Variation Of Critical Heat Flux With Radial Power Profile In The Low-Void Reactivity Fuel For UNCREPT And 5.1% CREPT Channels

L.K.H. Leung, M.K.Y. Ip And D.E. Bullock

Thermalhydraulics Branch
Atomic Energy of Canada Limited
Chalk River Laboratories
Chalk River, Ontario
CANADA K0J 1J0

ABSTRACT

An experiment has been completed to obtain CHF data using a horizontal, axially uniform-heated, CANFLEX LVRF bundle string cooled with Freon flow in uncrept and 5.1% (uniformly) crept channels. It covered three radial power profiles corresponding to the fresh and mid-burnup LVRF, and fresh CANFLEX NU fuel (similar to that of the discharge-burnup LVRF). Results showed that CHF values for the fresh LVRF profile are generally the lowest while those for the fresh CANFLEX NU fuel profile are the highest. CHF values for the LVRF profiles remain higher than those for the 37-element bundle. CHF ratios between LVRF (both fresh and mid-burnup) and fresh CANFLEX NU fuel profiles are slightly lower for the uncrept channel than the 5.1% crept channel. Good agreement has been observed between experimental CHF ratios and predictions from an existing correlation for the uncrept channel. The predicted ratios are lower than the experimental values for the crept channel.

1. INTRODUCTION

The low void reactivity fuel (LVRF) bundle is being qualified for implementation in CANDU® reactors at the Bruce nuclear generating station (BNGS) [1]. Compared to the 37-element fuel, the benefits of using the LVRF design include reductions in void reactivity and element power rating, and an improvement in critical channel power (CCP). The LVRF bundle is based on the CANFLEX® design, and 1% slightly enriched uranium (SEU) fuel in all ring elements and a mixture of dysprosium (Dy) and natural uranium (NU) in the centre element. This fuel configuration exhibits a steeper radial power profile than the CANFLEX NU fuel at the initial fuel loading stage. The radial power profile gradually approaches that of CANFLEX NU fuel (except for the centre element) with increasing burnup and decreasing coolant density.

CANDU® - Canada Deuterium Uranium (a registered trademark of Atomic Energy of Canada Limited, AECL).
CANFLEX® - CANDU Flexible (a registered trademark of AECL).

Part of the qualification program for the LVRF bundle includes a thermalhydraulic assessment of the fuel bundle to ensure that thermalhydraulic-related design requirements are met (i.e., an appropriate operating margin is maintained). Performing the thermalhydraulic assessment requires the characteristics of critical heat flux (CHF) for the LVRF bundle in uncrept and crept channels. Water CHF tests were performed using full-scale CANFLEX bundles of the NU fuel profile [2]. An improvement in dryout power was shown for the CANFLEX bundle as compared to the 37-element bundle. CHF correlations derived using experimental data from the full-scale CANFLEX bundle test are directly applicable for analyses of critical channel power for the LVRF, since the radial power profile of the LVRF bundle at the dryout location resembles closely that of the CANFLEX NU fuel. The impact of varying radial power profile on CHF is required for refuelling simulation and safety analyses. Applying an existing correlation [3] showed a relatively minor effect of radial power profile on CHF for fresh and high-burnup LVRF bundles. The objective of this study is to obtain experimental data to verify the effect of radial power profile on CHF for the LVRF bundle.

2. LOW-VOID REACTIVITY FUEL SPECIFICATIONS

The LVRF bundle (as illustrated in Figure 1) is based on the CANFLEX design, with minor differences in the staggered bearing-pad configuration and flat Bruce-type end caps. It consists of 43 elements with the outer diameter of elements in the outer and intermediate rings being smaller than that of inner-ring elements and the centre element. Each element, with the exception of the centre element, contains SEU. Fuel in the centre element comprises a mixture of Dy and NU. Spacers are installed to maintain the gap between elements in the middle plane. Two planes of non-load-bearing buttons are brazed on elements at the quarter planes from each end of the bundle. Bearing pads are installed on elements in the outer ring; one plane located at the middle of the bundle and others staggered between the button plane and junction at either end of the bundle.

