SIMULATION OF CRITICAL-HEAT-FLUX ENHANCEMENT IN FUEL BUNDLES BY TUBES EQUIPPED WITH INSERTS

by

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ABSTRACT

CHF-enhancement data obtained in tubes equipped with inserts and tested in water and Freon-134a, were compared to those obtained in 37-element bundles equipped with extra planes of spacer and bearing pads. The objective of the studies was to identify the following effects on CHF enhancement in both geometries: (i) spacing between insert planes, (ii) the number of similar/dissimilar insert planes, (iii) fluid type, and (iv) flow conditions. The spacing was found to be the major geometric factor affecting the CHF-enhancement ratio K (defined as the ratio in CHF enhancement-equipped tube to the CHF in a bare tube for the same local flow conditions). By decreasing the relative spacing, L/D_{hy}, for example from 30 to 10, K can reach the value from 1.0 to 1.7, depending on flow conditions. Among the flow parameters, the critical quality, x_c, can very strongly affect K (K increases with x_c in both geometries, for mass flux $G_W > 2$ Mg/m^{2}s); pressure has a much weaker effect on K. CHF enhancement does not depend on fluid type, provided that the conditions in the fluids meet the CHF fluid-to-fluid modelling requirements. The above-mentioned K characteristics found in tubes with inserts are qualitatively similar to those in rod bundles. This observation has permitted the derivation of a CHF-enhancement prediction method for a subchannel code based on the tube data, and has subsequently been used to perform many separate-effect studies in support of optimization of CHF-enhancing devices applied to CANFLEX: a new 43-element fuel bundle for CANDU reactors.

NOMENCLATURE

CHF	critical heat flux defined as the test-section power to heated-area ratio,
D	inner tube diameter; bundle equivalent diameter,
G	mass flux defined as the mass-flow rate to flow-area ratio,
K	CHF-enhancement ratio defined by Equations (1) and (2)
L	spacing between insert planes; downstream distance from an insert plane to the test-section heated-length end,
P	pressure at test-section outlet,
SP	spacer plane,
T	temperature,
x	quality,
ε	flow-obstruction area of an insert/appendage plane.

Subscripts

c	critical at CHF conditions,
F	Freon,

hy	hydraulic,
H	heated length,
in	inlet conditions,
NS	no spacers, smooth geometry,
ref	reference,
W	water.

INTRODUCTION

Water-cooled nuclear reactors are usually designed to operate at power levels which allow an adequate margin to critical heat flux (CHF). One method of increasing the reactor-power output is to improve the CHF performance. Many attempts have been made to do so by introducing various inserts into the flow area of reactor-fuel bundles. Twisted tapes, grids with different mixing vanes, various types of spacers, and single appendages are some examples of the inserts used. The inserts increase the turbulence level in two-phase flow, affect vapour- and liquid-phase distributions, increase droplet deposition on the heated wall in a dispersed-flow regime, and prevent bubble crowding near the wall in a bubbly-flow regime. These mechanisms increase or enhance the CHF by providing more liquid to better cool the heated wall.

Since the early 1960s', various promising CHF-enhancement techniques have been investigated quite extensively in many heat-transfer laboratories. For example, Becker and Hernborg (1964) studied CHF in a circular 7-rod bundle with grid spacers. A similar 7-rod bundle geometry was tested by Adorni et al. (1966), where ferrule spacers (obstructing the flow area by 19%, having a pitch of 400 mm) were used. In both cases the CHF increased by 10 to 18%. Perepelitsa et al. (1978) used a square 4-rod bundle with the following types of grids: (i) honeycomb regular grids, (ii) grid-flow spoilers, and (iii) a combination of both. The (ii) design performed much better than the (i) design. Stevens and Wood (1966) investigated the effectiveness of three types of grids in a circular 19-rod bundle: (i) castellated, (ii) tubular, and (iii) helical wire wraps. The wire wraps turned out to be the worst performer, but the castellated grid improved the CHF by 14%, and the tubular grid by 26%, as compared to that by the wire wraps. Groeneveld and Yousef (1980) reviewed the effects of various spacing devices on CHF, post-CHF heat transfer and pressure drop in nuclear fuel bundles. The majority of studies indicated beneficial effects of spacing devices on CHF. In general, it was found that the maximum increase in critical power occurred at high flows, high qualities, and short axial grid spacings.

Over the past 30 years, researchers at Chalk River Laboratories (CRL) have gained substantial experience in the development of CHF-enhancement techniques to improve the thermal performance of nuclear fuel bundles for CANDU reactors. In a reactor, a string of twelve fuel bundles is contained in an unheated pressure tube. As a result of this design a liquid film flowing along the pressure tube does not contribute effectively to heat removal from the fuel. For this reason, early CRL CHF-enhancement studies, concentrated on decreasing the film flow by redirecting it to the heated fuel surfaces using rings or film trippers. Further designs, that included grid spacers and extra spacer planes, turned out to be more effective than the film trippers.

Groeneveld (1981) reported a significant increase in CHF (up to 230%) when the grid-spacer pitch was decreased from 45.7 to 15.2 cm, as applied to a 6-m long 31-element bundle, tested in Freon-12. He also reported a beneficial effect of extra spacer planes added to a 6-m long string of twelve CANDU 37-element bundles. When two extra spacer planes were added to each 50-cm long bundle segment (thus decreasing the pitch from 25 cm to 12.5 cm) the CHF increased by 30 to 50%. Groeneveld et al., (1986) reviewed other techniques (e.g., vortex generators) to enhance CHF in CANDU fuel bundles.

The search for a more efficient CHF-enhancement technique for CANDU reactor fuel bundles culminated in the development of a new CHF-enhancing device, called button, for which AECL was awarded a patent (Sollychin et al., 1995). This method has been applied to a new fuel-bundle design, CANFLEX, which is presently being tested extensively (e.g., Dimmick et al., 1997).

This paper addresses whether CHF data obtained in a simple geometry, a circular tube equipped with planes of appendages, can adequately simulate the CHF enhancement in a fuel bundle equipped with a number of spacer planes. This will be done by comparing the CHF-enhancement data obtained in both flow geometries at CRL. Furthermore, another tool will be presented to investigate the CHF enhancement in rod bundles based on post-dryout data.

