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# A PREDICTION METHOD FOR THE EFFECT OF RADIAL HEAT-FLUX DISTRIBUTION ON CRITICAL HEAT FLUX IN CANFLEX BUNDLES

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## Abstract

A generalized prediction method has been derived for predicting the effect of radial heat-flux distribution (RFD) on critical heat flux (CHF) in CANFLEX bundles. The ratio of CHF for the RFD of interest to that for the optimum RFD of the CANFLEX fuel bundle is expressed in terms of a bundle imbalance factor. The optimum RFD for the CANFLEX fuel bundle has been established with available CHF data of various RFDs. The variation of CHF ratios with bundle-imbalance factor has been verified against experimental values for 37-element and CANFLEX bundles. An assessment of the prediction method has been performed using CHF data obtained with a CANFLEX bundle simulating the 1.6% slightly enriched uranium (SEU) fuel RFD. Good agreement of predicted and experimental CHF values has been observed. On average, the experimental CHF ratio is 0.94, as compared to the predicted CHF ratio of 0.93 between the 1.6% SEU fuel RFD and natural uranium fuel RFD.

## 1. INTRODUCTION

The CANFLEX® (CANDU Flexible) fuel bundle design allows for the use of various levels of fuel enrichment in a CANDU® reactor. AECL is currently assessing all aspects associated with the use of slightly enriched uranium (SEU) in the CANFLEX bundle. For enrichment levels around 0.9%, recycled uranium (RU) from the reprocessing of spent pressurized water reactor fuel is a potential source of enrichment. The use of SEU (or RU) fuel would lead to a change in radial heat-flux distribution (RFD) from the natural uranium (NU) fuel bundle and a significant variation in RFD for various burn-up levels. Therefore, the impact of variation of RFD on dryout power must be quantified for regional overpower protection (ROP) and safety analyses of the reactor.

An accurate prediction of critical heat flux (CHF) is required in the evaluation of fuel-string dryout power. CHF is predicted using methods derived from full-scale bundle test data that correspond to a specific RFD. Yin et al. (1991) observed a minor effect of RFD variation due to burnup on CHF for NU fuel, but a strong effect for SEU fuel in 37-element bundles. Leung et al. (2000) assessed the dryout power variation for the CANFLEX 0.9% SEU fuel bundle and

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applied a generalized prediction method for the RFD effect on CHF. The objective of this study is to (i) present the generalized prediction method and (ii) assess the result of the method against experimental data obtained with a CANFLEX bundle string having a RFD corresponding to the 1.6% SEU fuel.

## 2. MODIFICATION FACTOR FOR RFD EFFECT

Yin et al. (1991) examined the CHF variation for 37-element bundles of different RFDs, and introduced a bundle-imbalance factor, Z, to account for the RFD effect. The bundle-imbalance factor represents the maximum deviation in the local-to-bundle-average heat-flux ratio of the bundle of interest from an optimum bundle[1]. It is defined as

$$Z = \max(R_i / R_{i,o}) \tag{1}$$

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. Two approaches were applied in predicting the RFD effect for 37-element bundles. The first approach was based on the experimental trend of CHF ratios between non-reference and reference NU fuel RFDs, which corresponded to the profile tested in the full-scale bundle experiments. This approach relied on data covering a relatively wide range of bundle-imbalance factors (from 1 to 1.3) for the 37-element bundle. Within this range, the CHF ratios between non-reference and reference NU fuel RFDs follow a linear variation with bundle-imbalance factors. The second approach was based on the general trend of CHF ratios between bundles of various RFDs and the optimum bundle RFD. The optimum profile was determined with the corresponding bundle type. Therefore, the difference in bundle design has been incorporated into the methodology, and the presented RFD effect becomes geometry independent.

The experimental database of the RFD effect for CANFLEX bundles was small at the time when the current prediction method was developed. It covered a range of bundle imbalance factor from 1.1 to 1.15, and hence was insufficient to apply the first approach, as described above, to derive a RFD modification factor. Therefore, the second approach was employed and utilized the available data for both 37-element and CANFLEX bundles.

