DRYOUT POWER OF A CANFLEX BUNDLE STRING WITH RAISED BEARING PADS

L.K.H. LEUNG*, J.S. JUN†, G.R. DIMMICK*, D.E. BULLOCK*, W.W.R. INCH*, H.C. SUK†

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

†Korea Atomic Energy Research Institute
150 Dukjin-dong,
Yusong-ku, Taejon,
KOREA 305-353

Abstract

Dryout power data have been obtained with CANFLEX® bundle strings equipped with raised bearing pads (1.7 mm and 1.8 mm height as compared to 1.4 mm in the current Mk-IV design) at Stern Laboratories. The experiment covered a wide range of steam-water flow conditions in three flow tubes simulating uncrept, and 3.3% and 5.1% crept profiles. The dryout power follows consistent parametric trends: it increases with increasing mass-flow rate, and decreases with increasing pressure, inlet-fluid temperature and channel creep. Local and boiling-length-average (BLA) critical-heat-flux (CHF) values were evaluated from the dryout-power measurements. The dryout power and BLA CHF values of the high bearing-pad bundles are higher than those of the low bearing-pad bundles at the same channel inlet flow conditions. On average, the dryout powers for bundles with 1.7 mm and 1.8 mm bearing pads are about 8% and 10%, respectively, higher than those for the bundle with 1.4 mm bearing pads. Compared to the 37-element bundle, an enhancement in dryout power is shown with CANFLEX bundles for all bearing-pad heights, at flow conditions of interest for reactor licensing. The average dryout power enhancement varies from 4% for the CANFLEX bundle with 1.4 mm bearing pads in the uncrept channel to 27% for the CANFLEX bundle with 1.8 mm bearing pads in the 5.1% crept channel.

1. INTRODUCTION

Since 1991, Atomic Energy of Canada Limited (AECL) and the Korea Atomic Energy Research Institute (KAERI) have jointly developed the CANFLEX® [1](CANDU® Flexible) bundle as an advanced nuclear-fuel carrier for CANDU pressurized-heavy-water reactors. Using AECL patented, non-load-bearing, heat-transfer enhancing buttons attached to the surface of elements, the CANFLEX fuel bundle is designed to improve thermalhydraulic performance over that of the current 37-element bundle. The development of the CANFLEX (Mk-IV) fuel bundle is complete, and a demonstration irradiation of 24 bundles with natural-uranium fuel was performed between 1998 September and 2000 August at the Point Lepreau Generating Station (PLGS) in Canada [1].

[1] CANDU® and CANFLEX® are registered trademarks of Atomic Energy of Canada Limited (AECL).

A similar demonstration irradiation program is also being prepared for the Wolsong-1 reactor in Korea.

The CANFLEX fuel bundle contains about the same amount of uranium in weight as the 37-element bundle but uses 43 fuel pins. It is characterized by a moderately flat radial-power profile, with the outer and intermediate rings consisting of 21 and 14 elements of 11.5 mm O.D., and the inner ring and center rod consisting of 7 and 1 element(s) of 13.5 mm O.D. A full-scale out-reactor test of the CANFLEX design was performed under contract with Stern Laboratories (SL) to provide thermalhydraulic data for the CANFLEX Mk-IV design [2]. The dryout power measurements were shown to be higher than those of the 37-element bundle in the 5.1% crept channel [3]. Dryout in the CANFLEX bundle was initiated at the bottom elements of the bundle. This is caused in part by the small subchannel sizes between the pressure tube and elements in the outer ring due to bundle eccentricity. Kobori [4] performed an experiment with a vertical 28-element bundle string and observed a dryout power improvement through the reduction of bundle eccentricity (i.e., to arrange the bundle in the concentric position within the flow tube). Similar to the CANFLEX bundle, dryout was initiated on elements in the outer ring at the small-subchannel region neighbouring to the flow tube. Therefore, a dryout power improvement would be anticipated through a reduction in the eccentricity of the CANFLEX bundle string inside the pressure tube.

One of the options to reduce the bundle eccentricity is to raise the bearing-pad height (from the Mk-IV design of 1.4 mm). This would result in an increase in local subchannel area and flow rate at the narrow-gap region and improve the heat transfer and dryout power. Based on the current CANDU 6 fuel bundle and fuel channel designs, the bearing-pad height is limited to a maximum of about 2.1 mm. Including the manufacturing tolerance, however, the maximum acceptable bearing-pad height is anticipated to be about 1.85 mm.

The full-scale bundle test has been extended to obtain dryout power measurements for the bundle string with two additional bearing-pad heights (1.7 and 1.8 mm). These measurements provide a means to quantify the dryout power improvement with the reduction in bundle eccentricity. The objectives of this paper are to

- Present the dryout power measurements obtained with the CANFLEX bundle string of raised bearing pads,
- Compare the dryout power values for CANFLEX bundle of various bearing-pad heights, and
- Quantify the dryout power improvement of the CANFLEX raised bearing-pad bundles as compared to the 37-element bundle in various crept channels.

