SINGLE-PHASE PRESSURE-DROP MEASUREMENTS OVER LOW VOID REACTIVITY FUEL

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ABSTRACT

An experiment has been performed to obtain pressure-drop measurements over Low Void Reactivity Fuel (LVRF) bundles in Refrigerant-134a flow. Production LVRF bundles were inserted into the test station with either an uncrept or a 5.1% crept flow channel. For comparison purposes, several production Bruce 37-element bundles were also included in the test string.

Overall, the single-phase pressure drop of the LVRF bundle is slightly higher than that of the Bruce 37-element bundle. Pressure-drop measurements were used to derive bundle and junction loss coefficients for hydraulic calculations in safety analyses. Applying these loss coefficients, an assessment showed that the overall pressure drop over a string of 12 LVRF bundles (after core conversion) remains less than that over a string of 13 Bruce 37-element fuel bundles (before core conversion) at the Bruce Nuclear Generating Station.

INTRODUCTION

Atomic Energy of Canada Limited (AECL) has developed the Low Void Reactivity Fuel (LVRF) bundle [1] for deployment in CANDU®[1] reactors at the Bruce-B Nuclear Generating Station (BNGS) [2], [3]. Qualification of the LVRF bundle requires the hydraulic characteristics, which are established from pressure-drop measurements over relevant production bundles.

The LVRF bundle (as illustrated in Figure 1) is based on the CANFLEX®[2] 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.

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1 CANada Deuterium Uranium. CANDU is a registered trademark of Atomic Energy of Canada Limited.
2 CANDU FLEXible. CANFLEX is a registered trademark of Atomic Energy of Canada Limited and the Korea Atomic Energy Research Institute.

Each element, with the exception of the centre element, contains slightly enriched uranium. Fuel in the centre element comprises a mixture of dysprosium (Dy) and natural uranium. 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 set is located at the middle of the bundle and others are staggered between the button plane and junction at either end of the bundle.

Experiments were performed at AECL's Chalk River Laboratories (CRL) to gather single-phase and two-phase pressure-drop data for the LVRF bundle. For comparison purposes, data were also obtained for the Bruce 37-element fuel bundle. This paper describes results from the single-phase pressure-drop tests, and compares the pressure-drop characteristics of the LVRF bundle with those of the Bruce 37-element fuel bundle as applicable to deploying LVRF bundles in the BNGS reactors.

Figure 1: LVRF Bundle

EXPERIMENTAL SET-UP AND TEST MATRIX

The pressure-drop experiment for the LVRF bundle was performed in the MR-3 loop at CRL. The loop, illustrated in Figure 2, comprises two primary coolant pumps, a pre-heater, a vertical and a horizontal test station, two condensers, a vapour drum and a cooler. It is fully instrumented to measure the flow rate through the test stations, and fluid temperature and system pressure at various locations. Data are collected via a computer-based data acquisition system (DAS). Refrigerant-134a (R-134a) is currently used as the working fluid in the loop.

The experiment was performed with the horizontal test station. A zircaloy liner tube housing the test string was inserted inside the test station. Two liner tubes were tested: one with an inner diameter simulating the reference (uncrept) channel and the other with an inner diameter simulating the peak inner diameter of a 5.1%-crept pressure tube. The test string was made up of six production LVRF and four Bruce 37-element fuel bundles as shown in Figure 3. Differential pressure cells and three-way valves were used to obtain pressure-drop measurements over LVRF and Bruce 37-element bundles, in sequence, and a mixed-bundle junction as follows:

1. Two measurements over junctions between adjacent LVRF or Bruce 37-element bundles.
2. Two measurements over one LVRF or Bruce 37-element bundle enveloping a set of adjacent end plates and one bundle length.