Yin et al. (1991) expressed the CHF for the RFD of interest as

$$CHF_{rfd} = K_{rfd}\, CHF_{NU} \tag{2}$$

where $K_{rfd}$ is the modification factor for the RFD effect with respect to the NU fuel and $CHF_{NU}$ is the CHF for the 37-element bundle with NU fuel (as simulated in the full-scale bundle tests). Based on the first approach, the RFD modification factor, $K_{rfd}$, was correlated using available data obtained with bundle string of various RFDs. In the second approach, the RFD modification factor is written as

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

$$K_{rfd} = \frac{CHF_{rfd}}{CHF_{NU}} = \frac{CHF_{rfd}/CHF_{Optimum}}{CHF_{NU}/CHF_{Optimum}} = \frac{K_{rfdo}}{K_{rfdo,\,NU}} \tag{3}$$

where $K_{rfdo}$ is the RFD modification factor with respect to the optimum RFD, and $K_{rfdo,\,NU}$ is the corresponding optimum-RFD-based factor for the NU fuel. Yin et al. (1991) introduced a generalized relation between the optimum-RFD-based modification factor and the bundle-imbalance factor. The relation is written as

$$1 - K_{rfdo} = Z - 1 \tag{4}$$

Figure 1 presents the variation of "1-$K_{rfdo}$" with "Z-1" for 37-element and CANFLEX bundles. Each point represents the average value of $K_{rfdo}$ for all test conditions in the experiment, and the line represents the generalized relationship as presented in Equation (4). Overall, the variation of "1-$K_{rfdo}$" follows the general trend and increases with bundle-imbalance factor (or "Z-1"). The experimental values at small bundle-imbalance factors appear to be slightly lower than the generalized relationship, while those at large bundle-imbalance factors are higher. This deviation is probably due to the uncertainty among data (particularly those corresponding to the optimum RFD), and the dominant effect of local element heat flux at high bundle-imbalance factors.

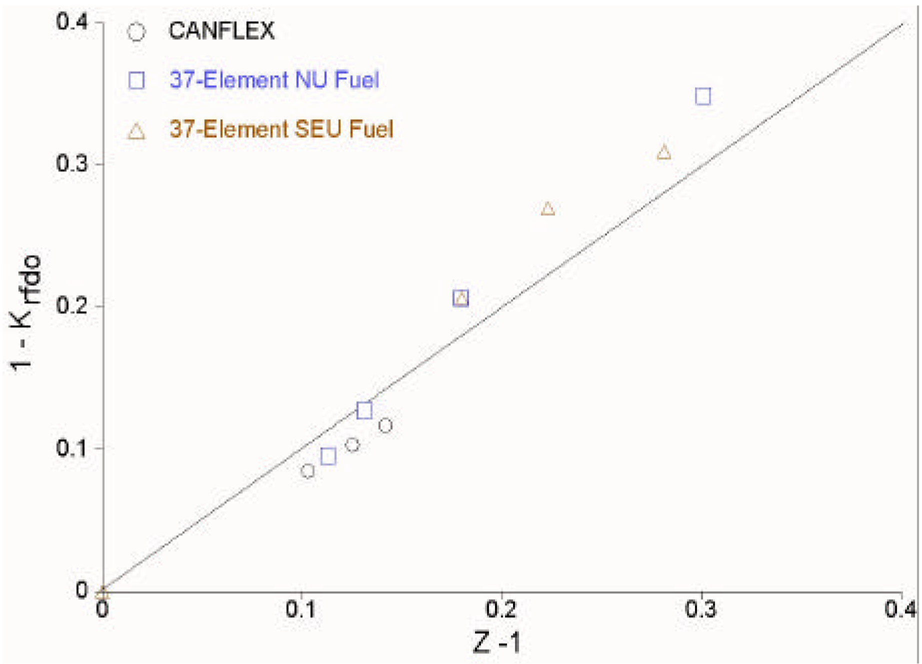


Figure 1. Variation of "1-$K_{rfdo}$" with "Z-1" for 37-element and CANFLEX bundles

The approach of Yin et al. (1991) accounts for the global RFD effect, rather than the local element heat-flux variation, in the bundle and is mainly applicable for low bundle-imbalance factors. For example: the element corresponding to the initial dryout occurrence is one of the elements having low local heat-flux ratio in the 37-element bundle. With increasing bundle-imbalance factor, the local heat-flux effect becomes dominant and the variation of "1-$K_{rfdo}$" with "Z-1" is anticipated to deviate from the linear trend. This limiting trend is exhibited in Equation (4), which is valid only for bundle-imbalance factors up to 2 and provides erroneous predictions beyond that value. The variation of "1-$K_{rfdo}$" with "Z-1" is relatively linear within the range of bundle-imbalance factors. This implies that the global effect remains dominant and Equation (4) is therefore valid over this range.