2. FULL-SCALE CANFLEX BUNDLE TESTS

Full-scale CANFLEX bundle tests were performed to obtain licensing data in the high-pressure steam-water loop at SL [2]. The 6-m test string was designed and fabricated to simulate as closely as possible a string of 12 aligned CANFLEX bundles in a fuel channel, and includes endplates, bearing pads, buttons and inter-element spacers. Each of the 43 heater rods consisted of Inconel-718 tubes, 481.0 mm heated length, joined by nickel-201 spool pieces to form a 12-segment, 6-m bundle string. The 12-segment heated length of the bundle string was joined to the power bus-bars by nickel-plated copper extensions with the same overall diameter as the Inconel tubes.

Appendages (i.e., spacers, bearing pads and more than 2,000 buttons) were spot-welded at various locations, as specified in the bundle design. The nominal bearing-pad height was 1.4 mm, which corresponds to the design value of the CANFLEX Mk-IV bundle. Thin metal shims (0.3 and 0.4 mm thick) were added to the bearing pads of six elements located at the bottom portion of the bundle to raise the bundle from the flow tube (Figure 1). This resulted in nominal bearing-pad heights of 1.7 and 1.8 mm, respectively. The modification was performed only on the bottom six elements to minimize the preparation procedure. This modification provides the same effect as reducing the bundle eccentricity and increasing the subchannel flow area at the dryout region.

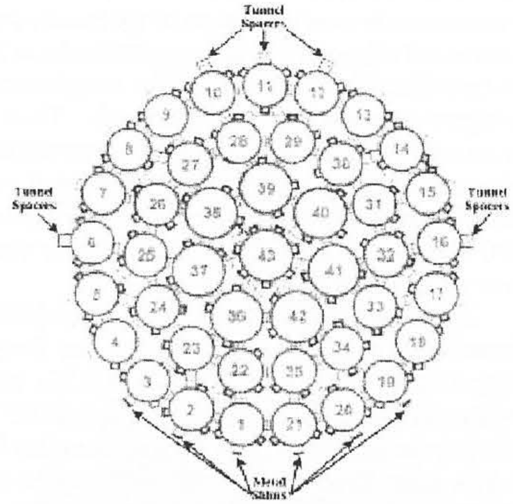

Figure 1: Modified CANFLEX bundle with

Additional spacers were introduced to maintain the bundle string at the eccentric position. These spacers, referred to as "tunnel spacers", were formed into a "U" shape from small pieces of Inconel-718 sheet and were spot welded over the downstream bearing pads of Elements 6, 10, 11, 12 and 16 (see Figure 1). Figure 2 shows the shape and location of a tunnel spacer on the bearing pad. As these spacers are hollow and remote from the dryout locations, they will have an insignificant effect on the dryout power.

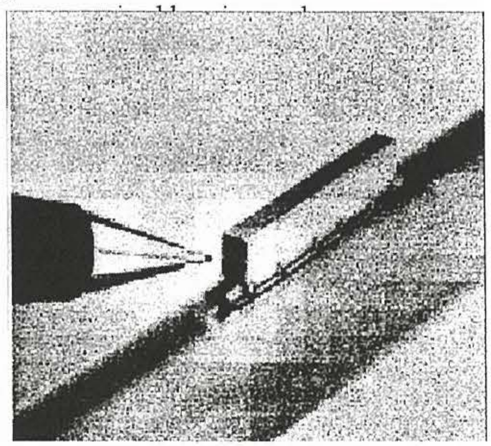
Figure 2: Shape and position of a tunnel spacer.

Power was applied to the bundle string through Joule heating. The sheath thicknesses of the elements were varied along the axial length and from ring to ring. This provided accurate simulations of non-uniform radial and axial power distributions. The radial power distribution simulated a bundle with natural-uranium fuel (local-to-average element power ratios are 1.034, 1.081, 0.873 and 1.056 for the center rod, inner ring, intermediate ring and outer ring). The axial power distribution corresponded to a downstream skewed-cosine profile [2]. Figure 3 presents the normalized axial-flux distribution (i.e., local to average heat-flux ratio) along the heated length. A ceramic flow tube electrically insulated the bundle string from the metal pressure boundary. Three different flow tubes were used in the test [2]; one had a uniform inside diameter of 103.86 mm and the other two had axially varying inside diameters, with a maximum diameter of 107.29 mm and 109.16 mm (3.3% and 5.1% larger than the uniform tube). The uniform flow tube simulated an uncrept pressure tube, while others simulated pressure tubes with various diametral creeps. Figure 4 shows the axial variations in inside diameter of the flow tubes for the crept channels.

Figure 5 shows the set-up of the test station. Fourteen taps were installed along the test section, and were connected to differential-pressure (DP) cells to provide pressure-drop measurements over the length of the bundle string. The taps at the inlet and outlet ends were also connected separately to pressure transmitters to measure the absolute pressures at those locations. K-type thermocouples and resistor temperature devices (RTDs) were used to monitor the fluid temperature at the inlet and outlet ends. The inside surface temperature of the heated sheath was measured with thermocouple-slider assemblies located inside the element. The sliders in all elements were moved axially and rotated at various locations to map out the surface-temperature distributions. Generally, dryout was established when a sharp surface temperature rise of about 5°C from the nucleate-boiling temperature was observed. Details of the experimental set-up and test procedure are described in [2].