EXPERIMENTS IN TUBES WITH INSERTS

Facilities

The CHF-enhancement tests in tubes were performed in water and Freon-134a; therefore, two facilities were used: (i) the high-pressure and high-temperature water MR-1A loop, and (ii) the Freon MR-7A loop. In general, the flow path in both loops is similar, consisting of a circulatory pump, a main flow-control valve, a flowmeter, an electric preheater, a test section, a condenser, and a subcooler. The MR-1A loop can be operated at P_W up to 11 MPa, and T_{in} up to 315 ^oC, whereas P_F up to 2 MPa, and T_{in} up to 75^oC, limit the operation of the MR-7A loop. Flow rates up to ~ 500 g/s can be obtained in both loops.

Test Sections

For all tests, two types of test sections were used: (i) the reference, and (ii) the CHF-enhancement test section (Figures 1 and 2 are the examples of (ii)). They were made of Inconel 600 tubes, having an 8-mm ID, a 1-mm wall thickness, and L_H varied from 1.3 m to 1.98 m. The test sections were positioned vertically, with upward flow. The reference test section was a bare tube, whereas the CHF-enhancement test section was equipped with inserts, spaced equally along the heated length.

When the effect of spacing on CHF enhancement was important, a smooth tube equipped with moveable inserts was used. The inserts were relocated by a novel CRL technique using external magnets (Figure 1). These tests could only be performed in Freons because low test-section wall temperatures (up to 80°C) did not affect the magnets' performance. Two types and sizes of moveable inserts were used: the rings (flow blockage, ε = 30%; to simulate the effect bundle junctions) and three spacers per plane (ε = 17.8%, to simulate the effect of bundle spacer plane, similar to those shown in Figure 2).

When parametric trends on CHF enhancement were important in water, the above-described technique could not be used (wall temperatures up to 800°C). The inserts had to be permanently welded to the test-section wall (Figure 2). To better utilize the test section, two different types of inserts were placed at both ends. At one end, four planes of inserts, three spacers per plane (ε = 21.3%), were spaced by L = 25 cm. At the other end, six planes of inserts, two cylindrical buttons per plane (ε = 14.2%) were spaced by L = 12.5 cm (the buttons are not discussed in the paper). Figure 2 shows the test section to study the effect of spacer-type flow inserts, located at the downstream end. By turning the test section upside down, the button types could be tested using the same test section.

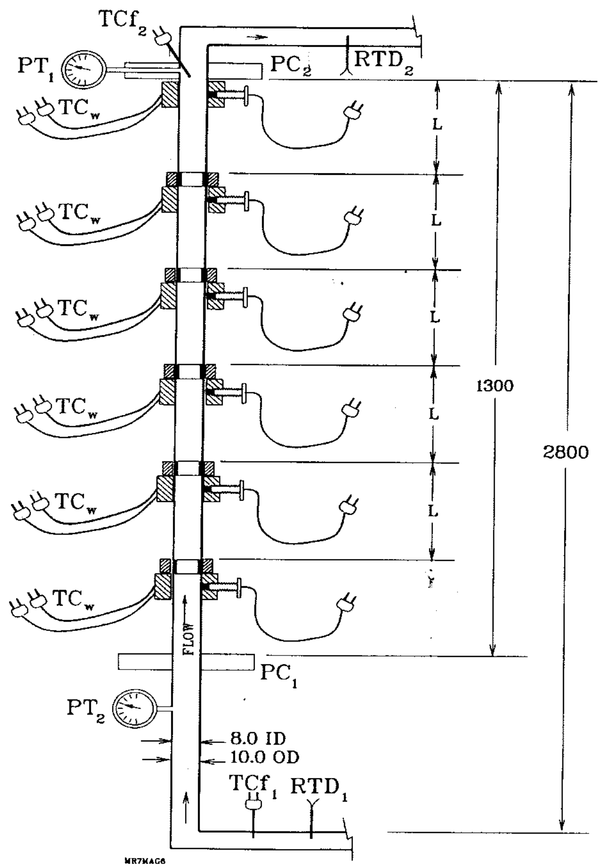

Figure 1: Test Section with Moveable CHF-Enhancement Inserts Held by External Magnets (to test the spacing effects on CHF enhancement in Freon-134a; Doerffer et al., 1996).

The test sections were axially uniformly resistance-heated by DC generated by two power supplies: (i) 350 kW in the MR-1A loop, and (ii) 50 kW in the MR-7A loop.

Test Conditions

Test matrices covered the following ranges of parameters: (i) in Freon-134a, P_F from 0.96 to 1.84 MPa, G_F from 0.5 to 5 Mg/m^{2}s, T_{in} from its available minimum to saturation, and (ii) in water, P_W from 6 to 11 MPa, G_W from 0.5 to 6 Mg/m^{2}s, T_{in} over a similar range as above. Usually, the conditions in both fluids were equivalent to each other, meeting the CHF fluid-to-fluid modelling requirements. The test matrices depended on a given test type. At times, they were limited to one mass flux and pressure only, when a significant number of runs was required (e.g., to investigate the effect of spacing or a number of insert planes).

CHF-Enhancement Ratio

The CHF-enhancement ratio, K, was defined as

$$K_{\frac{L}{NS}} = \frac{CHF_L(P, G, x_c, L/D_{hy})}{CHF_{NS}(P, G, x_c, \infty/D_{hy})} \tag{1}$$