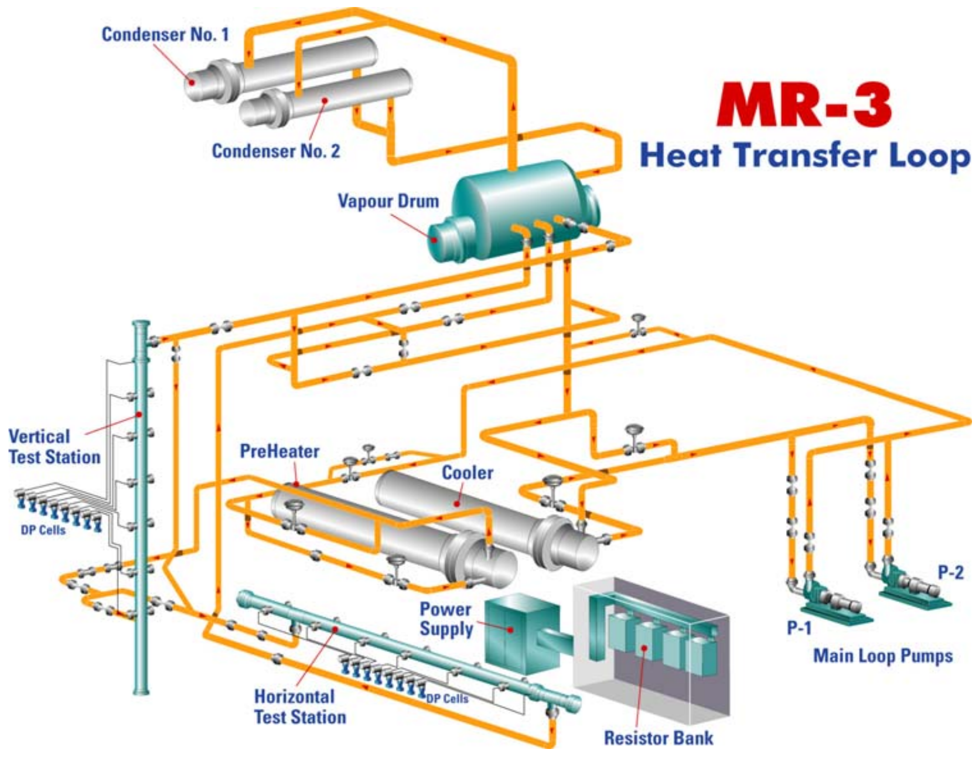

Figure 2: The MR-3 Loop

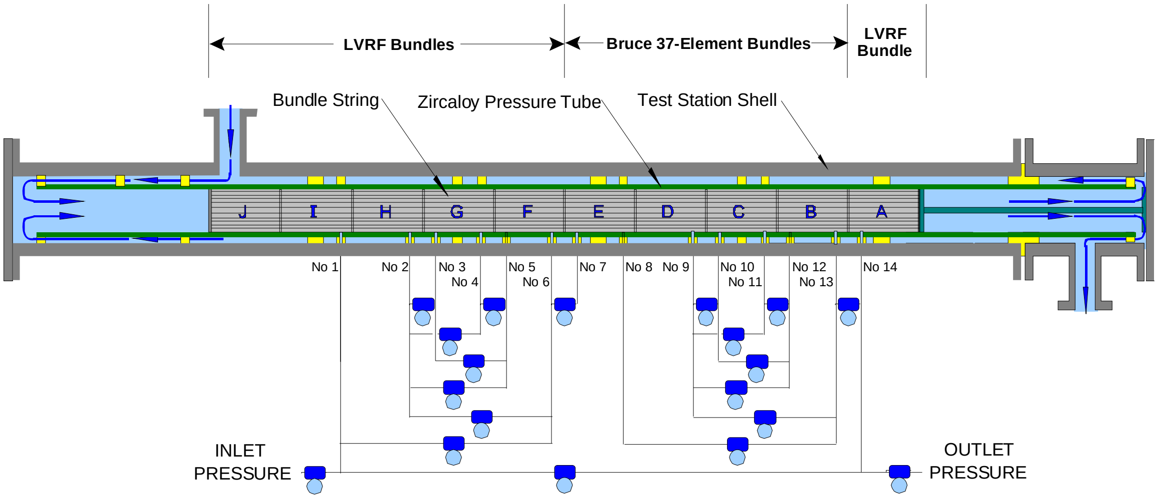

Figure 3: The Horizontal Test Station in the MR-3 Loop

3. One measurement over two LVRF or Bruce 37-element bundles enveloping the corresponding end plates and bundle lengths.
4. One measurement over three adjacent LVRF or Bruce 37-element bundles enveloping the corresponding end plates and bundle lengths.
5. A confirmatory measurement over LVRF or Bruce 37-element bundles enveloping two junctions and a bundle length.
6. One measurement over a mixed-bundle junction between adjacent LVRF and Bruce 37-element bundles, with the flow moving either from an LVRF bundle to a Bruce 37-element bundle (the configuration identified as "43/37") or from a Bruce 37-element bundle to an LVRF bundle (the configuration identified as "37/43").
7. A confirmatory measurement of pressure drop between the first and last taps.