A wide range of steam-water flow conditions was covered in the CHF experiment; an outlet-pressure range from 6 to 11 MPa, a mass-flow-rate range from 7 to 29 $kg.s^{-1}$, and an inlet-fluid-temperature range from 200 to 290°C. The majority of the data are directly relevant to the analyses of the regional overpower trip (ROPT) set point in the reactor. Single-phase and two-phase pressure-drop tests were performed at lower pressures and fluid temperatures, as well as at higher mass-flow rates. In addition, specific ONB (Onset of Nucleate Boiling) and OSV (Onset of Significant Void) runs were performed. The flow conditions corresponded closely to those previously obtained with the CANFLEX Mk-IV and 37-element bundles at the same test facility.

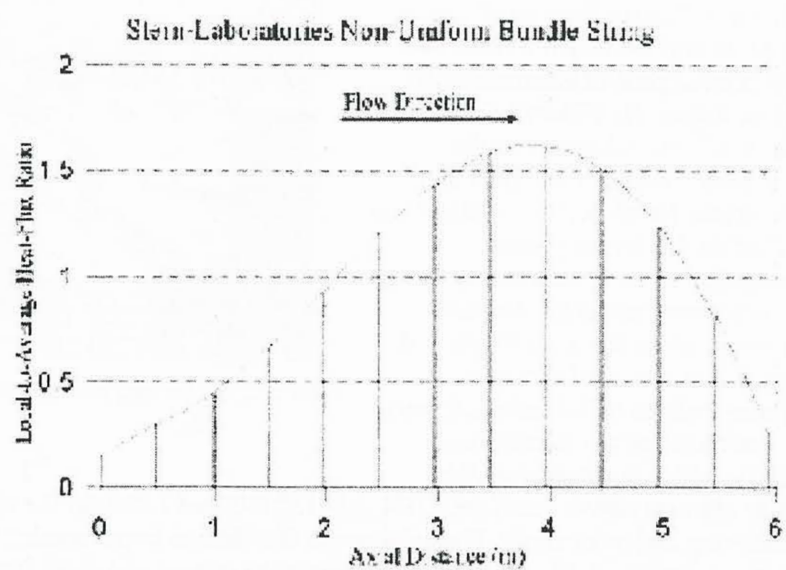

Figure 3: Axial heat-flux distribution of the full-scale bundle-string simulator.

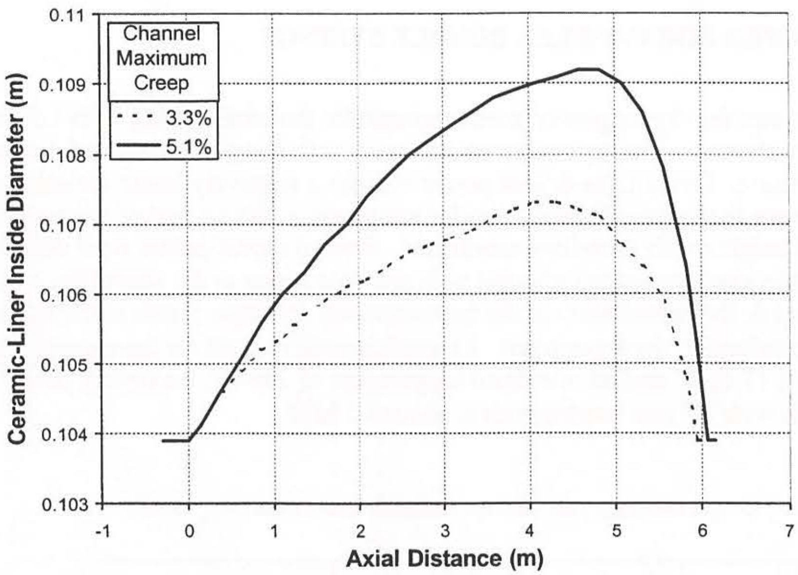

Figure 4: Axial variations of inside diameter in the crept channels.

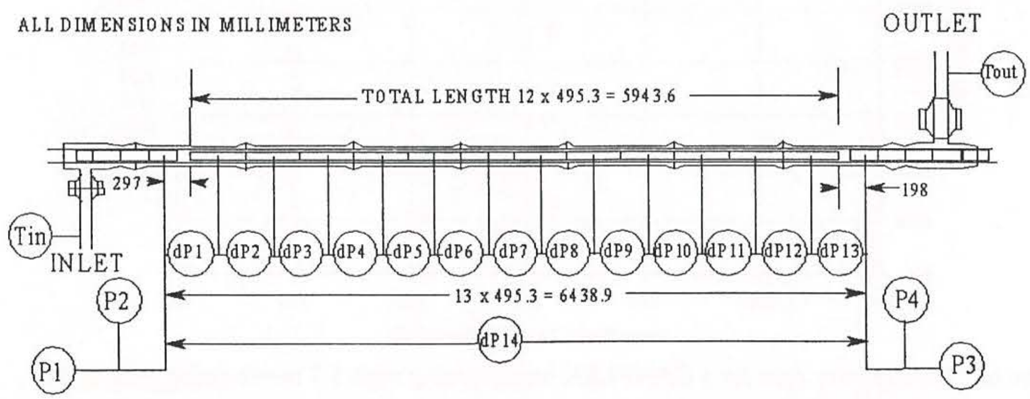

Figure 5: A schematic diagram of the test station in the high-pressure steam-water loop at Stern Laboratories.