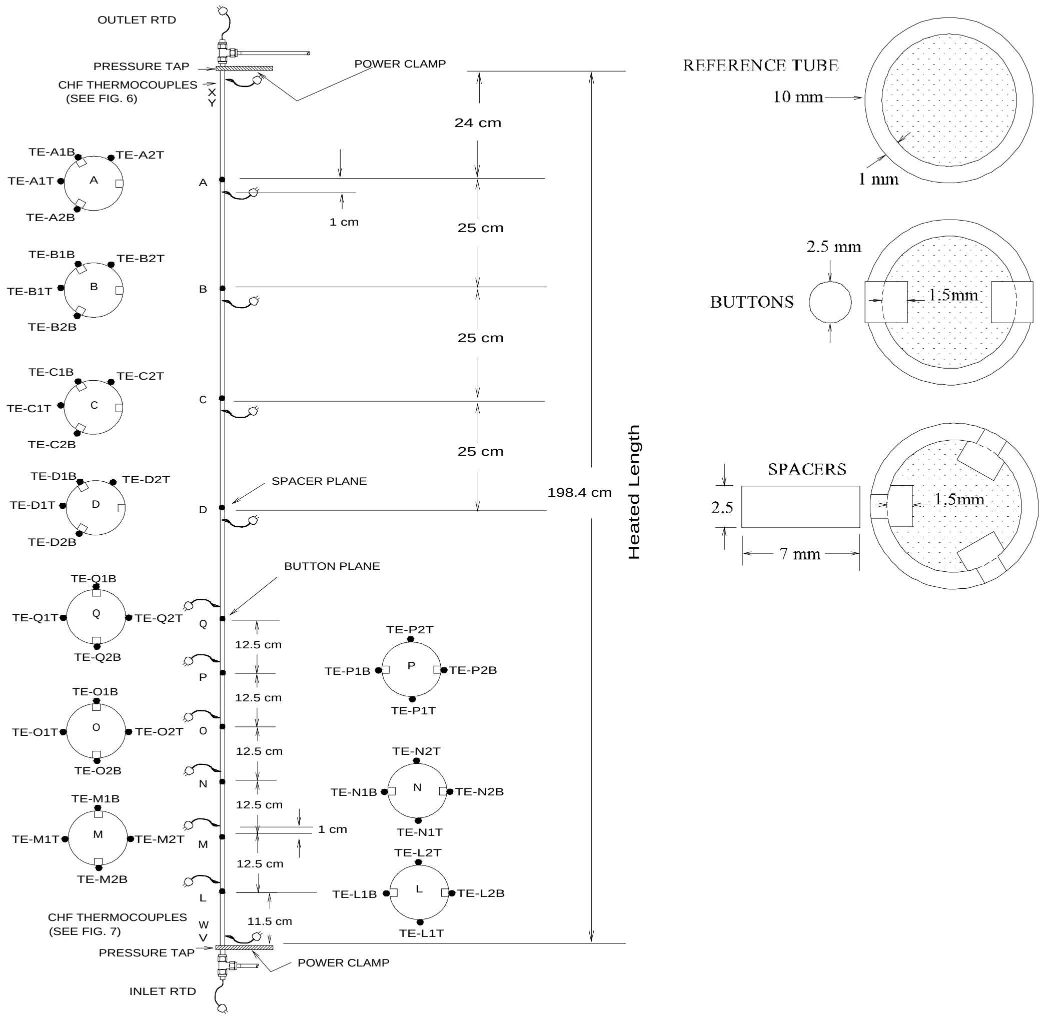

Figure 2: Test Section with CHF-Enhancement Inserts (four planes of three-spacer planes at the downstream end, and six planes of two cylindrical-button planes at the upstream end; insert-plane details are shown at the left-hand side; Doerffer and Groeneveld, 1999).

where: L is the downstream distance from an insert plane, where CHF enhancement was assessed, or the pitch between insert planes; NS denotes “no spacers” or a smooth tube without any inserts. The ratio was obtained at the same local conditions (P, G, and x_c). The overall accuracy in the K values was obtained within ±5% from both the water and the Freon-134a tests.

EXPERIMENTAL RESULTS OF CHF ENHANCEMENT IN TUBES WITH INSERTS

Effect of Spacing

To study the effect of spacing, L, (and the effect of the downstream distance, L, from the insert to the heated-length end), the insert was placed at L = 150 cm and the CHF was reached (it occurred at the test-section end). Then the insert was relocated 10 to 15 cm downstream by moving the external magnet. Again, the CHF was obtained under the same flow conditions. The procedure (moving the insert towards the downstream end with the same steps) was repeated until the CHF location shifted just upstream of the insert (upstream dryout occurred). The upstream dryout occurred because a higher heat flux applied to the test section (enhancing the effect of the insert) increased the local quality (just upstream of the insert) to the value corresponding to the CHF value, in a bare tube at given P, G, and T_{in}. The calculations and comparisons with the CHF-reference results confirmed this observation.

To suppress the upstream dryout, the second insert was introduced from the test-section inlet and placed behind the first one, at the same distance, L, as that between the first insert and the test-section end. The enhancing effect of the second insert suppressed the upstream dryout and shifted its location back to the test-section end. Then, two inserts were moved simultaneously downstream in steps, maintaining the same L. If upstream dryout occurred again, the third insert was introduced, and this procedure was repeated.

These tests were performed with the sets of spacers (ε = 17.8%) and rings (ε = 30%). Figure 3 shows an example of the effect of L/D_{hy} on K for the sets of spacers. K increases strongly with decreasing L/D_{hy}.

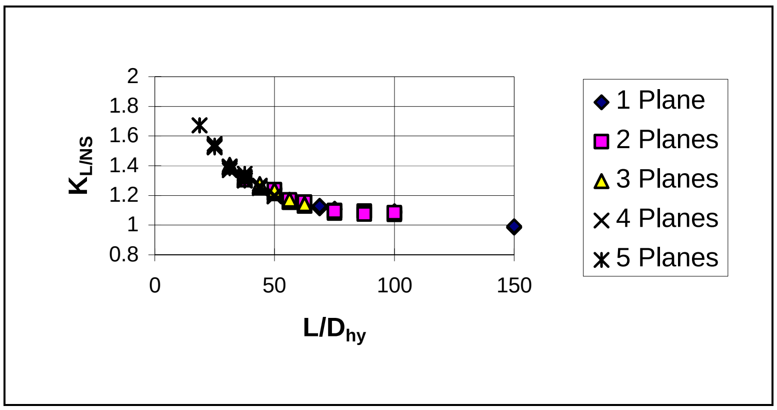

Figure 3: Effect of Spacing and Number of Spacer Planes (ε =17.8%) on CHF Enhancement in a Tube (tested in Freon-134a at P_F = 1.67 MPa, G_F = 4 Mg/m^{2}s, and x_c = 0.15-0.22).

Effect of Identical Insert Planes

The above-mentioned tests also allowed an opportunity to investigate the effect on a number of identical insert planes either made of rings or spacers, on K. Figure 3 shows that regardless of the number of insert planes, there is no effect on K. It indicates that there is no cumulative effect of identical multiple planes on K within the tested ranges of spacing L (or L/D_{hy}).