Pressure-drop measurements were obtained with the test string assembled to achieve adjacent fuel bundles at full alignment, most-probable misalignment or maximum misalignment, in turn, in the uncrept and crept channels. Misalignment angles between adjacent bundles for the most probable and maximum misalignment were established from the average and the maximum blockage areas, respectively, at the junctions. In the case of mixed-bundle junctions, a minimum misalignment was used in place of the fully aligned arrangement since a LVRF and a Bruce 37-element bundle adjacent to each other is never fully aligned.

This paper discusses only single-phase pressure-drop measurements of LVRF and Bruce 37-element bundles at the most probable misalignment angle in the uncrept and 5.1%-crept channels. These measurements (and corresponding hydraulic characteristics) are of the most interest to critical channel power (CCP) analyses. Information on mixed-bundle junctions is not included since it is only relevant for transient-core analyses.

The matrix of the single-phase test is listed in Table 1. Pressure-drop measurements of the bundles are used to compute loss coefficients, which are presented as a function of Reynolds number. These parameters, being dimensionless, are applicable to heavy water at reactor conditions.

Table 1: Test Matrix for Most Probable Bundle Misalignment

Flow-Tube Creep (%)	R-134a Flow Conditions			Reynolds Number
	Pressure (kPa)	Temperature (°C)	Flow Rate (kg/s)	
0	1500, 1864, 2000	10 - 60	3.5 - 34	29,000 - 450,000
5.1	1500, 1864	10	3.5 - 34	29,000 - 300,000

RESULTS AND DISCUSSION

Single-phase pressure-drop data over LVRF and Bruce 37-element bundles and junctions are discussed first. Bundle and junction loss coefficients (which include skin friction), form loss coefficients (excluding skin friction) and fuel-string pressure drop are presented next.

Single-Phase Pressure-Drop Data

Figure 4 compares pressure-drop measurements over single and multiple LVRF bundles in the uncrept channel at the most-probable misalignment angle. Pressure-drop measurements in the test station are consistent over the range of flow conditions. Separate measurements over one bundle length are nearly equal over the range of flow conditions. Those over two or three bundles are multiples of either two or three of the single-bundle measurement, respectively. The effect of system pressure on bundle pressure drop is insignificant. The same consistent trend was observed for Bruce 37-element bundles in the uncrept channel, as well as for each bundle type in the 5.1% crept channel. At a constant mass flow rate, the pressure drop for a selected bundle type is higher in the uncrept channel than in the 5.1% crept channel.