The optimum RFD for the CANFLEX bundle has not been determined experimentally, and was established through analyses of available CHF data for other RFDs. Similarly, the RFD modification factor for the NU RFD with reference to the CHF for the optimum RFD, $K_{rfdo,NU}$, is evaluated with the calculated optimum RFD and the NU CHF data. It corresponds to a value of 0.9174.

## 3. ASSESSMENT OF RFD MODIFICATION FACTOR

An experiment has recently been completed using a uniformly heated CANFLEX bundle simulating the RFD of 1.6% SEU fuel. The test section simulated a string of 12 aligned CANFLEX bundles, including bundle junctions and appendages (i.e., spacers, bearing pads, and buttons). Figure 2 shows the cross-sectional view of a CANFLEX fuel bundle.

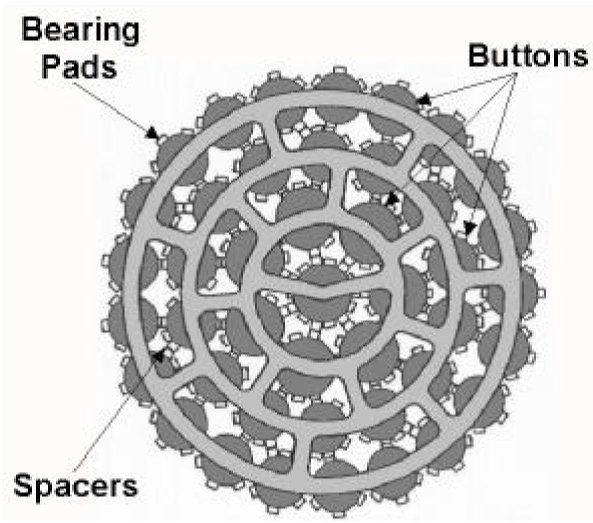


Figure 2. Cross-Sectional View of a CANFLEX Fuel Bundle

The bundle consisted of 43 elements with two different outer diameters: the large-diameter elements were used for the centre rod and inner rings, and the small-diameter elements were used for the middle and outer rings. Spring-loaded thermocouples, mounted on sliding carriers, were installed inside all the elements of the three downstream bundles. Insulated spacer pads were spot-welded to the tubes, and bearing pads were spot-welded to the tubes in the outer ring. The insulated pads isolated the elements from different rings, thus allowing different powers to be applied to elements in each ring. Two radial power profiles (RPPs), representing the ratio of element to total power at each ring, were simulated in the current experiment; one corresponded to the NU fuel and the other to the 1.6% SEU fuel. Figure 3 compares the RPPs and RFDs for the NU and 1.6% SEU fuel bundles. The bundle simulator was installed in the vertical test station of the MR-3 Freon loop at Chalk River Laboratories. Figure 4 shows the schematic diagram of the MR-3 loop.

