CRITICAL HEAT FLUX AND HEAT TRANSFER ENHANCEMENT IN NUCLEAR FUEL BUNDLES - A REVIEW OF THE PAST 50 YEARS

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EXTENDED ABSTRACT

The power output of CANDU fuel bundles is limited by CHF occurrence. Because of this, there has been a long interest in optimizing the fuel bundle CHF (Critical Heat Flux) and CCP (Critical Channel Power, or power corresponding to the first occurrence of CHF in any fuel channel). An important reason for increasing the CCP is the need to regain operating margins in ageing CANDU reactors. Ageing will result in pressure-tube diametric creep, a reduction of reactor inlet-header temperature, and an increase of the hydraulic resistance in parts of the flow circuits. These effects will all reduce the CCP with time but can be partially recovered by remedial action (chemical cleaning of parts of the circuit, pressure tube replacement). Increasing the CCP can complement these actions, and delay pressure tube replacement. In this presentation, various methods of increasing the CHF power of CANDU-type fuel bundles are reviewed, e.g. increased bundle surface area, reduced hydraulic resistance, CHF-enhancing bundle appendages, and redefining CHF. The application of several of these CHF enhancement principles have been used in the design of the 43-element CANFLEX bundle. The following sections describe the most promising methods

(A) Increasing the bundle surface area by bundle subdivision

The design of CANDU fuel bundles has evolved from the early design of NPD's 7-rod bundle to the CANFLEX 43-element bundle design. Many of the basic design parameters have remained unchanged: (i) string of 50 cm long segmented bundles, (ii)bundles are located in horizontal pressure tubes, (iii) design allows for on-line refueling, and (iv) fuel elements are kept together by endplates. In order to increase the channel power and still maintain an adequate margin to CHF, recently proposed fuel bundles designs have became more subdivided (larger number of rods, increased surface area) resulting in higher powers while maintaining the element rating to acceptable levels. There is a practical limit to bundle subdivision since too much subdivision would lead to a bundle of small-diameter elements, prone to element bowing and flow-induced vibration, with possibly large enthalpy and flow imbalances among the subchannels.

(B) Reducing the hydraulic resistance

Higher channel flow rates increase the channel enthalpy and increase the CCP. In an existing reactor having a fixed pump curve, the only option for increasing the flow rate is by decreasing the hydraulic resistance of the various components in the flow path. One of the largest contributors to the fuel channel pressure drop is the bundle junction (~ 30%). The junction pressure drop can vary significantly – for a maximum bundle misalignment the junction pressure drop is about 50%. This suggests three ways of reducing the hydraulic resistance and hence increasing the flow: (i) using double length bundles, (ii) aligning adjacent bundles (this option was explored about 15 years ago and a patent was obtained for interlocking or wavy endplates; since bundles always move in pairs through the fuel channel of the

CANDU-6 reactor, having a pair of bundles that are always aligned would reduce the channel hydraulic resistance by 15-20% and increase the CCP by 1.5-3%), and (iii)streamlining the endplate and endcap design to reduce junction hydraulic resistance.

(C) Turbulence Promoting Appendages

During the past 40 years, many thermalhydraulic experiments have been performed on bundles equipped with CHF-enhancing rod-spacing devices, turbulence-promoting appendages, or flow deflectors. The impact of the various CHF enhancement techniques on the CCP power was thus determined. The CHF-enhancing appendages result in a higher hydraulic resistance which by itself has a negative effect on CCP because of a resulting reduction in flow. However the increase in CHF more than compensates for the flow reduction effect. The impact on CHF (constant inlet subcooling) and pressure drop is summarized in Table 1. The magnitude of the CHF enhancement in obstacle-equipped geometries depends primarily on:

- Geometric parameters (e.g. flow blockage ratio, shape of leading and trailing edge, location of blockage in subchannel cross section , distribution of flow blockages across the bundle, axial pitch of blockage), and,
- Flow conditions (e.g. quality , mass flux).