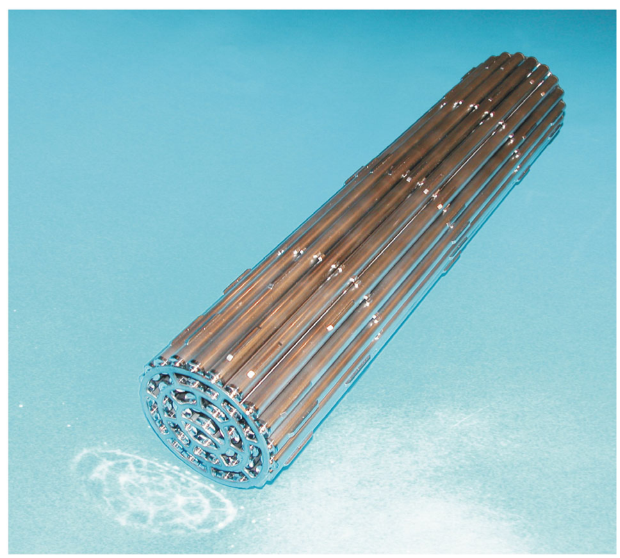

FIGURE 1: LVRF BUNDLE.

The use of SEU fuel results in a steeper radial power profile than that of the CANFLEX NU fuel bundle during the initial fuel loading stage. The radial power profile gradually approaches that of the CANFLEX NU fuel bundle with increasing burnup. The fuelling scheme for the LVRF bundles is the same as that for 37-element bundles.

Furthermore, the discharge burnup of the LVRF bundle will be similar to that of the 37-element NU fuel bundle. This results in similar axial power distributions for the two fuel types.

3. LVRF CHF EXPERIMENT

An experiment has been completed to obtain CHF data using a horizontal, axially uniform-heated, CANFLEX bundle string cooled with Freon flow in uncrept and 5.1% (uniformly) crept channels. Figure 2 shows a schematic diagram of the loop. The test station comprised a steel pressure boundary and a fibreglass flow tube electrically isolating the bundle string from the pressure boundary. Fourteen pressure taps were installed at various locations along the test station. Figure 3 illustrates a schematic of the horizontal test station. Two flow tubes of axially uniform internal diameter (103.4 and 108.7 mm) were used to simulate the reference (uncrept) and 5.1% crept channels.

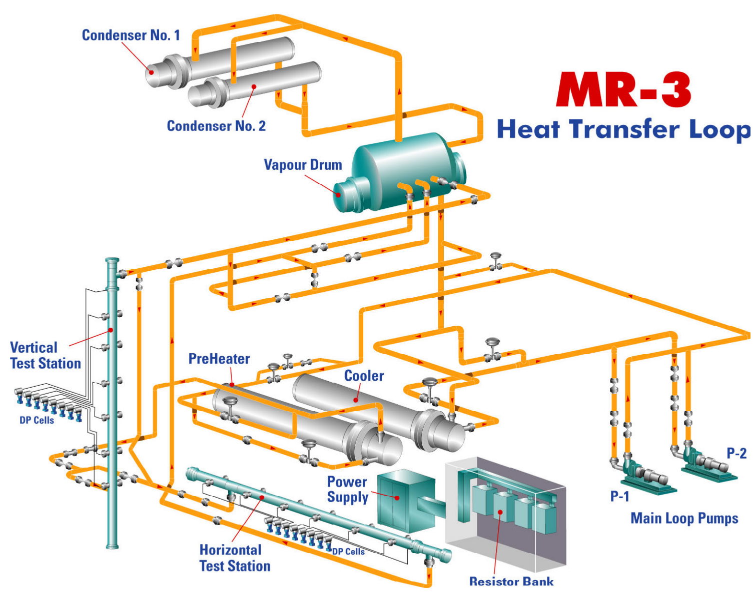

FIGURE 2: MR-3 FREON HEAT-TRANSFER LOOP AT CRL.