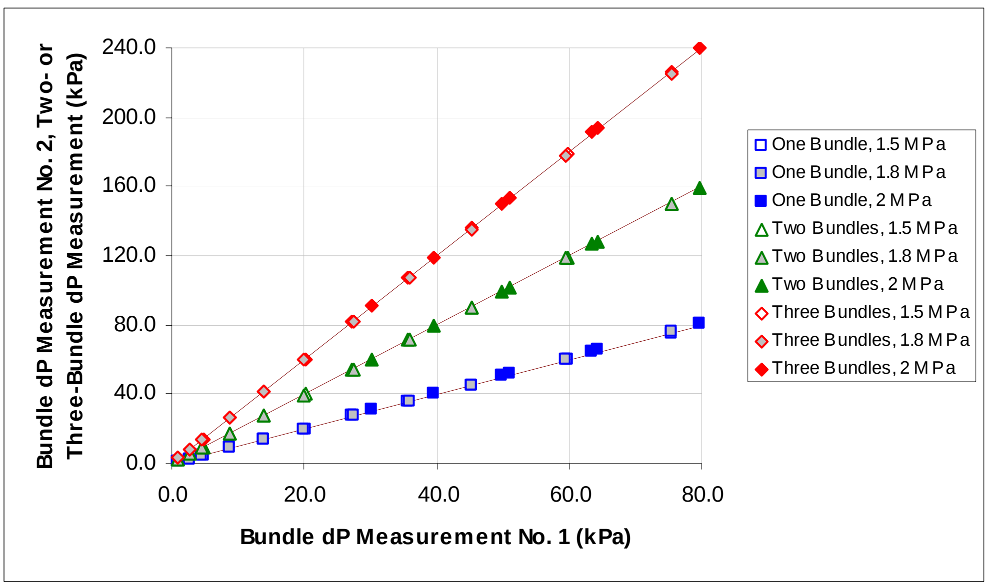

Figure 4: Pressure Drops over LVRF Bundles in the Uncrept Channel

Figure 5 compares pressure-drop measurements over two junction regions of LVRF bundles in the uncrept channel at the most-probable misalignment angle. These measurements are also consistent over the range of flow conditions. Pressure drops at Junction 2 are slightly higher than those at Junction 1. This difference is small and is probably due to a slight variation in the misalignment angle. The effect of system pressure on junction pressure drop is insignificant. Similar trends have been observed for the Bruce 37-element bundle junctions in the uncrept channel and for both LVRF and Bruce 37-element bundle junctions in the 5.1% crept channel.

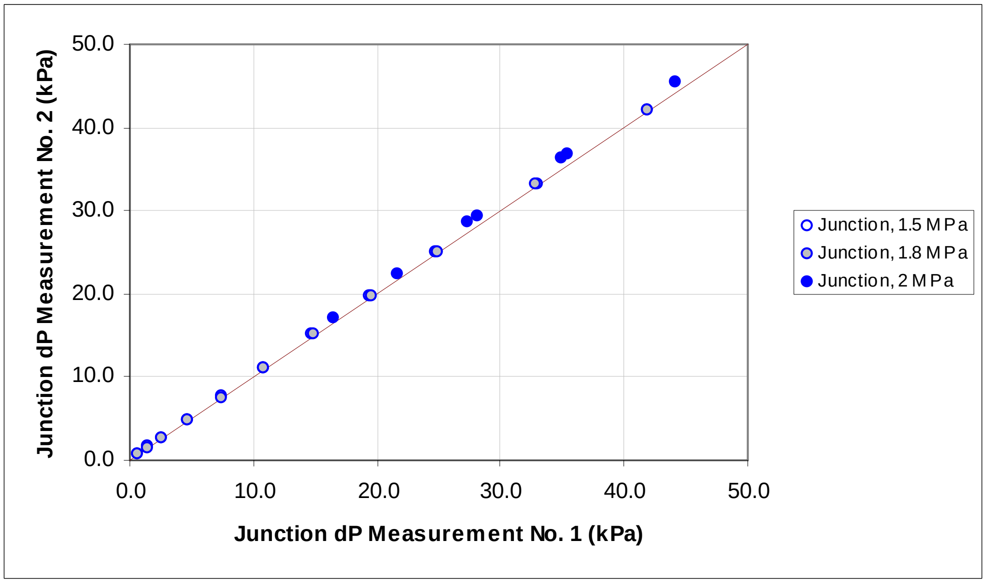

Figure 5: Pressure Drops over LVRF Bundle Junctions in Uncrept Channel

Loss Coefficients

Single-phase pressure-drop data from the tests were used to compute bundle and junction loss coefficients for LVRF and Bruce 37-element bundles. The bundle pressure drop is expressed as:

$$\Delta P_b = k_{1,b} \frac{G^2}{2\rho} \tag{1}$$

Here, ΔP_b is the measured pressure drop over one bundle length, Pa, $k_{1,b}$ is the bundle loss coefficient, G is the mass flux, kg/m^{2}s and ρ is the density of working fluid in the region of measurement, kg/m^3. (Pressure loss due to acceleration is negligible in single-phase flow at the test conditions, and is not included in the equation. That due to gravity is not present in horizontal flow.)

The bundle loss coefficient combines frictional loss and form-loss coefficients, and is defined as:

$$k_{1,b} = \frac{f_b\, l_b}{D_h} + k_{2,b} \tag{2}$$

Here, f_b is the bundle friction factor, l_b is the bundle length, D_h is the hydraulic diameter of the test section (7.64 mm with the LVRF bundle in the uncrept flow channel and 7.62 mm with the Bruce 37-element bundle in the uncrept flow channel) and $k_{2,b}$ is the bundle form-loss coefficient. The form-loss coefficient accounts for form losses at the junction (i.e., interface between two adjacent bundles) and all appendages (i.e., bearing pads, spacers and buttons) over one bundle length.