3. DRYOUT POWER FOR CANFLEX BUNDLE STRINGS

Figure 6 illustrates the dryout power[2] measurements for the bundle string with 1.7 mm bearing pads in the uncrept channel. The dryout power increases with mass-flow rate and decreases with inlet-fluid temperature. Overall, the dryout power follows a relatively linear variation with the flow parameters over the test conditions. Similar variations in dryout power were observed for other bearing-pad heights with inlet-flow conditions. Several repeat points were obtained at various stages of the experiment (as indicated with multiple points at the same flow conditions). As shown in Figure 6, the repeatability of the measurements (multiple points at the same conditions) was excellent in the experiment. At conditions of interest for the uncrept channel (i.e., a mass-flow rate of 17 $kg.s^{-1}$ and an inlet-fluid temperature of 268°C), the dryout power for the CANFLEX bundle with 1.7 mm bearing pads is about 9.6 MW.

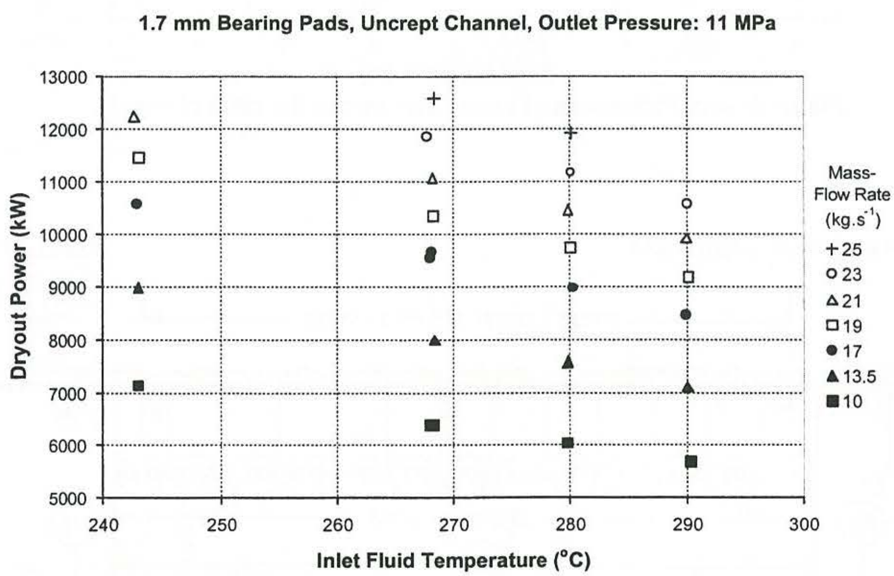

Figure 6: Dryout-power data for a CANFLEX bundle string with 1.7 mm bearing pads in the uncrept channel.

Figure 7 shows the dryout power variation for the 1.7 mm height bearing-pad bundle in a 5.1% crept channel. Overall, the measurements follow the same trend as exhibited in Figure 6 (i.e., dryout power increases with mass-flow rate, and decreases with inlet-fluid temperature). However, the dryout powers are consistently lower than those for the uncrept channel at the same inlet-flow conditions. The dryout power for the 5.1% crept channel is 7 MW at the mass-flow rate

[2] The dryout power represents the total power applied to the bundle string at which the onset of intermittent dryout (OID) occurs. This corresponds to only a single point at the sheath of an element, where the liquid film has broken down, while a continuous liquid contact is maintained at the remaining surfaces of the bundle string. Because of the high heat-transfer rate due to convection (at high flow velocity) and conduction (from the dry spot to the surrounding wet area), a gradual temperature rise is associated with this type of dryout.

of 17 kg.s^{-1} and inlet-fluid temperature of 268°C, as compared to 9.6 MW for the uncrept channel. Based on a constant fuel-string pressure drop, however, the mass-flow rate at dryout for the crept channel is higher than that for the uncrept channel and the dryout power reduction becomes less.