The CANFLEX bundle string consisted of a 6-m long, electrically heated, 43-element simulator. Each element was constructed with Inconel-718 tubes. The sheath thickness of elements in different rings was varied to simulate the reference radial power profile of natural uranium fuel. Spacer pads were installed at the middle plane of each element to maintain the gap sizes. Non-insulating pads were used in the gaps between elements in the same ring, and insulating pads in the gaps between elements in neighbouring rings for electric isolation. Bearing pads were spot-welded to elements in the outer ring at locations corresponding to the LVRF bundle design. Supplemental spacing devices were introduced to maintain the bundle in an eccentric position inside the flow tube. A stainless-steel spring was attached to each upstream bearing pad of five top elements in the bundle for the uncrept-channel tests. Attaching these springs to the upstream bearing pads minimized the influence to the dryout location at the downstream end of the bundle string. In addition, “tunnel” spacers were installed to these five elements for the 5.1% crept-channel tests (see [2] for details). All elements were equipped with sliding thermocouples for temperature mapping and CHF detection.

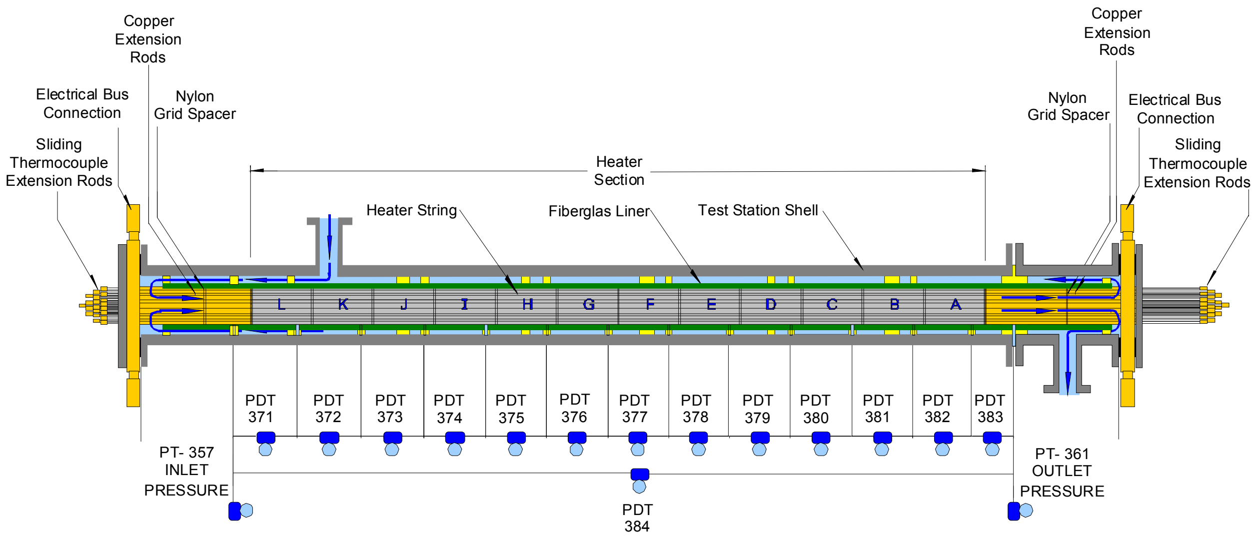

FIGURE 3: HORIZONTAL TEST STATION IN THE MR-3 LOOP.

Bundle segmentation was simulated with specially designed spool pieces that simulated the radial and cross webs of the endplate in a fuel bundle. Elements in the same ring were joined with nickel-plated brackets at the spool pieces; the brackets simulated the circular webs of the endplate. Neighbouring brackets between rings were joined with fibreglass webs, which simulated the cross webs of the endplate and electrically insulated the rings from each other. Current shunts and a custom-designed electronic instrument were used to measure individual ring powers. A separate resistor bank (with four resistors) was installed in series to the ring elements. The radial power profile in the bundle string was arranged by adjusting the resistance in each of the four resistors. Three radial power profiles, corresponding to the fresh and mid-burnup LVRF, and fresh CANFLEX NU fuel (similar to that of the discharge-burnup LVRF) at high coolant-density conditions (see Figure 4), were tested in the experiment.

The CHF test covered a wide range of flow conditions. Table 1 lists Freon conditions together with their water-equivalent values, which have been converted using fluid-to-fluid modelling parameters [4].