The junction pressure drop is expressed as:

$$\Delta P_j = k_{1,j} \frac{G^2}{2\rho} \tag{3}$$

Here, ΔP_j is the measured pressure-drop over the junction and $k_{1,j}$ is the junction loss coefficient. The junction loss coefficient consists of frictional loss and form-loss coefficients in the current test set-up of pressure taps. It is defined as:

$$k_{1,j} = \frac{f_b\, l_j}{D_h} + k_{2,j} \tag{4}$$

Here, l_j is the distance over which junction pressure-drop measurements were obtained and $k_{2,j}$ is the junction form-loss coefficient. For LVRF or Bruce 37-element bundles with staggered bearing pads, the junction form-loss coefficient accounts for form losses at the junction of two adjacent bundles, two planes of outboard bearing pads and two half-planes of inboard bearing pads.

Equations (3) and (4) are applicable to mixed-bundle junctions as well, with the mass flux in Equation (3) being established with the upstream bundle flow area.

The pressure-drop measurement over multiple bundles was used to calculate the loss coefficient. This study focuses mainly on the relative difference in loss coefficient between LVRF and Bruce 37-element bundles. Figure 6 compares the ratio of bundle and junction loss coefficients, $k_{1,b}$ and $k_{1,j}$, for LVRF and Bruce 37-element bundles in the uncrept flow tube at the most-probable misalignment angle to the bundle loss coefficient for LVRF bundles at a Reynolds number of around 460,000 (which is the approximate Reynolds number at normal reactor operating conditions). The rate of change in bundle and junction loss coefficients decreases with increasing Reynolds number. The decreasing trend is more rapid at low Reynolds numbers than at high Reynolds numbers.

The bundle loss coefficient for the LVRF bundle is higher than that for the Bruce 37-element bundle. This is mainly due to differences in the end-plate configuration and the spacer-pad configuration of the LVRF bundle relative to the Bruce 37-element bundle, and the presence of critical heat-flux enhancement buttons on the LVRF bundle. However, the impact on pressure drop is reduced at a constant mass flow rate, after accounting for the flow-area differences between the two bundle types. The flow area of a LVRF bundle is larger than that of a Bruce 37-element bundle. The difference in loss coefficient at the junction is smaller between LVRF and Bruce 37-element bundles than that over the bundle.

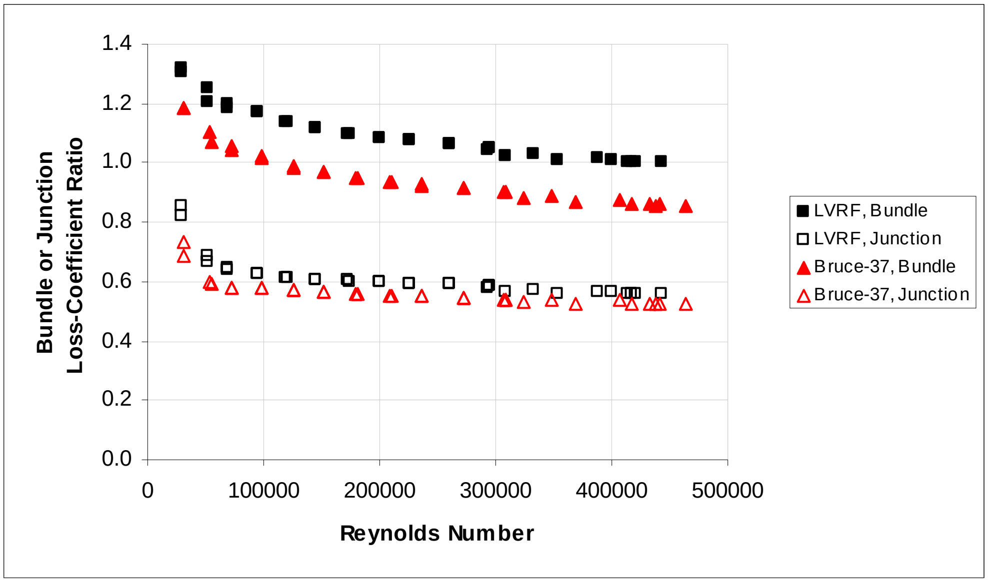

Figure 6: Bundle and Junction Loss Coefficients for LVRF and Bruce 37-Element Bundles in the Uncrept channel

Figure 7 compares relative bundle and junction loss coefficients in LVRF bundles at the most-probable misalignment angle in uncrept and 5.1%-crept channels. The reference loss coefficient is the bundle loss coefficient for the LVRF bundle at a Reynolds number of approximately 460,000, as in Figure 6. Loss coefficients in the 5.1%-crept flow tube are systematically lower over a bundle length or a junction compared with corresponding values in the uncrept channel. Similar trends have been observed for the Bruce 37-element bundle.