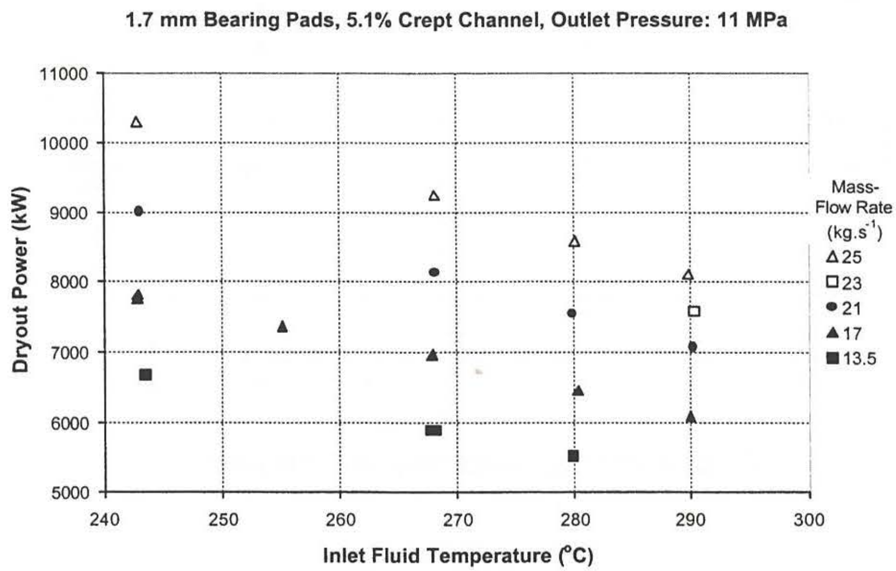

Figure 7: Dryout-power data for a CANFLEX bundle string with 1.7 mm bearing pads in the 5.1% crept channel.

Figure 8 shows the dryout power variation with creep at a pressure of 11 MPa and mass-flow rate of 21 kg.s^{-1}. For given inlet conditions, the dryout power decreases with increasing creep. The dryout power reduction is slightly steeper at low creep values compared to higher creeps. This is to be expected as low values of creep have a higher relative effect on the bypass flow over the bundle (and hence the flow in the critical subchannel) compared to higher creeps. Similar variation is shown for various inlet temperatures and other pressures and mass-flow rates.

The effect of bearing-pad height on dryout power is shown in Figure 9 for the uncrept channel and Figure 10 for the 5.1% crept channel. Overall, the dryout power increases with bearing-pad height. The increasing trend is relatively linear within the current range of bearing-pad height. No significant differences on the dryout power variation with bearing pad height have been noticed between uncrept and 5.1% crept channels. On average, the dryout power increase as a result of increasing the bearing-pad height from 1.4 mm to 1.7 mm is about 8%, and from 1.4 mm to 1.8 mm is about 10%, at the inlet-fluid temperature of 268°C.

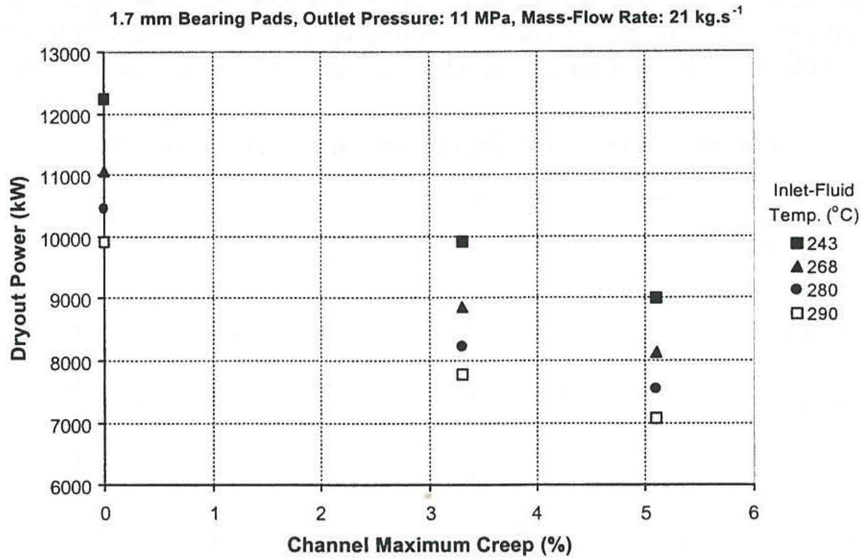

Figure 8: Effect of channel creep on dryout power.

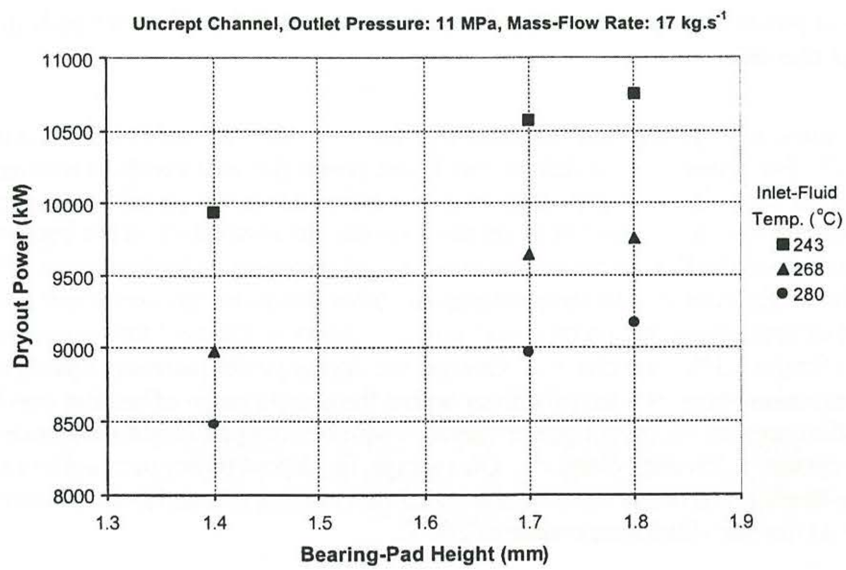

Figure 9: Effect of bearing-pad height on dryout power in the uncrept channel.