Effect of Dissimilar Insert Planes

CANDU reactor fuel bundles do not have identical planes of appendages in a series, each plane is different. For example, a typical 37-element bundle contains an end plate, a mid-spacer plane, an end plate again, followed by the end plate of the next bundle (creating a bundle junction), and so on (L = 25 cm). In a CANFLEX 43-element bundle, in addition to the planes of the 37-element bundle, there are two planes of buttons, each located between the end plate and the mid-spacer plane (L = 12.5 cm).

A special test was performed to simulate the situation encountered in the rod bundles. The main purpose of it was to find out if an insert plane of a larger ε (simulating the bundle junction) affects K generated by a plane of a smaller ε (simulating the mid-spacer plane). The new insert set-up was arranged as follows (using the previously tested inserts: the spacers (ε = 17.8%) and the rings (ε =

30%)): the last downstream insert was a plane of spacers, the next upstream insert was the ring, and again the spacers, the ring, the spacers, etc. One series of the tests was performed with L = 12.5 cm (L/D_{hy} = 15.62), and the second with L = 25 cm (L/D_{hy} = 31.25).

Figure 4 shows an example of the CHF results obtained with: (i) the new set-up (rings/spacers), (ii) the spacers only (both (i) and (ii) with L/D_{hy} = 15.62), and (iii) the reference (in Freon-134a at P_F = 1.67 MPa, and G_F = 3 Mg/m^{2}s). No cumulative effect of the dissimilar multiple planes was found. CHF (or K) is practically the same for both configurations, and it implies that K was generated by the last downstream insert plane (in an axially uniformly-heated test section). Note that such an investigation of the cumulative effect in rod bundles would be practically impossible.

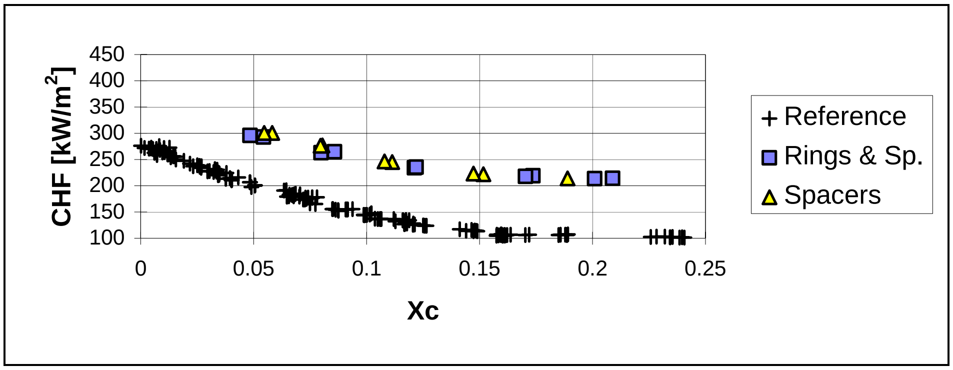

Figure 4: Comparison of Effect of Similar and Dissimilar Insert Planes on CHF Enhancement in a Tube (in both cases the spacer plane was the most downstream; tested in Freon-134a at P_F = 1.67 MPa, G_F = 3 Mg/m^{2}s and L = 12.5 cm (L/D_{hy} = 15.6)).

Effect of Fluid Type

Doerffer and Groeneveld (1999) tested CHF enhancement in water and Freon-134a using identical test sections in both fluids (Figure 2). The equivalent test conditions in both fluids were established from the CHF fluid-to-fluid modelling technique (Ahmad 1973; Doerffer et al., 1991). Figure 5 shows an example of the CHF-enhancement results obtained in both fluids.

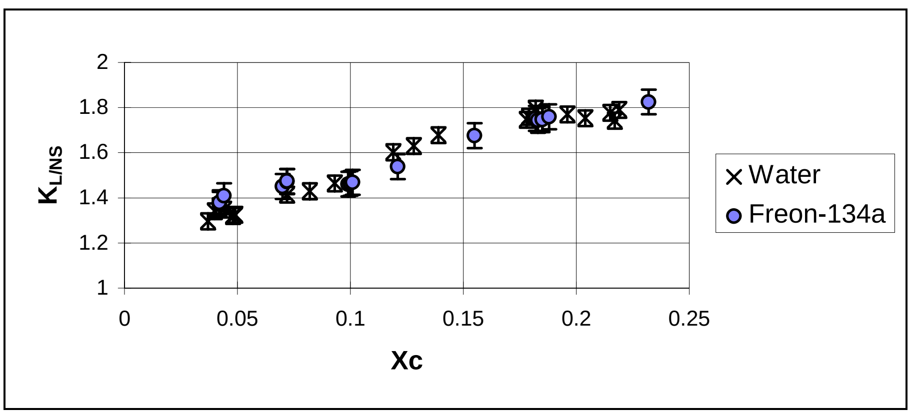

Figure 5: CHF Enhancement due to Planes of Spacers at L/D_{hy} = 15.62 cm (ε = 21.3%) Obtained in Water and Freon-134a under Equivalent Conditions (P_W = 10 MPa and G_W = 5.5 Mg/m^{2}s, and P_F = 1.67 MPa and G_F =3.92 Mg/m^{2}s).

They proved that this technique is also valid for the fluid-to-fluid modelling on the CHF enhancement. K is the same regardless of fluid type if the conditions in the fluids are equivalent (determined from the CHF fluid-to-fluid modelling technique). This conclusion supports the relevance of CHF experiments on a full-length-bundle string in Freon-134a, as their results can be valid and applicable to those in the equivalent-water conditions.

Effect of Flow Conditions

K depends strongly on the critical quality, and it increases with increasing quality (Figure 5). This increase is observed at a higher mass flux ($G_W > 2$ Mg/m^{2}s).

Figure 6 shows the effect of G on K, which seems to be quality dependent. For lower critical-quality values ($x_c < 0.1$) this effect is not significant, but K increases with G for higher qualities. The effect of pressure on K (Figure 7) seems to be significant only at the lowest pressure tested ($P_W = 6$ MPa), whereas over the pressure range from 9 to 11 MPa, there is no noticeable effect.

