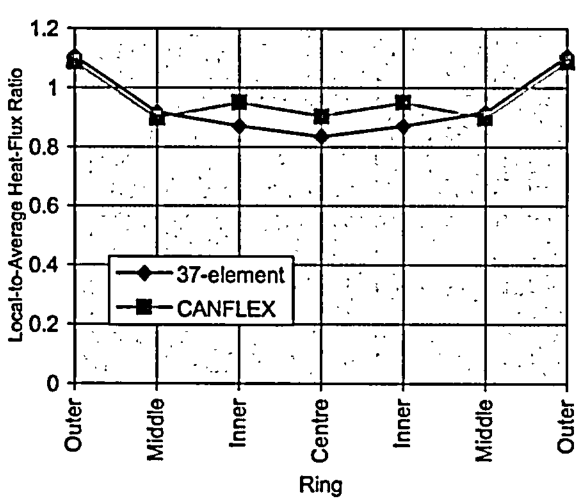

Figure 3: Radial Heat-Flux Profiles of the Full-Scale Bundle Simulators.

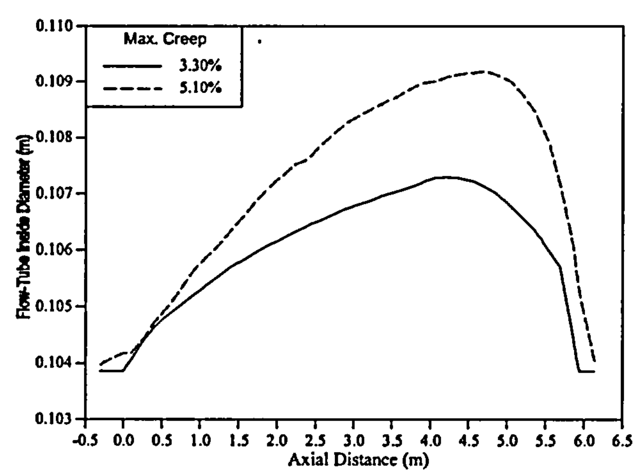

Figure 2: Axial Variations in Pressure-Tube Diameter in the Full-Scale Bundle Tests.

$$K_{rfd} = \frac{K_{rfdo}}{K_{rfdo,NU}} \quad (2)$$

where

$$K_{rfdo} = \frac{CHF\ for\ Flux\ Shape\ of\ Interest}{CHF\ for\ Optimum\ Flux\ Shape} \quad (3)$$

Yin et al. (1991) introduced a bundle-imbalance factor, Z, which represents the maximum deviation in the local-to-bundle-average heat-flux ratio of the bundle of interest from an optimum bundle[1]. The factor is defined as

$$Z = \max(R_i / R_{i,o}) \quad (4)$$

where R_i and $R_{i,o}$ are the ratios of local heat-flux to bundle-average heat-flux for Ring i of the RFD of interest and of the optimum RFD, respectively. Based on the same methodology, a bundle-imbalance factor has been derived for the CANFLEX bundle. Analysis of experimental CHF data obtained with Freon-cooled CANFLEX bundles of various RFDs has provided the optimum RFD as 0.9892/1.080/0.8884/0.8884 (outer-ring/middle-ring/inner-ring/centre-rod). Yin et al. (1991) stated that the fractional reduction in CHF from the optimum value (i.e., 1-K_{rfdo}) is approximately the same as the fractional deviation from the optimum RFD (i.e., Z-1). Hence, the K_{rfdo} for the bundle of interest is expressed as:

$$K_{rfdo} = 2 - Z \quad (5)$$

The value of $K_{rfdo,NU}$ is 0.9174, based on the experimental CHF data for CANFLEX bundles of various RFDs.

3. DRYOUT POWER FOR THE CANFLEX SEU FUEL-BUNDLE STRING

The current assessment focuses on the dryout power for the 0.9% SEU fuel bundle at conditions of interest (i.e., pressures of 9 and 11 MPa, mass-flow rates of 17-21 kg/s and an inlet-fluid temperature of 265°C). The dryout power for the CANFLEX SEU fuel-bundle string is calculated by accounting for the variations in RFD and AFD, using the methodologies described in Section 2.

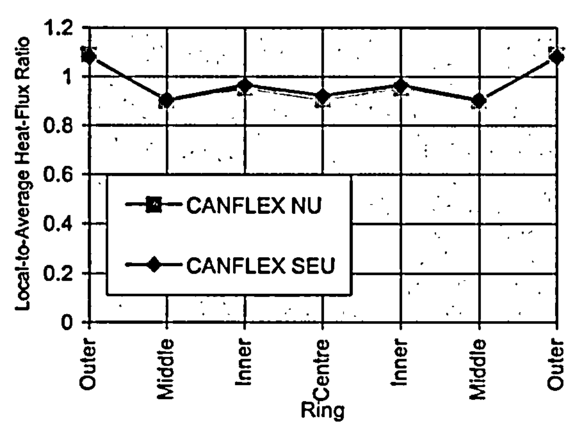

Figure 4: Radial Heat-Flux Profiles for SEU Fuel Bundles.