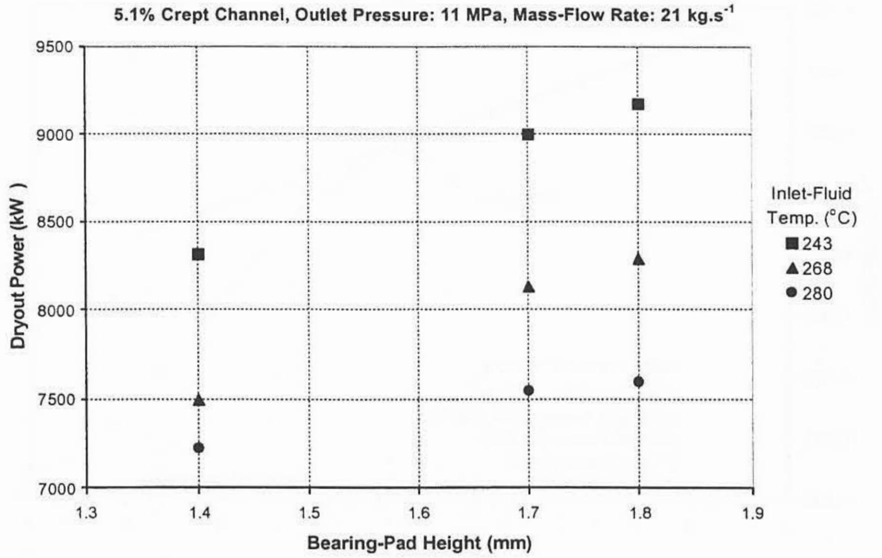

Figure 10: Effect of bearing-pad height on dryout power in the 5.1% crept channel.

4. CHF FOR CANFLEX BUNDLE STRINGS

Local and boiling-length-average (BLA) CHF values[3] were evaluated with the dryout-power measurements and axial heat-flux distribution. Leung et al. [3] defined the BLA CHF as

$$CHF_{BLA} = \frac{1}{z_{DO} - z_{OSV}} \int_{z_{OSV}}^{z_{DO}} q_{local} dz$$

where z_{DO} and z_{OSV} are the locations at dryout and onset of significant void (OSV), respectively, q_{local} is the local heat flux in W/m², and z is the axial distance in metres. The OSV point was located from the pressure distribution established with the pressure-drop measurements along the channel. Figure 11 illustrates the pressure distribution and the OSV point in an uncrept channel. The pressure distribution follows a linear trend, which corresponds to the single-phase region, at the upstream section of the channel. It exhibits a non-linear trend at the downstream section, where two-phase (boiling) flow is encountered. The transition point between single-phase and two-phase flow is referred as the OSV point.

Figure 12 shows the CHF values based on the local and BLA heat-flux approaches for the same flow conditions in the 5.1% crept channel. The scatter among the CHF values is larger for the local than the BLA approach. Leung et al. [3] observed similar scatter among the CHF values for the CANFLEX bundle with the 1.4 mm height bearing pads. The BLA CHF values are more consistent than the local CHF values with increasing dryout quality.

---

[3] Heat fluxes and flow conditions represent cross-sectional average values over the bundle.

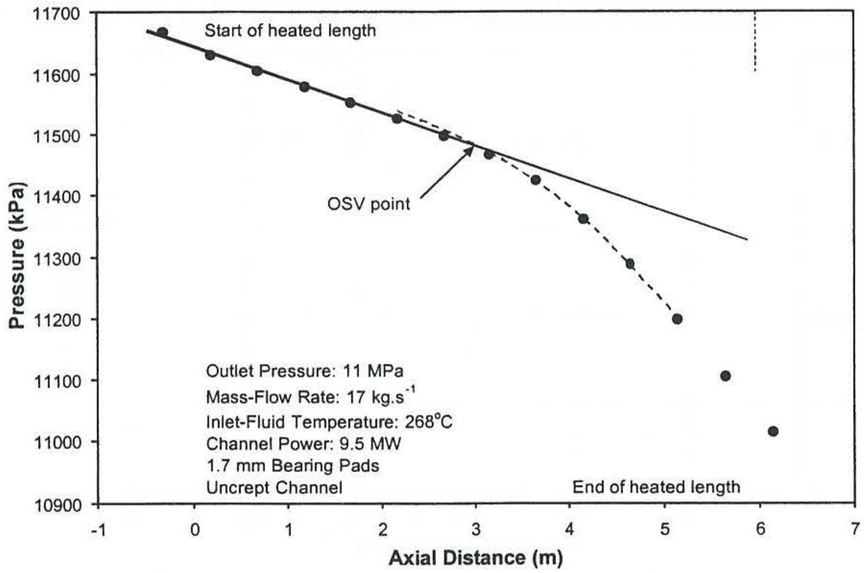

Figure 11: Pressure distribution along the channel.