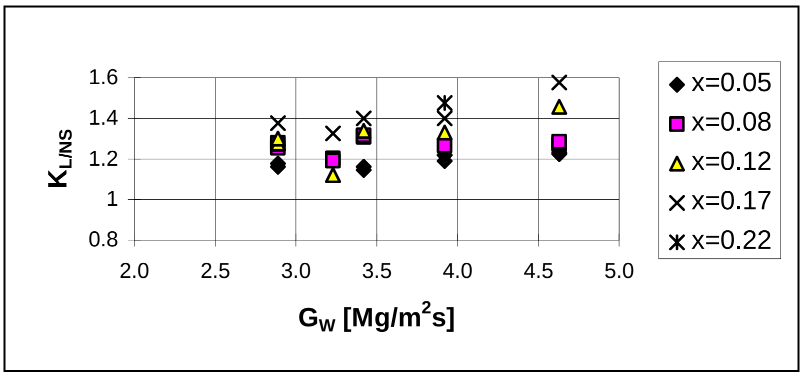

Figure 6: Effect of Mass Flux on CHF Enhancement as Observed in a Tube ($L/D_{hy} = 31.25$, $\varepsilon = 21.3\%$) in Water at $P_W = 10$ MPa and Various Critical Qualities.

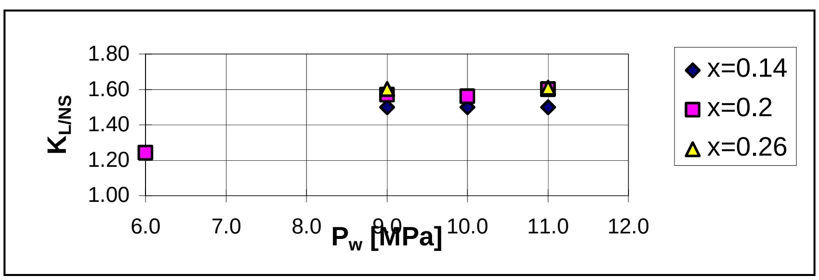

Figure 7: Pressure Effect on CHF Enhancement Effect as Observed in a Tube ($L/D_{hy} = 31.25$, $\varepsilon = 21.3\%$) in Water at $G_w = 4$ Mg/m^{2}s and Various Critical Qualities.

CHF-ENHANCEMENT RESULTS OBTAINED IN ROD BUNDLES

Many CHF tests were performed at CRL with 37-element bundles using various types of CHF-enhancement techniques (mentioned in the introduction). In this paper, we will consider only the technique which generated CHF enhancement using various number of spacer planes as that in tubes with insert planes. Thus the CHF enhancement can be compared in both geometries. Note that these rod bundles were axially uniformly heated, and as a result of that the CHF occurred always at the end of the heated length, thus being controlled by the downstream spacer plane of the last bundle.

Figure 8 shows a typical 37-element bundle (with one mid-spacer plane, serving as a reference) and an example of the CHF-enhanced 37-element bundle using extra four spacer and bearing-pad planes.

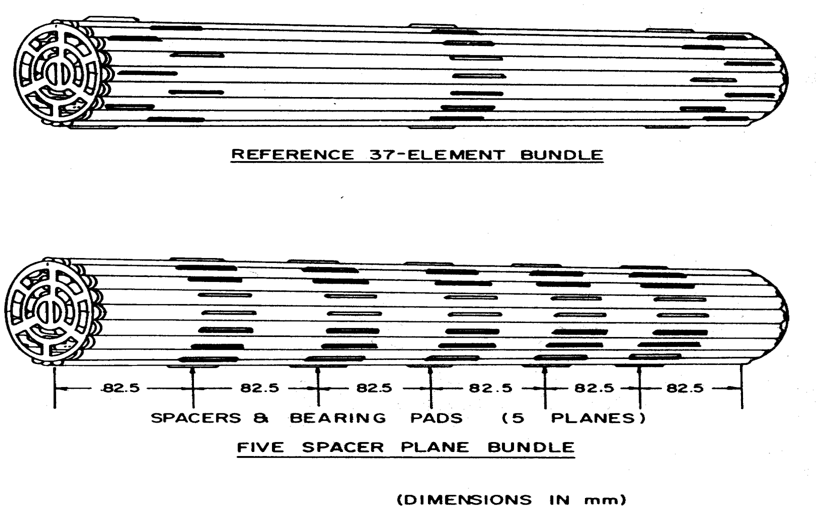

Figure 8: Reference 37-element Bundle with One Mid-Spacer Plane and CHF-enhanced 37-element Bundle with Five Spacer Planes.

The CHF-enhancement ratio in rod bundles was defined relative to a reference geometry, where the appendage-plane pitch (L = 25 cm in a 37-element CANDU rod bundle is considered "bare" without any CHF-enhancing planes) serves as the distance at which the CHF is assumed as the reference value. K was defined by the following ratio:

$$K_{\frac{L}{\mathrm{Re}\,f}} = \frac{CHF_L(P, G, x_c, L/D_{hy})}{CHF_{\mathrm{Re}\,f}(P, G, x_c, 25/D_{hy})} \tag{2}$$

In this approach, the CHF ratio provides *a relative value* of the CHF enhancement above the reference value. The CHF-reference value reflects itself the CHF enhancement existing at the initial CHF location caused by the upstream appendage plane. This is in contrast to the approach defined by Equation (1), where the CHF ratio provides *an absolute value* of the CHF enhancement. Note that P, G, and x_c are the cross-section average values for rod bundles, and not those of the critical subchannel where CHF occurs (unfortunately the local values are not measured in rod bundles during CHF tests).

The major CHF-enhancement characteristics in 37-element bundles are shown in the following figures:

- Figure 9: the effect of critical quality, x_c, at an equivalent pressure P_W = 9.7 MPa and various mass-flux values, for the rod bundles with five spacer planes (5 SP where L/D_{hy} = 11.15),
- Figure 10: the effect of mass flux at an equivalent pressure P_W = 9.7 MPa and a quality x_c = 0.35, for the rod bundles equipped with two spacer planes (2 SP where L/D_{hy} = 22.36), three spacer planes (3 SP where L/D_{hy} = 16.74) and with 5 SP,
- Figure 11: the effect of pressure at various G values and x_c = 0.35, for the 37-element bundles with 5 SP, and
- Figure 12: the effect of spacing (or the equivalent effect of the number of spacer planes), the combined results obtained in three bundle designs.