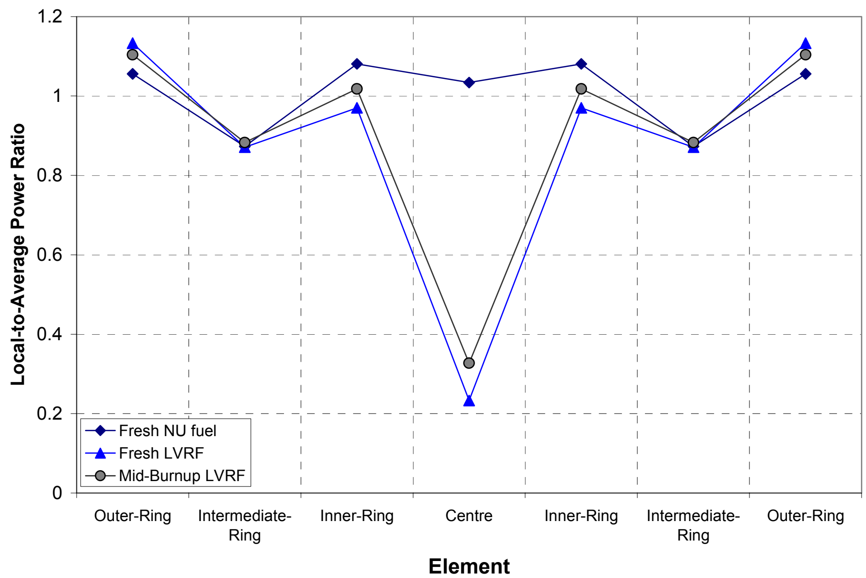

FIGURE 4: RADIAL POWER PROFILES COVERED IN LVRF CHF TEST.

4. RESULTS AND DISCUSSION

Dryout power measurements and their corresponding CHF values were analysed. Figure 5 shows that dryout powers are the lowest for the fresh LVRF profile and the highest for the fresh CANFLEX NU fuel profile at constant inlet-fluid temperature in the uncrept-channel test. The effect of radial power profile is less significant for the 5.1% crept channel than the uncrept channel. Dryout power values for the CANFLEX NU fuel profile are about the same as those for the LVRF fuel profiles. This is due mainly to the change in radial dryout location from elements in the outer ring for the LVRF profiles to intermediate and inner rings for the fresh CANFLEX NU fuel profile. Dryout occurred generally at the same ring for various profiles in the uncrept channel.

TABLE 1: FLOW CONDITIONS COVERED IN LVRF CHF TEST

	Freon	**Water Equivalent**
Outlet Pressure (MPa)	0.96 to 2.2	6 to 13
Mass Flow Rate (kg.s^{-1})	4.8 to 22.4	7 to 31.6
Inlet Subcooling (kJ/kg)	12 to 72	100 to 600
Critical Quality	-0.1 to 0.4	-0.1 to 0.4