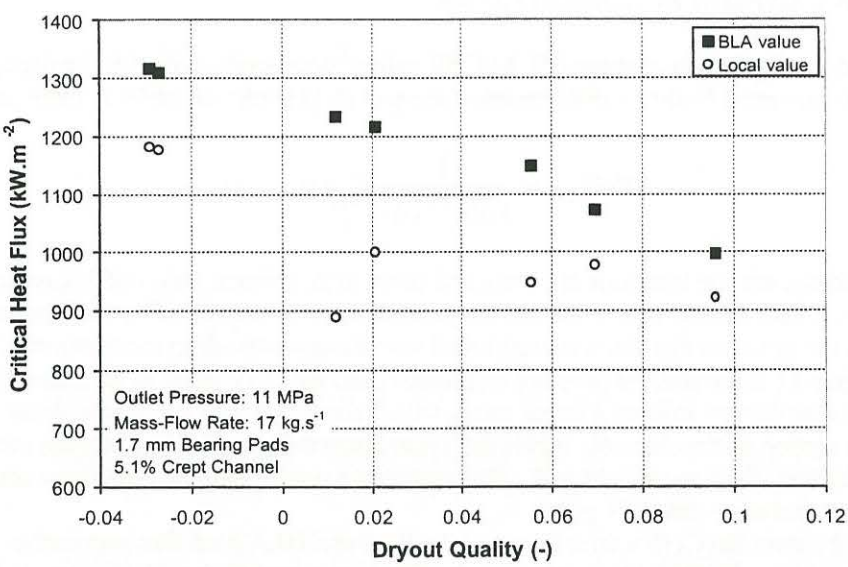

Figure 12: CHF values based on the local and BLA approaches.

Figure 13 compares the BLA CHF values for the CANFLEX bundle with 1.7-mm height bearing pads at various dryout qualities and mass-flow rates. In general, the BLA CHF increases with decreasing dryout quality and increasing mass-flow rate. The same trend was observed in data obtained with tubes, 37-element bundles, and CANFLEX bundles with other bearing pads. A number of data points were obtained at cross-sectional-average[4] subcooled conditions (negative thermodynamic quality). Based on the BLA approach with boiling initiated at the OSV point, these data follow the same trend as exhibited among the saturated dryout data. Similar variations have been observed for other pressures in various crept channels.

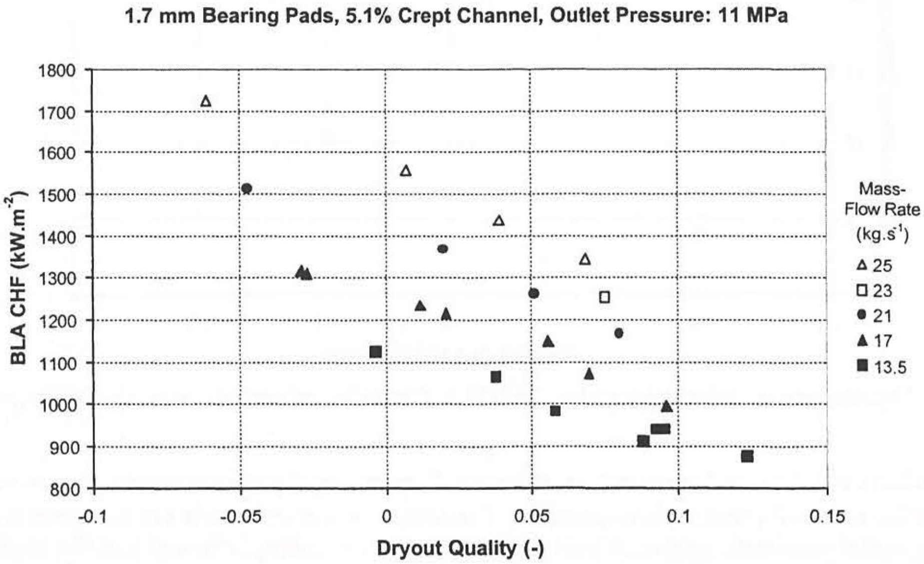

Figure 13: Variation of BLA CHF values with dryout quality and mass-flow rate.

5. COMPARISONS OF DRYOUT POWER BETWEEN CANFLEX AND 37-ELEMENT BUNDLE STRINGS

The dryout powers of CANFLEX bundles with various heights of bearing pads have been compared against those of the 37-element bundle[5] at the same inlet-fluid temperature, mass-flow rate and outlet pressure. Leung et al. [3] presented a similar comparison for the CANFLEX bundle with 1.4 mm bearing pads in a 5.1% crept channel. Figure 14 shows the average dryout-power enhancements of various CANFLEX bundles[6] as compared to the 37-element bundle at an outlet pressure of 11 MPa. Overall, the dryout powers of the CANFLEX bundles are higher than those of the 37-element bundle at conditions of interest for various crept channels. The dryout power enhancement increases with bearing-pad heights and channel creeps. On average, the enhancement

[4] The quality at the critical subchannel is much higher than zero, and annular-film dryout is anticipated.