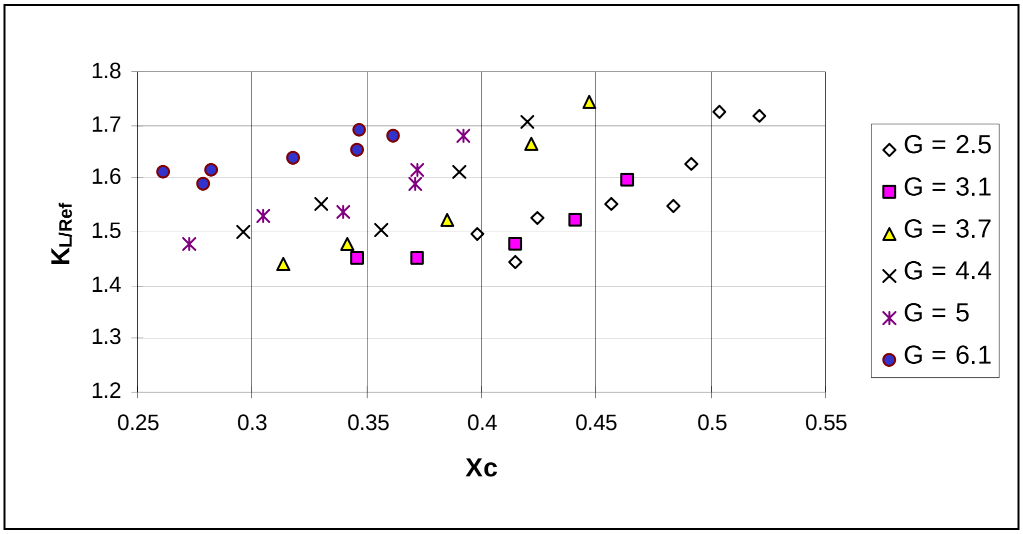

Figure 9: Dryout-Quality Effect on CHF Enhancement Observed in 37-element Bundle with Five Spacer Planes (L/D_{hy} = 11.15) at P_w = 9.7 MPa and Various Mass-Flux Values (G_W in Mg/m^2s; tests performed in Freon-12).

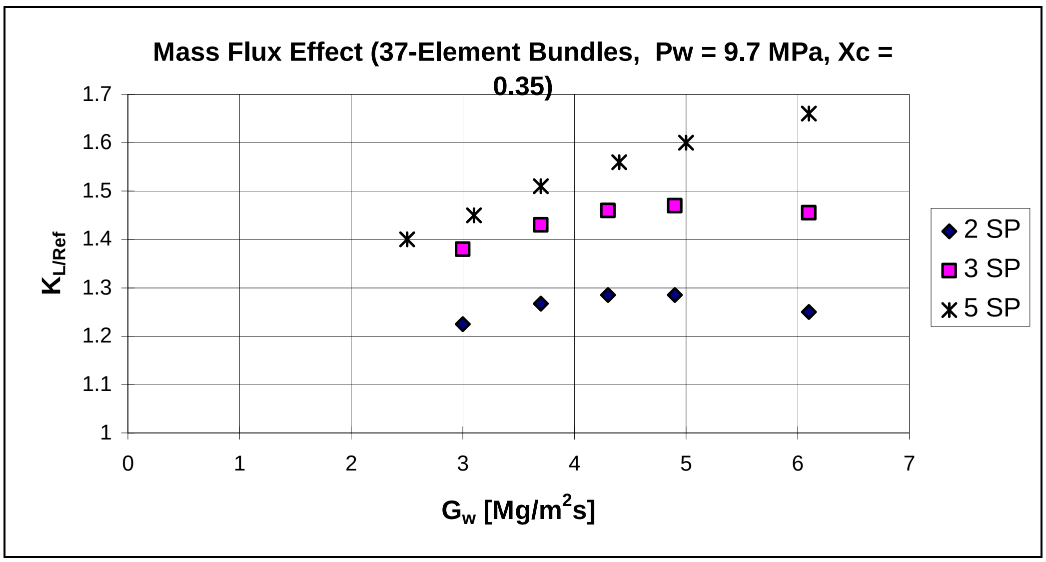

Figure 10: Mass-Flux Effect on CHF Enhancement Observed in 37-element Bundles with Various Number of Spacer Planes at P_w = 9.7 MPa and x_c = 0.35 (tests performed in Freon-12).

COMPARISON OF CHF-ENHANCEMENT RESULTS OBTAINED IN ROD BUNDLES AND TUBES WITH INSERTS

Strictly speaking, the direct quantitative comparison of CHF enhancement in rod bundles and tubes is impossible. K in rod bundles can be defined only in terms of the bundle cross-section average parameter values, not the local values of the critical subchannel (such values are not measured), whereas K obtained in tubes is based on the local values. Nevertheless, it is worth comparing this phenomenon in both geometries on a cross-section average basis.

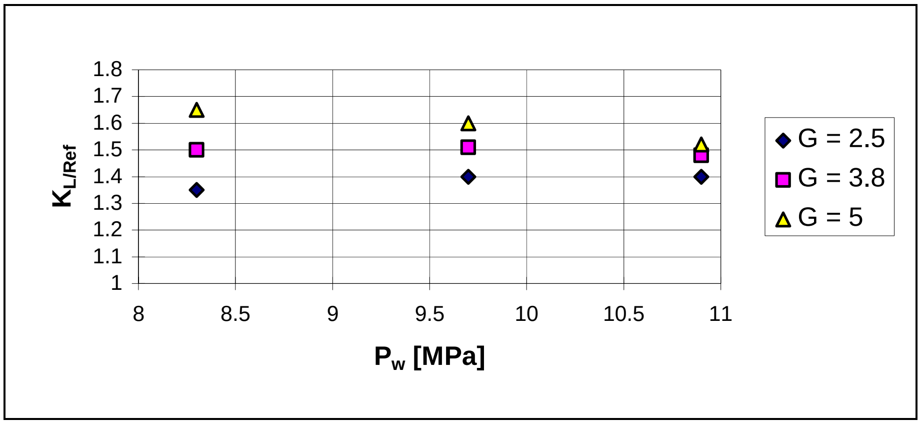

Figure 11: Pressure Effect on CHF Enhancement Observed in 37-element Bundle with Five Spacer Planes at Various Mass-Flux Values (G_W in Mg/m^2s) and $x_c = 0.35$ (tests performed in Freon-12).