The estimated uncertainty in the loss coefficients, at the 2σ level, is around ± 2 to ± 3% at Reynolds numbers exceeding 200,000 (which is the region of interest for normal reactor operation).

Bundle Friction Factors and Form-Loss Coefficients

The bundle friction factor, f_b, was expressed in terms of a correction, f_{COR}, to the Colebrook-White friction factor, f_{CW}, for tubes:

$$f_b = f_{CW}\ f_{COR} \tag{5}$$

The Colebrook-White friction-factor [4] is expressed as:

$$\frac{1}{\sqrt{f_{CW}}} = -2\log\left(\frac{\varepsilon / D_h}{3.7} + \frac{2.51}{\sqrt{f_{CW}}\ \mathrm{Re}}\right) \tag{6}$$

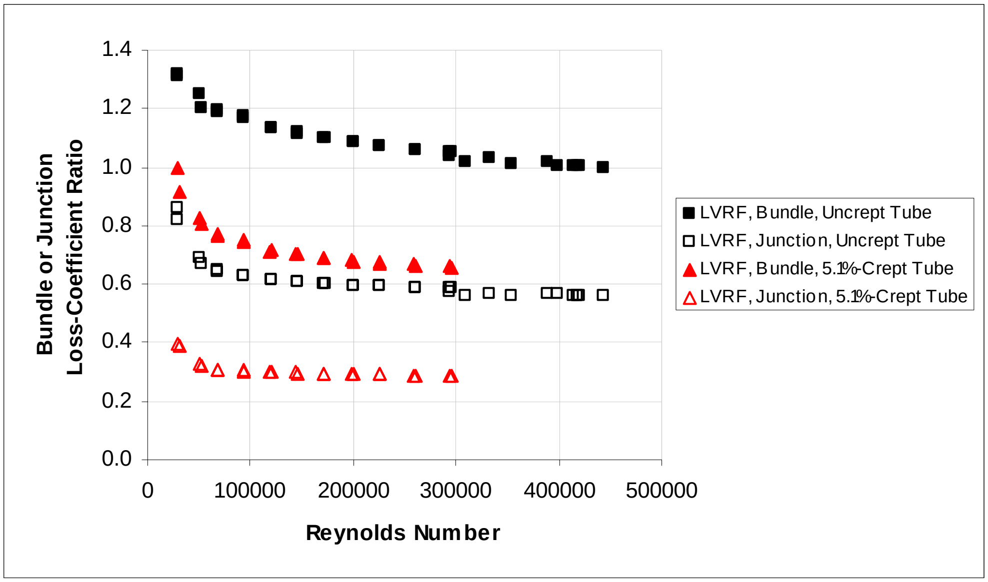

Figure 7: Bundle and Junction Loss Coefficients for LVRF Bundles in Uncrept and 5.1% Crept Channels

Here, ε / D_h is the ratio of absolute surface roughness to hydraulic diameter and *Re* is the Reynolds number. The friction-factor correction for bundles was expressed as:

$$f_{COR,LVRF} = \mathrm{A}_{LVRF} \ - \ (B_{\mathrm{LVRF}} \ \mathrm{Re}) \tag{7a}$$

for the LVRF bundle and

$$f_{COR,37-El} = \mathrm{A}_{37-El} \ - \ (B_{\mathrm{37\text{-}El}} \ \mathrm{Re}) \tag{7b}$$

for the Bruce 37-element bundle. Here, $f_{COR,\ LVRF}$ and $f_{COR,\ 37\text{-}El}$ are the friction-factor corrections for LVRF and Bruce 37-element bundles, respectively, and A_{LVRF}, B_{LVRF}, $A_{37\text{-}El}$ and $B_{37\text{-}El}$ are coefficients derived based on experimental data generated at CRL with these geometries. Substituting Equation (5) in Equations (4) and (2), in conjunction with values of $k_{1,\ b}$ and $k_{1,\ j}$ from Equations (1) and (3), yield values of $k_{2,\ b}$ and $k_{2,\ j}$.