Table 1 Comparison of CHF enhancement techniques in bundles

	% INCREASE IN CHF (RANGE)	% INCREASE IN CHF (AVG)	% INCREASE IN ΔP
2 Addt'l Bearing Pad Planes	1.7 to 10.6	3.0	2
2 Addt'l Spacer & Bearing Pad Planes	5 to 21	3.1	15
4 Addt'l Spacer & Bearing Pad Planes	9 to 20	14.1	24
2 Planes of Vortex Generators	-7 to 8	0.6	5
2 Planes of Flow Obstruction Vanes	-6 to 9	0.8	27
Grid Spacers 1/3 and 2/3 bundle length position (no spacers)	10 to 25	15.5	99
Grid Spacers Mid-plane and Endplate Position (no split spacers)	-2 to 7	1	103
2 Button Planes	10 to 20	15	9

In general the maximum increase in CHF enhancement is for flow blockages that are well distributed across the bundle, minimally interfere with the liquid film flow on the heated surface, provide a large increase in turbulence (blunt leading and trailing edge), and have a small axial pitch. Button planes are an example of an effective CCP enhancing appendages. The enhancement is often largest at high outlet enthalpies and high mass flow rates.

(D) Optimizing Fuel Bundle Design

The following options are available for increasing the critical power by optimizing the 37-element bundle design:

i. Reduce diameter of the centre element from 13.1 mm to 11.5 mm (this will increase flow area for inner 6 subchannels by a total of 30.5 mm^2. For same bundle power it lowers centre rod power by 23% and the heat flux by 12% but increases the heat flux on remaining 36 elements by ~0.5%. This approach of reducing the centre-element diameter was originally proposed 15 years ago and is employed in the so-called 37-M bundle design, that was recently tested at SL.
ii. Reduce the diameter of all 7 inner elements by 1.5% from 13.1 mm to 12.9 mm OD (this will give the same increased flow area as in (i) but it is divided among all subchannel surrounding

the 7 inner element). For same bundle power it lowers inner 7-element heat flux by ~1% and increases the heat flux on remaining 30 elements by ~0.5% (note that the CHF often occurs preferentially on inner-ring elements)

iii. Equip the 37-element bundle with CANFLEX type buttons, with locations optimized for the 37-element bundle in a crept channel (the increase in CCP could be less than optimum for an uncrept channel, which is acceptable since here the extra enhancement is a bonus rather than a requirement)

iv. Use reduced-height bearing pads on the top of the bundle and increased-height bearing pads at the bottom of the bundle (colour the reduced height bearing pads; this require bundles to be installed in the reactor with coloured bearing pads facing upwards (experiments have shown that bundle rotation occurs during the residence time of the bundles in the reactor but this is limited to a few degrees). This will reduce the impact of creep by reducing the bypass flow area on top of the bundle which can be quite significant in 5% crept channels. The current average bearing pad height is 1.2 mm - An ASSERT analysis has shown that a change to 1.6 mm on bottom 6 elements and 0.8 mm on top will noticeably reduce the bypass flow area and thus reduce the resulting enthalpy imbalance. A variation of this is to increase all bundle bearing pad heights to 1.4-1.5 mm which is near the maximum of the current bearing-pad-height tolerance range.

(E) Redefining CHF

The current power limiting criteria for CANDU-6 reactors is based on the Onset of Intermittent Dryout (OID) type of CHF. At conditions of interest in CANDU reactors, OID corresponds to the first occurrence of small temperature spikes on the thermocouple charts observed during bundle CHF tests. These spikes represents the first deviation from nucleate boiling and the start of the transition boiling regime and are not a safety concern. This is in contrast with PWR's where a sharp temperature rise is usually associated with the CHF point (due to different flow conditions and CHF mechanisms) and results in film boiling occurrence. Since the OID is of no practical significance, a phenomenologically more correct definition of CHF was proposed about 30 years ago, referred to as the "Onset of Dry Sheath" or ODS. ODS corresponds to the point where the sheath temperature reaches 374 °C (representing a theoretical limit to the minimum film boiling temperature). This temperature is selected because rewetting of the sheath is no longer possible at temperatures beyond this point. Based on an analysis of the water CHF and post-CHF data obtained on 37-rod bundles, it appears that the dryout power can be increased between 1.5 and 5% due to redefining the CHF in terms of ODS instead of OID.