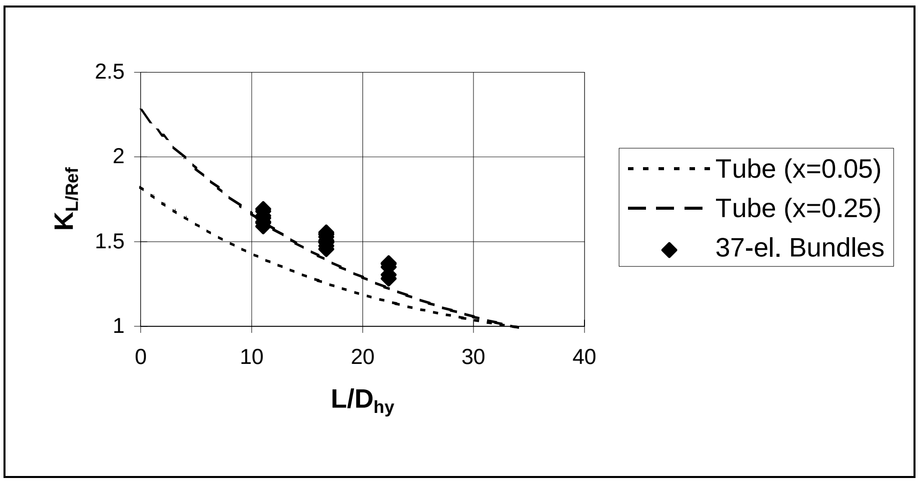

Figure 12: Comparison of Spacing Effect on CHF Enhancement in 37-element Bundles with the Trend Observed in a Tube with Inserts at $P_w = 9.7$ MPa and $G_w = 6\ Mg/m^2s$ Obtained at Minimum $x_c = 0.05$ and Maximum $x_c = 0.25$.

To compare the effect of spacing, the tube results have to be transformed to the same reference as those obtained in rod bundles (i.e., to the characteristic L = 25 cm). Using Equation (1) for tubes and Equation (2) for rod bundles, the tube results can be related to an equivalent rod-bundle as follows:

$$K_{\frac{L}{\mathrm{Re}f}} = K_{\frac{L}{NS}} \cdot \frac{CHF_{NS}(P,G,x_c,\infty/D_{hy})}{CHF_{\mathrm{Re}f}(P,G,x_c,25/D_{hy})} \tag{3}$$

Figure 12 shows a comparison of the CHF results obtained in 37-element bundles with two, three and five spacer planes with the corresponding trends obtained in a tube with inserts (transformed according to Equation (3)) at the same pressure and mass flux. The range of critical quality tested differs in both geometries: the maximum $x_c = 0.25$ in tubes (e.g., Figures 4 and 5) while in rod bundles this value was the minimum (e.g., Figure 9). Taking into account that the actual value of quality in the critical-bundle subchannel is usually much higher than that of the cross-section average value, the discrepancy is even larger. Thus extrapolating the tube trends to higher critical qualities (closer to those encountered in rod bundles) a better agreement (quantitatively and qualitatively) is reached as far as the effect of spacing in both geometries is concerned (Figure 12).

A similar increasing trend of K with critical quality is observed in tubes and rod bundles (compare Figures 5 with 9). In addition, the mass-flux effect (Figures 6 and 10), and the pressure effect (Figures 7 and 11) are found to be similar in both geometries.

The following section considers another tool to assess CHF enhancement in rod bundles.

CHF ENHANCEMENT OBTAINED FROM DRYPATCH SPREADING

The purpose of post-dryout tests in rod bundles is to determine the highest sheath temperature (and the corresponding heat-transfer coefficients), and the extent of drypatch area on all elements that can occur under accidental conditions. This is possible only using the CRL sliding-thermocouple technique.

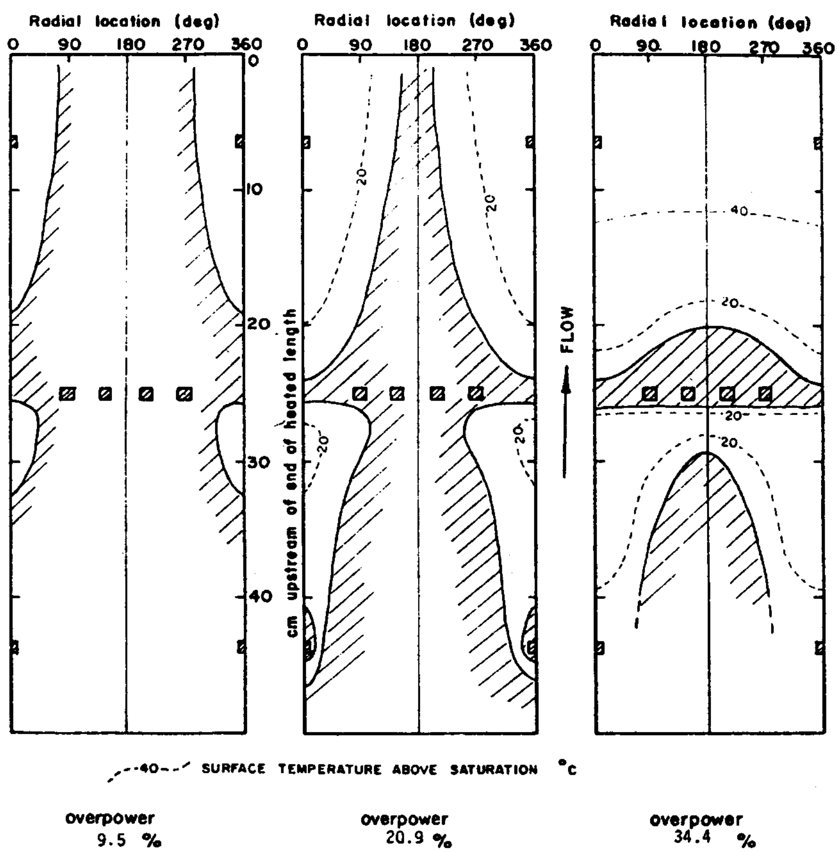

Figure 13: Drypatch Development on a Fuel Element with Increasing Overpower (shaded area = wetted area).

In addition, these tests can also provide important information on local CHF-suppression characteristics of bundle appendages. The axial extent of the wet region just downstream of a given appendage plane (to the drypatch boundary) determines directly the CHF-enhancing capability of the appendage plane. If, at the same conditions, the wet region downstream of a given appendage plane is longer than that for another plane, then the former generates a stronger CHF-enhancing effect.