Figure 8 shows the ratio of bundle and junction form-loss coefficients for LVRF and Bruce 37-element bundles to the highest calculated bundle form-loss coefficient at the most-probable misalignment angle in the uncrept flow tube. Form loss coefficients are independent of Reynolds number at Reynolds numbers exceeding 200,000. Bundle form-loss coefficients for LVRF bundles are higher than corresponding values for Bruce 37-element bundles. The same trend is observed for junction form-loss coefficients.

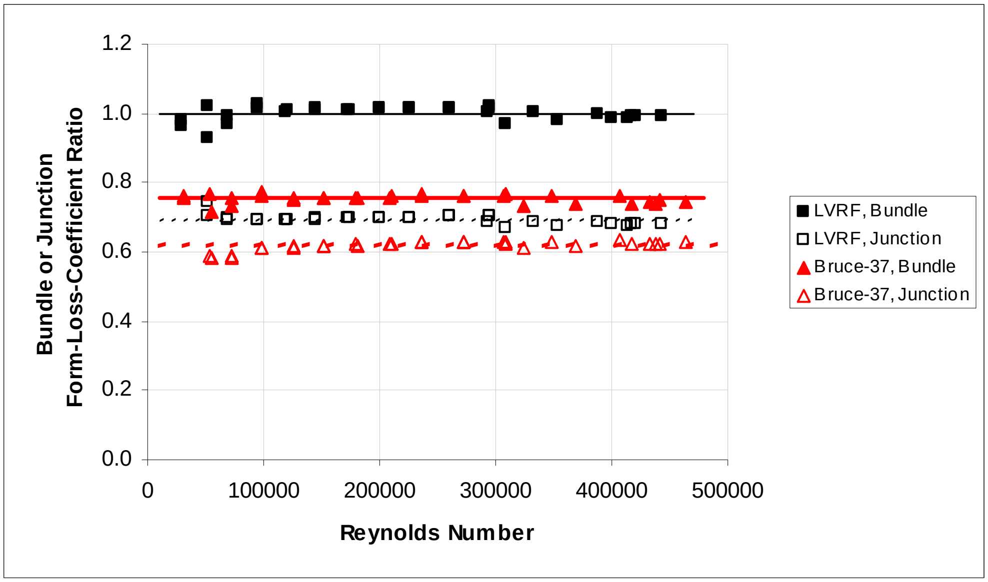

Figure 8: Bundle and Junction Form-Loss Coefficients for LVRF and Bruce 37-Element Bundles in the Uncrept Channel

Figure 9 compares the bundle and junction form-loss coefficients in LVRF bundles at the most-probable misalignment angle in uncrept and 5.1%-crept channels. Form-loss coefficients in the 5.1%-crept channel are lower compared with corresponding values in the uncrept channel. Similar trends are observed for Bruce 37-element bundles.

Fuel-String Pressure Drop

As part of the Improve Output Project at BNGS B, the fuelling method was changed from fuelling against flow to fuelling with flow and the number of fuel bundles in a channel was reduced from 13 to 12 [5]. Results from the present study were used to calculate the pressure drop over a fuel string in a BNGS fuel channel before and after core conversion from Bruce 37-element bundles to LVRF bundles. Figure 10 shows the fuel-string pressure-drop ratio, calculated as the ratio of the fuel-string pressure drop over twelve LVRF bundles (after core conversion) to that over thirteen Bruce 37-element fuel bundles (before core conversion). The single-phase pressure drop over a string of 12 LVRF bundles remains lower than that over a string of 13 Bruce 37-element bundles in the fuel channel.