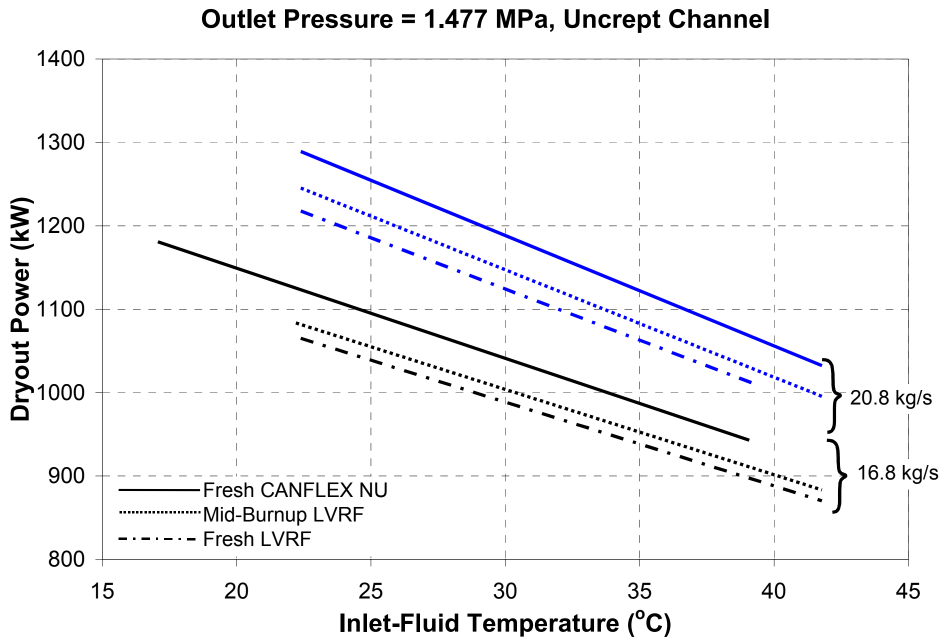

FIGURE 5: COMPARISON OF DRYOUT POWER DATA FOR VARIOUS PROFILES.

CHF is calculated from the dryout power measurement and heated area of the bundle. Examinations of CHF variations are based on local, cross-sectional average, dryout conditions (i.e., outlet pressure, mass flux and critical quality). The CHF values and local flow conditions have been converted into water-equivalent values using fluid-to-fluid modelling parameters [4]. Figure 6 compares CHF values of various radial power profiles. CHF values for fresh and mid-burnup LVRF profiles are consistently lower than those for the fresh CANFLEX NU fuel profile in the uncrept-channel test. Among the LVRF profiles, the CHF for the fresh fuel is lower than that for the mid-burnup fuel.

The effect of radial power profile on CHF is small for the 5.1% crept-channel test. CHF values for the fresh CANFLEX NU fuel profile are generally larger than those for the LVRF profiles. At low flows, however, some dryout occurrences were observed at elements in the outer ring for fresh and mid-burnup LVRF profiles while at elements in intermediate and inner rings for fresh CANFLEX NU fuel profile. The flatter radial power profile for the fresh CANFLEX NU fuel resulted in slightly lower CHF values than the steeper radial power profiles for LVRF due to void and enthalpy gradients in the crept channel.

CHF ratios between LVRF and fresh CANFLEX NU fuel profiles have been established from the experimental values. Figure 7 shows that CHF ratios are lower for the uncrept channel than the 5.1% crept channel. On average, the CHF ratio is 0.91 for the fresh LVRF profile and 0.94 for the mid-burnup LVRF profile (with a standard deviation of 3.4%) in the uncrept channel, and it is 0.95 for data of the fresh LVRF profile and 0.98 for data of the mid-burnup LVRF profile (with a standard deviation of 3.2%) in the 5.1% crept channel. The experimental CHF ratios for various profiles have been compared to an existing correlation that quantifies the effect of radial heat-flux distribution on CHF [3]. Good agreement has been observed between experimental and predicted ratios for the uncrept channel (overprediction of about 0.5% as shown in Figure 7). Predicted CHF ratios are lower than experimental values for the crept channel (this results in an underprediction of the critical channel power).