Figure 13 illustrates the development of drypatch on an element with increasing power (above the dryout power). The weaker CHF-enhancing effect of a mid-spacer plane than that of a bundle junction is clearly demonstrated at the overpower of 34.4%, where the wetted region downstream of the mid-spacer plane is much shorter than the upstream one due to the bundle junction. This observation confirms the findings from the tube tests with the planes of spacers (of lower ε and weaker K simulating the mid-spacer plane in a bundle) and the rings (of higher ε and stronger K simulating the bundle junction).

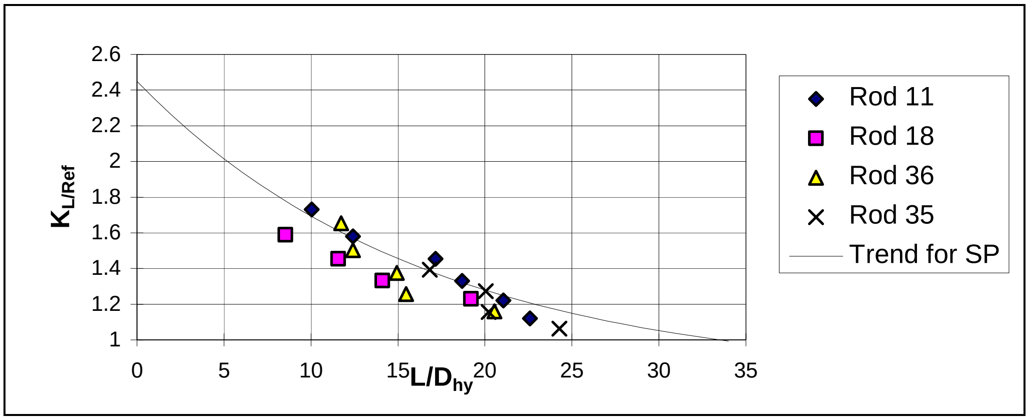

Figure 14: Comparison of CHF-enhancement Results due to Mid-spacer Plane Obtained from Drypatch Spreading Tests for Several Elements with Trend Obtained from 37-element Bundles with Different Number of Spacer Planes (Trend SP) at P_w = 9.7 MPa, and G_w =3.5 Mg/m^{2}s x_c = 0.3-0.38.

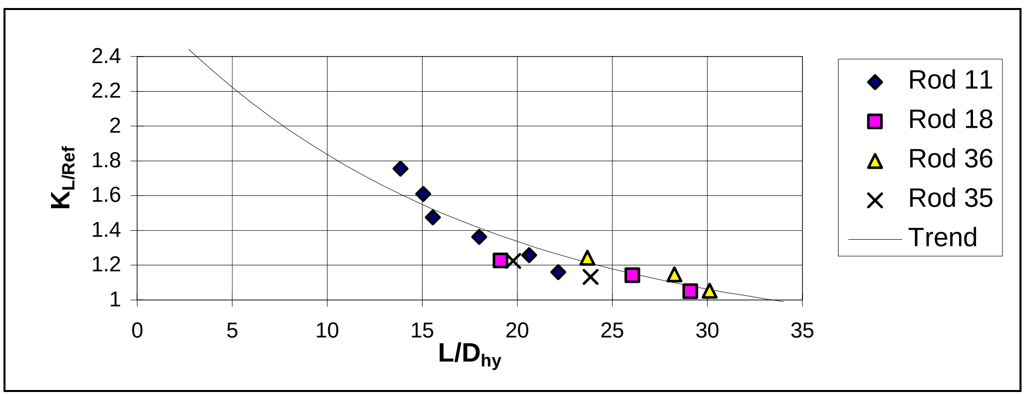

Figure 15: CHF Enhancement Results for Bundle Junction Obtained from Drypatch Analysis for the Same Elements and Parameters as in Figure 14.

K generated by a mid-spacer plane is assumed to be one for the initial CHF occurring at the downstream end of the bundle (i.e., at L = 25 cm or L/D_{hy} = 34). With increasing overpower, K increases (as the ratio of the CHF, corresponding to a given overpower level, to the initial CHF), and it corresponds to the actual L which is the minimum axial distance downstream from the spacer plane to the wet-dry boundary.

Figure 14 shows the K results obtained from the drypatch-spreading analysis for a few elements of a 37-element bundle, and compares it with the trend obtained from rod bundles with a different number of spacer planes. The CHF-enhancement results obtained from both approaches are equivalent.

Analysis of the drypatch spreading is the only technique allowing the determination of CHF enhancement for other types of appendage planes in a rod bundle. Figure 15 shows an example of a bundle junction, where K is assessed for the same elements and conditions as that of a mid-spacer plane (Figure 14).

CONCLUSIONS AND FINAL REMARKS

Various aspects of CHF enhancement obtained in a tube with inserts have been compared with those encountered in 37-element bundles. Even though a direct quantitative comparison is impossible due to different definitions of the parameters describing CHF enhancement (the local parameters in tubes versus the cross-section average parameters in rod bundles) the following has been observed in both geometries:

- similar effects of the critical quality, pressure and mass flux,
- similar effects of geometry: (i) shorter spacing between the appendage planes results in higher CHF enhancement (follows an exponential trend), and (ii) a larger flow obstruction area of the plane results in higher the CHF enhancement, and
- in both geometries CHF enhancement does not depend on fluid type, provided that the conditions in the fluids meet the CHF fluid-to-fluid modelling requirements.

The tests in a tube with inserts have expanded our knowledge of the CHF-enhancement phenomenon and provided us with information that was either too difficult or impossible to obtain in rod bundles. This can be summarized as:

- there is no cumulative effect on CHF enhancement for a series of appendage planes within the ranges tested even if the planes have very different shape and flow-obstruction areas, and
- CHF enhancement is determined by the upstream appendage plane closest to the CHF location.

The results obtained in tubes (defined by the local parameters) have been used to derive a CHF-enhancement prediction method to be used in a subchannel code (presently being implemented and tested). Also, various separate-effect studies were performed in a tube with inserts to optimize and finalize the design of CHF-enhancing devices applied to the CANFLEX 43-element fuel bundle.

The CHF enhancement inferred from drypatch-spreading tests with a reference bundle (one spacer plane) has been found to be equivalent to that obtained during CHF tests with several bundle designs, with a various number of extra spacer planes. This can be an effective tool to investigate CHF enhancement due to additional appendage planes in rod bundles.

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