[5] The dryout power for the 37-element bundle string is calculated with an optimized equation derived from the database.

[6] Test was not performed for the CANFLEX bundle with a 1.8-mm bearing-pad height in the 3.3% crept channel.

varies from 4% for the 1.4-mm height bearing pads in an uncrept channel to 27% for the 1.8-mm height bearing pads in a 5.1% crept channel.

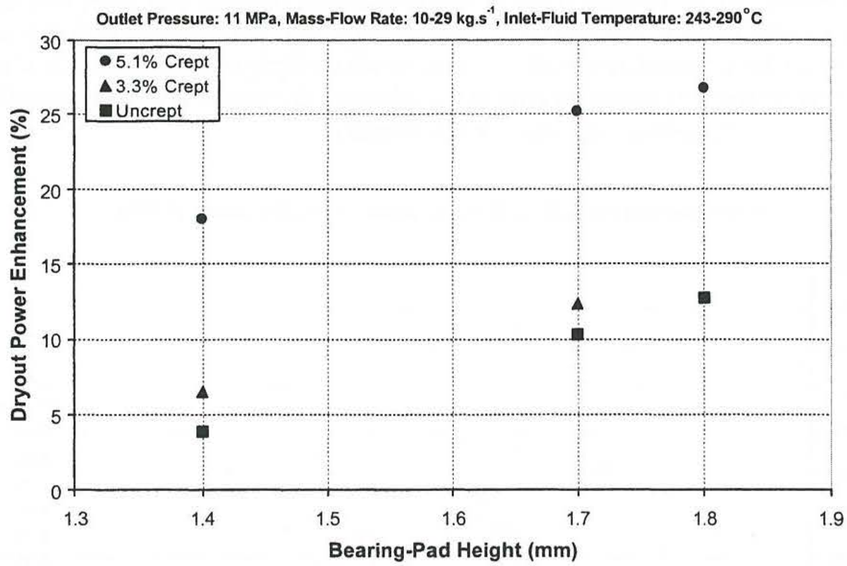

Figure 14: Dryout-power enhancement for CANFLEX bundles of various bearing-pad heights.

The effects of inlet-fluid temperature and mass-flow rate on the enhancement are generally small, but the effect of pressure is noticeable. The dryout power enhancement increases with increasing outlet pressures, generally being 4% higher for the uncrept channel and 9% higher for the 5.1% crept channel at 11 MPa compared to that at 9 MPa.

6. CONCLUSIONS AND FINAL REMARKS

- Bearing pads of several elements in the full-scale bundle simulator at Stern Laboratories have been modified to increase the height from 1.4 to 1.7 and 1.8 mm.
- Dryout power measurements have been obtained with CANFLEX bundles of various bearing-pad heights. The data are consistent and follow established parametric trends with various flow parameters.
- Local and BLA CHF values have been calculated with the dryout-power data. The scatter is much larger for the local CHF values than the BLA CHF values at the same local dryout conditions.
- The dryout power is consistently higher for the CANFLEX bundles with high bearing pads than those with low bearing pads. On average, the dryout power improvements are about 8% and 10%, respectively, for the 1.7 mm and 1.8 mm bearing pads, compared to 1.4 mm bearing pads.
- The dryout power is higher for the CANFLEX bundles than for the 37-element bundles at conditions of interest. The average dryout power enhancement varies from 4% for the 1.4 mm

bearing pads in the uncrept channel to 27% for the 1.8 mm bearing pads in the 5.1% crept channel at an outlet pressure of 11 MPa.

ACKNOWLEDGEMENT

The authors would like to thank the test engineers at Stern Laboratories for performing the experiment and providing the experimental data.

REFERENCES

[1] Inch, W. and Suk, H.C., "Demonstration Irradiation of CANFLEX in Pt. Lepreau", Proc. of the IAEA Technical Committee Meeting on Fuel Cycle Options for LWRs and HWRs, Victoria, Canada, 1998.

[2] Dimmick, G.R., Inch, W.W., Jun, J.S., Suk, H.C., Hadaller, G.I., Fortman, R.A. and Hayes, R.C., "Full Scale Water CHF Testing of the CANFLEX Bundle", Proc. of the 6^{th} International Conference on CANDU Fuel, Vol. 2, pp. 103-113, Sept. 26-30, 1999.

[3] Leung, L.K.H., Groeneveld, D.C., Dimmick, G.R., Bullock, D.E. and Inch, W.W., "Critical Heat Flux and Pressure Drop for a CANFLEX Bundle String Inside an Axially Non-Uniform Flow Channel", Proc. of the 6^{th} International Conference on CANDU Fuel, Vol. 1, Sept. 26-30, 1999.

[4] Kobori, T., "Critical Heat Flux Measurements in a Full Scale Rod Cluster", Bulletin of the JSME, Vol. 19, No. 131, pp. 540-546, 1976.