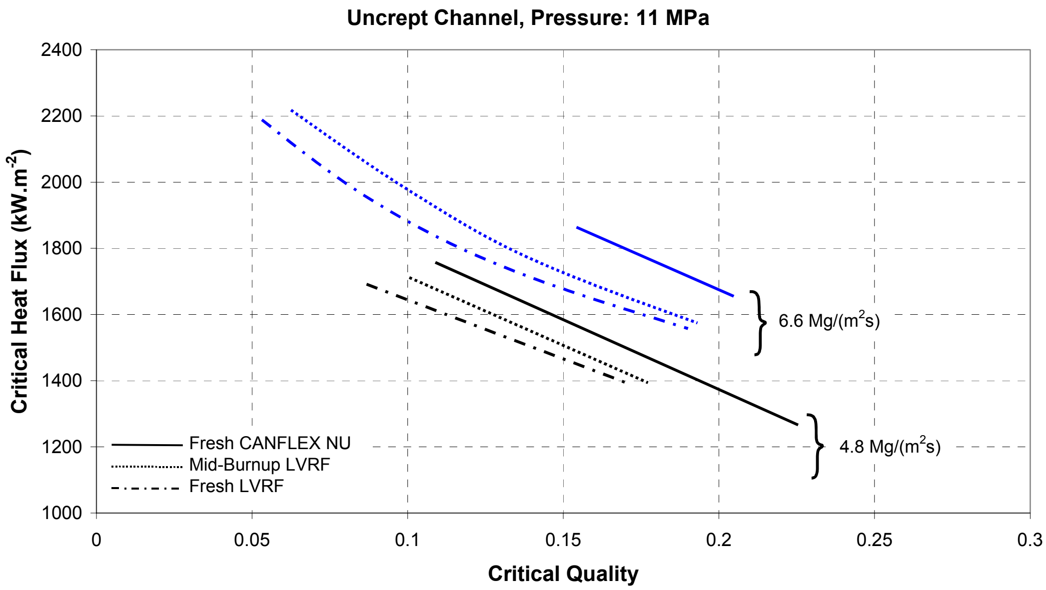

FIGURE 6: COMPARISON OF CHF VALUES FOR VARIOUS PROFILES IN UNCREPT-CHANNEL TEST.

5. CONCLUSION

- Experiments were performed to obtain confirmatory data on CHF for the LVRF bundles with fresh and mid-burnup radial power profiles for uncrept and 5.1% crept channels.
- Dryout power and CHF values for the fresh CANFLEX NU profile are generally higher than those for the LVRF profiles. All values are higher than those for the 37-element bundle.
- The average CHF ratio is 0.91 between fresh LVRF and fresh CANFLEX NU fuel profiles and 0.94 between mid-burnup and fresh CANFLEX NU fuel profiles for the uncrept channel. The impact on critical-channel power is smaller.
- The impact of radial power profile on CHF is smaller for the 5.1% crept channel than the uncrept channel. Average CHF ratios between LVRF and fresh CANFLEX NU fuel profiles for the 5.1% crept channel are larger than those for the uncrept channel (i.e., 0.95 for the fresh LVRF profile and 0.98 for the mid-burnup LVRF profile).

- The existing correlation for the effect of radial power profile on CHF predicts closely CHF ratios for LVRF profiles in the uncrept channel, but underpredicts those for the 5.1% crept channel. This results in underprediction of the critical channel power for crept channels.

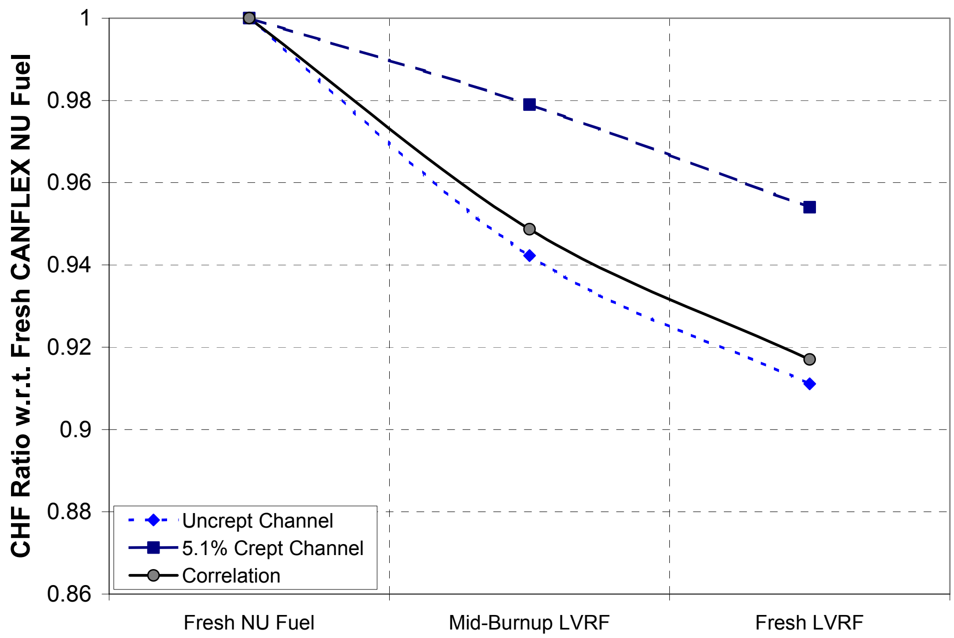

FIGURE 7: COMPARISON OF EXPERIMENTAL CHF RATIOS FOR VARIOUS RADIAL POWER PROFILES OF LVRF BUNDLE.

6. REFERENCES

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