3.1 Impact of RFD Variation

The element power in each ring was calculated using the WIMS computer code for the

[1] An optimum bundle gives the highest dryout power, with dryout occurring on all rings simultaneously; i.e., Z=1.

CANFLEX bundles of NU and 0.9% SEU fuel. Figure 4 shows the local-to-average heat-flux ratio for elements in each ring based on the calculated element power at mid-burnup (corresponding roughly to the axial location of dryout). In general, the RFDs are similar for NU and 0.9% SEU fuel bundles at mid-burnup. The local heat-flux ratio for elements at the outer ring is slightly lower for the SEU than for the NU fuel bundle.

The average dryout-power enhancements for the CANFLEX 0.9% SEU fuel-bundle string over the CANFLEX NU fuel-bundle string were calculated for the same NU AFD and inlet-flow conditions in various crept[2] channels. The dryout power for the fuel-bundle string with the 0.9% SEU RFD is about 0.6% higher than that with the NU RFD, and is insensitive to pressure-tube creep.

3.2 Impact of AFD Variation

The assessment examines two different fuelling schemes (4-bundle shift and 2-bundle shift), and compares the dryout power for those schemes against the dryout powers for the typical 8-bundle-shift fuelling scheme currently used in the CANDU 6 reactor. Figure 5 shows the variation in AFD for various fuelling schemes. Table 1 lists the average dryout-power enhancements for various fuelling schemes of SEU fuel bundles, compared to the 8-bundle-shift fuelling scheme for NU fuel bundles. Overall, an enhancement of dryout power has been shown with a change in fuelling scheme, and it is slightly higher for the 4-bundle shift than the 2-bundle shift. In addition, the enhancement varies with channel creep[3] and system pressure (see Figure 6). The effect of mass flux on the enhancement is relatively minor.

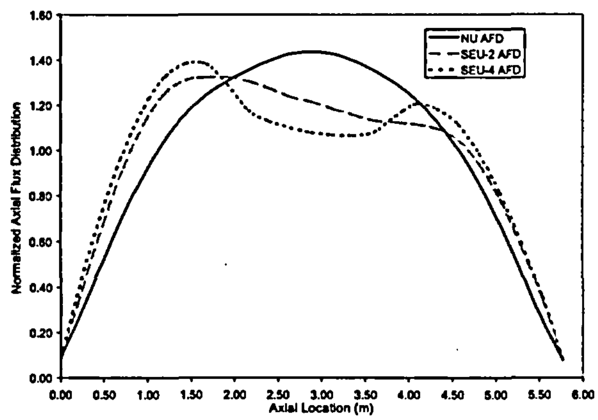

Figure 5: Axial Heat-Flux Profiles for the CANFLEX Bundles.

Table 1: Dryout-Power Enhancement for Various Fuelling Schemes of CANFLEX 0.9% SEU Fuel Bundles over the 8-Bundle-Shift Fuelling Scheme of CANFLEX NU Fuel Bundles

Maximum Creep (%)	Dryout-Power Enhancement over the 8-Bundle-Shift CANFLEX NU Fuel Bundles (%)	
	CANFLEX 0.9% SEU Fuel Bundles (2-Bundle Shift)	CANFLEX 0.9% SEU Fuel Bundles (4-Bundle Shift)
0	6.21	7.60
3.3	10.77	13.24
5.1	11.32	13.56

[2] In all cases, it was assumed that the effect of pressure-tube creep on RFD is small.
[3] In assessing the effect of AFD on dryout power, it was assumed that the effect of pressure-tube creep on AFD was small.

4. DRYOUT-POWER ENHANCEMENT OVER THE 37-ELEMENT NU FUEL-BUNDLE STRING

The dryout-power values for the CANFLEX 0.9% SEU fuel bundle with various fuelling schemes have been compared against those for the 37-element NU fuel bundle with the 8-bundle-shift fuelling scheme (the fuel carrier in the current CANDU 6 reactor). This comparison includes the geometry effect (between 37-element and CANFLEX fuel bundles), in addition to the RFD and AFD effects. The dryout power for the bundle string is calculated using the methodology described in Section 2. Table 2 lists the average dryout-power enhancements over the 37-element NU bundle string for various fuelling schemes with the CANFLEX NU and 0.9% SEU fuel bundles. Depending on the degree of channel creep, the CANFLEX NU bundle enhances the dryout power from 2.2 to 15.4%, compared to the 37-element NU fuel bundle. The CANFLEX 0.9% SEU fuel bundles results in an even larger average enhancement over the current assessed conditions: 8.4 to 26.8% for the 2-bundle-shift and 9.8 to 29% for the 4-bundle-shift fuelling scheme. Similar to the results shown in the comparison of various CANFLEX bundles (Figure 6), the level of enhancement depends strongly on the channel creep and system pressure but not on mass flux, as illustrated in Figure 7. The corresponding range of enhancement in CCP must be calculated with an analytical tool for regional overpower protection (ROP) (such as the NUCIRC code). It is estimated to be about 4 to 13% for the 2-bundle-shift fuelling scheme over the pressure-tube creep range from 0 to 5.1%.