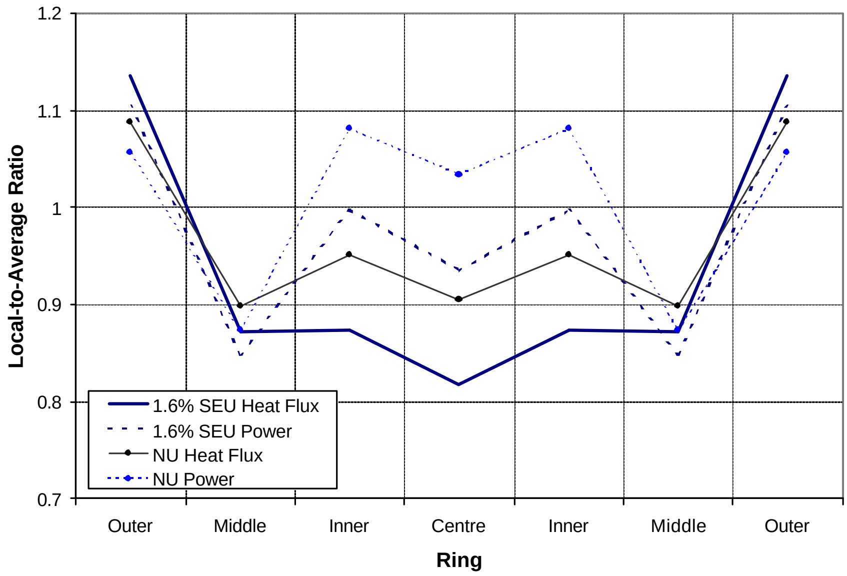


Figure 3. Comparisons of RPPs and RFDs between NU and 1.6% SEU Fuel Bundles

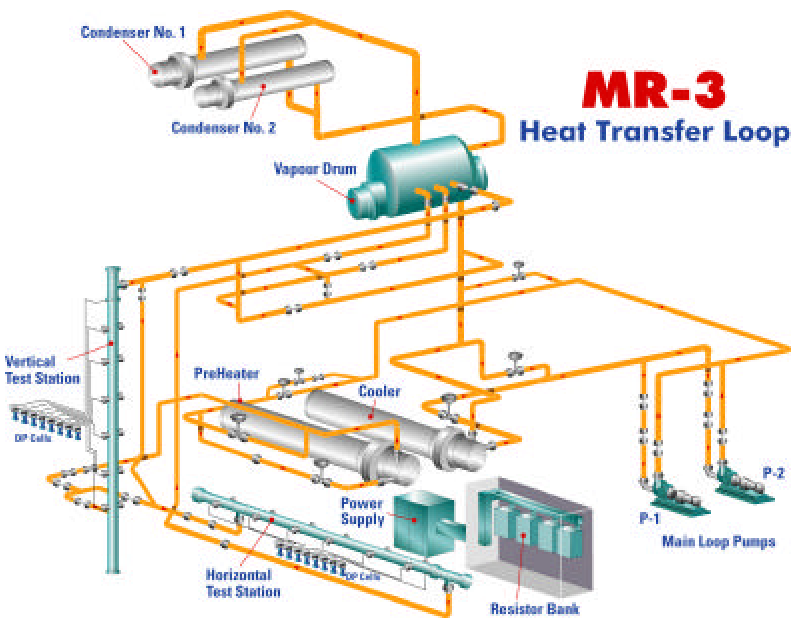


Figure 4. Schematic Diagram of MR-3 Loop

The CHF data for the 1.6% SEU fuel RFD are generally lower than those for the NU fuel RFD at the same dryout conditions. The reduction in CHF is anticipated because the local heat flux at elements in the outer ring is higher for the 1.6% SEU fuel RFD than for the NU fuel RFD (see Figure 3). The relative difference in CHF between the 1.6% SEU fuel RFD and NU fuel RFD is presented in terms of the CHF ratio (equivalent to the RFD modification factor), i.e.,

$$CHF\ \ Ratio = \frac{CHF_{1.6\%\ SEU}}{CHF_{NU}} = K_{rfd\,,\,1.6\%\ SEU} \tag{5}$$

where $CHF_{NU}$ is the NU fuel CHF at the same local dryout conditions. The NU fuel CHF is evaluated using a correlation derived with Freon data covering a similar range of flow conditions. Figure 5 shows the RFD modification factors at various critical qualities and pressures. The RFD modification factors are consistently less than 1 (from 0.85 to 0.95) at low qualities, but vary over a much wider range at high qualities (from 0.9 to 1.1). Most data with the value larger than 1 were obtained at a water-equivalent pressure of 13.5 MPa. There are no other available high-pressure data to verify the trend at this quality range. On average, the RFD modification factor is 0.94 for all data covered in the current test (shown in Figure 5).