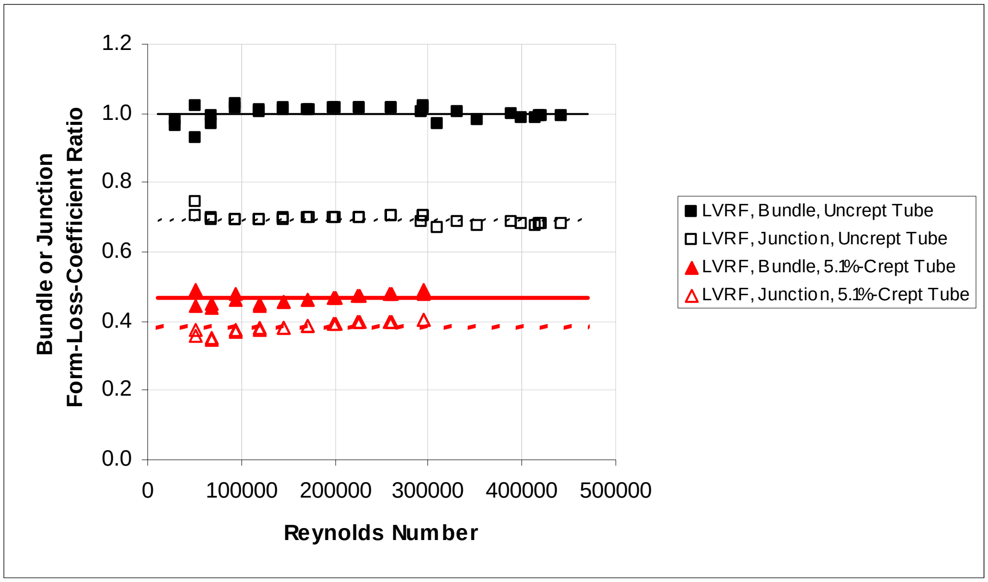

Figure 9: Bundle and Junction Form-Loss Coefficients in LVRF Bundles in Uncrept and 5.1% Crept Channels

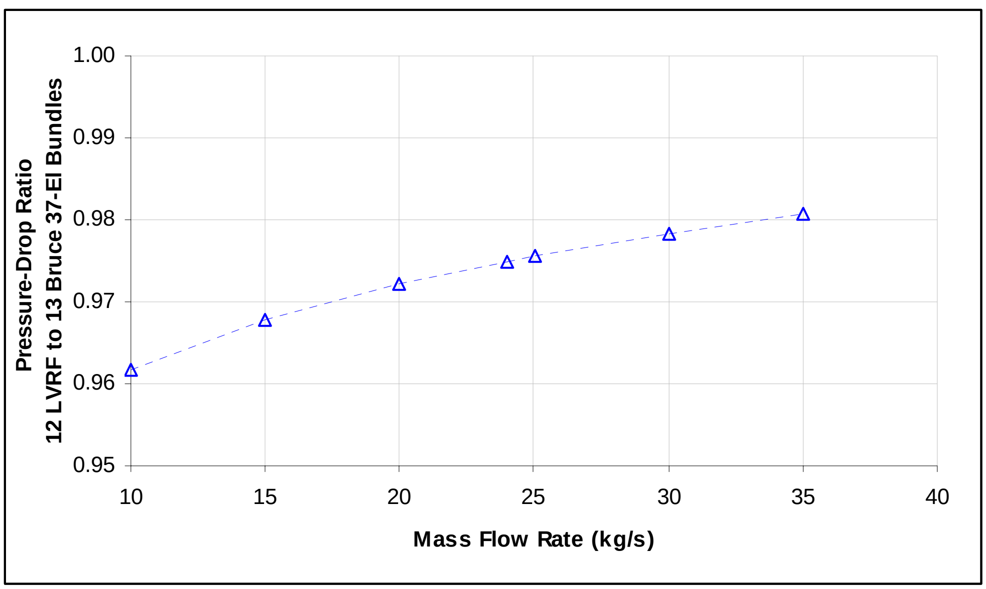

Figure 10: Pressure-Drops Over LVRF and Bruce 37-Element Bundles in the Fuel Channel

CONCLUSIONS

1. Consistent single-phase pressure-drop data over production LVRF and Bruce 37-element fuel bundles are gathered in the MR-3 loop. Independent junction measurements are nearly equal over the range of values measured. Measurements over one, two and three bundles are nearly equal in the case of independent measurements over a bundle length, and are appropriate integer multiples of the bundle measurement in the case of measurements over two and three bundle lengths.
2. The loss coefficient for LVRF bundles is higher than that for Bruce 37-element bundles at the most-probable misalignment in the uncrept channel. However, the impact on pressure drop is reduced at a constant mass flow rate, after accounting for the flow-area differences between the two bundle types.
3. The single-phase pressure drop over a string of 12 LVRF bundles remains lower than that over a string of 13 Bruce 37-element bundles in the fuel channel.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support by the Bruce Low Void Reactivity Fuel Project of AECL, which facilitated this experimental study.

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