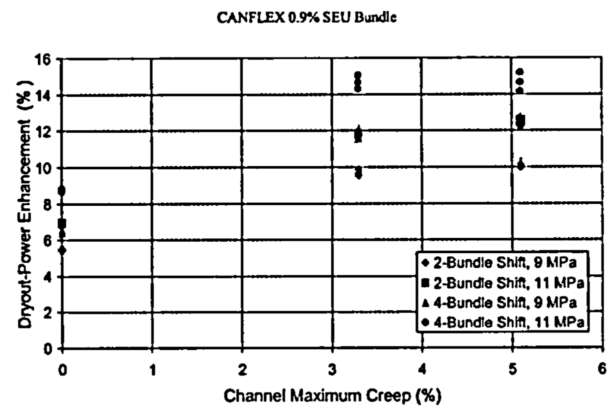

Figure 6: Dryout-Power Enhancement of the CANFLEX 0.9% SEU Fuel Bundles over the CANFLEX NU Fuel Bundles.

Table 2: Dryout-Power Enhancement for Various Fuelling Schemes of CANFLEX NU and 0.9% SEU Fuel Bundles over the 8-Bundle-Shift Fuelling Scheme of 37-Element NU Fuel Bundles

Maximum Creep (%)	Dryout-Power Enhancement over the 8-Bundle-Shift 37-Element NU Fuel Bundles (%)		
	CANFLEX NU Fuel Bundles (8-Bundle Shift)	CANFLEX 0.9% SEU Fuel Bundles (2-Bundle Shift)	CANFLEX 0.9% SEU Fuel Bundles (4-Bundle Shift)
0	2.23	8.43	9.83
3.3	7.99	18.76	21.23
5.1	15.43	26.75	28.99

5. CONCLUSIONS AND FINAL REMARKS

- The effect of AFD and RFD on dryout power for a string of CANFLEX 0.9% SEU fuel bundles has been assessed. The assessment is based primarily on the full-scale bundle data for CANFLEX NU fuel bundles of the mid-burnup RFD, and includes a modification factor to account for the RFD effect on CHF. The AFD effect is accounted for using the BLA heat-flux approach.
- The variation of RFD from NU to 0.9% SEU fuel results in an increase in dryout power of about 0.6% for the mid-burnup level.

- The variation of AFD from various fuelling schemes has a strong impact on dryout power. Depending on the degree of channel creep and system pressure, the dryout-power enhancement varies from 6.2 to 11.3% for the 2-bundle-shift and 7.6 to 13.6% for the 4-bundle-shift fuelling scheme with the CANFLEX 0.9% SEU fuel bundles as compared to CANFLEX NU fuel bundles.
- Use of the CANFLEX 0.9% SEU fuel bundles with a 2-bundle-shift fuelling scheme would increase dryout power from 8.4 to 26.8% over the range of pressures and channel creeps of interest, compared to the 37-element NU fuel bundles with an 8-bundle-shift fuelling scheme (a slightly larger improvement is shown for the 4-bundle-shift fuelling scheme). The equivalent improvement in CCP must be determined using an ROP analysis code (such as the NUCIRC code). It is estimated to be about 4 to 13%.
- The predictions are based on extensions of various correlations to cases beyond their database (e.g., AFD and RFD). Experimental data are needed to verify and confirm the estimated enhancements.

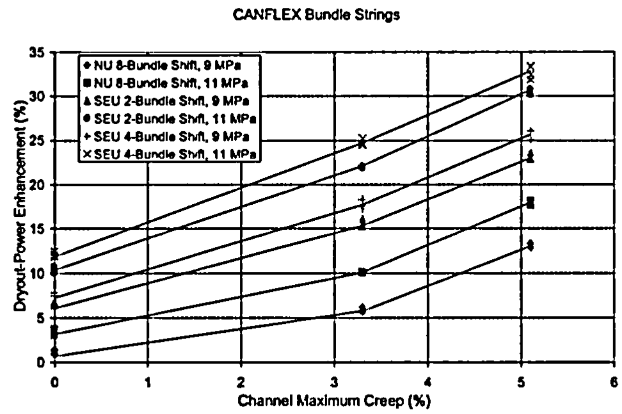

Figure 7: Dryout-Power Enhancement of the CANFLEX 0.9% SEU Fuel-Bundle String over the 37-Element NU Fuel-Bundle String.

6. REFERENCES

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