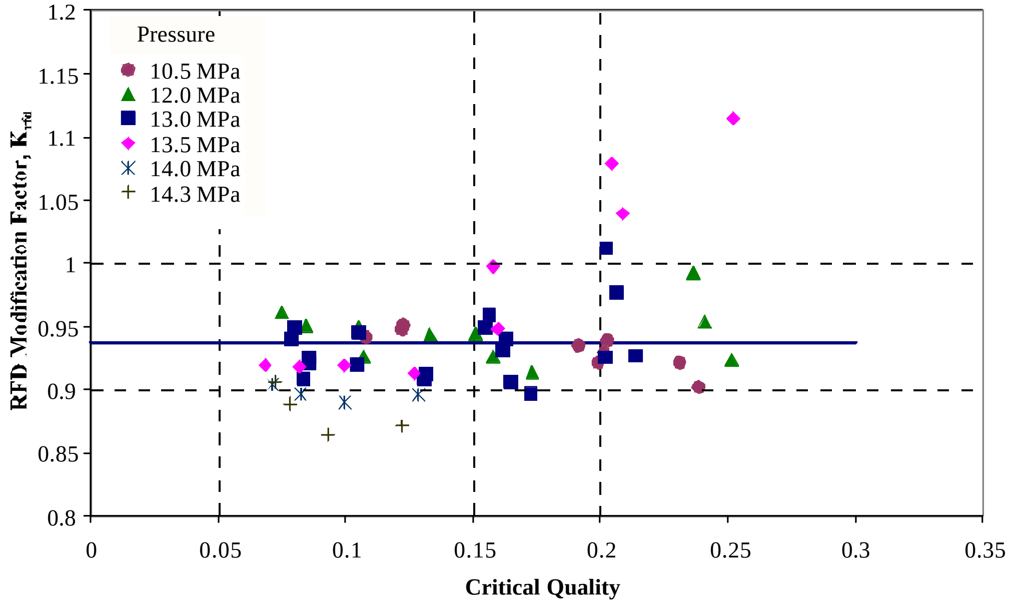


Figure 5. RFD modification factors between data of the 1.6% SEU fuel RFD and predictions of the NU correlation.

Applying the methodology described in Section 2 and the local-to-average heat-flux ratios presented in Figure 3, the bundle imbalance factor for the RFD of the 1.6% SEU fuel is 1.1485, and the RFD modification factor that corresponds to the optimum profile, $K_{rfdo}$, becomes 0.8515 (i.e., Equation (4)). The RFD modification factor, with respect to the NU profile, $K_{rfd}$, is expressed as

$$K_{rfd,\,1.6\%SEU} = \frac{CHF_{1.6\%SEU}}{CHF_{NU}} = \frac{K_{rfdo,\,1.6\%SEU}}{K_{rfdo,\,NU}} = \frac{0.8515}{0.9174} = 0.93 \qquad (6)$$

The calculated RFD modification factor (representing the CHF ratio between 1.6% SEU fuel and NU fuel RFDs) agrees closely with the average CHF ratio of 0.94 shown in Figure 5.

## 4. CONCLUSION AND FINAL REMARKS

- A generalized prediction method has been derived for the effect of RFD on CHF in 37-element and CANFLEX bundles. It is based on the general experimental trend of the CHF data for these bundles and is valid for bundle-imbalance factors between 1 and 1.3. Extrapolation of this method to bundle-imbalance factors beyond this range is not recommended.
- The prediction method has been assessed against the experimental data obtained with a uniformly heated CANFLEX bundle string simulating the 1.6% SEU fuel RFD. CHF values for the 1.6% SEU fuel are generally lower than those for the NU fuel. On average, the experimental CHF ratio between the 1.6% SEU and NU fuel is 0.94 (or a 6% reduction in CHF as compared to the NU fuel) within the current range of test conditions. Applying the prediction method results in a RFD modification factor of 0.93, which agrees closely with the experimental CHF ratio.
- The prediction method accounts only for the effect of local element heat-flux variation on CHF. Flow conditions variations are shown to have an impact on the RFD effect.
- Additional CHF data were recently obtained with SEU CANFLEX bundles having various RFDs. These data have been used to derive a CANFLEX-specific correlation to improve the prediction accuracy and the range of applications.
- An experiment has been scheduled to determine the optimum RFD of the CANFLEX bundle. The data would lead to further reduction of the uncertainty in the prediction.

## 5. ACKNOWLEDGEMENTS

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