EFFECT OF CANFLEX BUNDLE DESIGN ON CANDU-6 REACTOR SAFETY

D.J. OH, C.H. CHO and H.C. SUK

Advanced HWR Fuel Design and Analysis
Korea Atomic Energy Research Institute
P.O. Box 105, Yusong, Taejon, Korea 305-600

ABSTRACT

A recently developed advanced CANDU fuel bundle, CANFLEX has two major design improvements over the 37-element standard bundle: bundle ring power flattening and CHF enhancement. Effect of each of the two design changes of CANFLEX bundle on CANDU-6 reactor safety has been assessed for the two representative accident scenarios, 30% RIH break (large break LOCA) and total loss of class IV power to all PHT pumps (non-LOCA) using CATHENA and SOPHT simulations.

The bundle ring power flattening increases the safety margin for both large break LOCA and non-LOCA, but the 10% CHF enhancement increases the safety margin for non-LOCA only.

1. INTRODUCTION

Presently, KAERI (Korea Atomic Energy Research Institute) and AECL (Atomic Energy Canadian Limited) are jointly developing an advanced CANDU fuel, CANFLEX (CANDU Flexbile Fuelling) (Reference 1). The CANFLEX 43-element bundle design (shown in Figure 1) for CANDU 6 reactor has evolved from Nuclear Power Demonstration (NPD) 7-element, Douglas Point 19-element, Pickering 28-element, Bruce 37-element and CANDU-6 37-element fuel bundle designs. The CANFLEX bundle has two major design improvements over the standard CANDU-6 37-element bundle while maintaining compatibility with the existing CANDU reactor fuel handling systems and all other fuel performance characteristics. First, the CANFLEX bundle contains 43 elements of two different diameters, thereby flattening bundle element ring power distribution and reducing peak linear element power by 20% (i.e., less than 50 kW/m). Secondly, the CANFLEX bundle has attachment of critical heat flux (CHF) enhancement pads called 'buttons', which increases the CHF of a fuel bundle by a minimum of 15% with a minimal pressure-drop penalty. The resulting improvement of both safety and operating margins for CANFLEX bundle will facilitate the use of various fuel cycles such as RU (Recovered Uranium), SEU (Slightly Enriched Uranium), MOX (Mixed Oxide Fuel), DUPIC (Direct Use of Spent PWR Fuel in CANDU Reactors), etc., in CANDU reactors.

This paper describes the effect of each of the two design changes of CANFLEX-NU (Natural Uranium) bundle on CANDU-6 reactor safety. The two representative design base accidents are analyzed for this purpose: large break loss of coolant accident (LOCA) and loss of flow accident (LOFA), i.e. non-LOCA. For large break LOCA, 30% RIH break is chosen to be analyzed, and for LOFA, the total loss of class IV power to all primary heat transport (PHT) pumps. Effects of each of the two design changes on the fuel and fuel channel integrities are assessed for the two accident scenarios using CATHENA and SOPHT simulations (References 2 and 3).

2. ANALYSIS METHODOLOGY

The responses of the heat transport system to the 30% RIH break and total loss of class IV power for a CANDU-6 reactor are analyzed using CATHENA and SOPHT full circuit models, respectively. SOPHT code is used for the trip coverage analyses for non-LOCAs due to its better control model, compared to CATHENA code. The effects of individual channel characteristics (channel power, elevation, feeder geometry etc.) on fuel and fuel channel behaviour are analyzed by way of CATHENA single channel simulations using header boundary conditions predicted by the full circuit simulations. The CATHENA single channel contains a more detailed model for fuel and PT than the full circuit model. The CATHENA single channel models for the CANFLEX and standard bundle cases are described in Reference 4. A node-link model of the fuel channel assembly is constructed and the transient thermalhydraulic header boundary conditions (pressure, enthalpy and void fraction) from the full-circuit simulations are applied to the inlet and outlet headers.

All fuel bundles in the channel are assumed to have a bundle element ring power profile at a burnup corresponding to the plutonium peak. The profiles give the most severe temperature transients for the fuel elements in the outermost ring, and hence are limiting for both fuel and fuel channel integrities. Table 1 presents the profiles for the CANFLEX and standard bundles and shows the bundle ring power flattening for the CANFLEX bundle.

3. ANALYSIS RESULTS

Transient thermalhydraulic header boundary conditions obtained from the full circuit analyses for the reactor loaded with the standard bundles are used for the slave channel simulations of both the CANFLEX and standard bundle cases.

The reference CATHENA single channel simulation is taken as the one with the 37-element standard bundle. Effects of the bundle ring power flattening on the fuel and fuel channel behaviours are assessed from the simulations with the 43-element CANFLEX-NU bundle without any CHF enhancement pad attachment. Effects of the CHF enhancement on the fuel and fuel channel behaviours are assessed from the simulations with the hypothetic standard bundle having CHF enhancement pad attachments. The amount of CHF enhancement is assumed to be 10%, i.e., 5% lower than the minimum enhancement.

3.1 30% RIH Break Case

3.1.1 Effect of Bundle Ring Power Flattening

Figure 2 shows the temperature transients for the centerline, sheath of the top fuel element and the inside surface of the PT top sector at mid-channel. The maximum fuel centerline temperatures for the CANFLEX and standard bundles are well below melting (1960 °C and 2348 °C, respectively) and occur both at 1.6 s. The maximum sheath temperatures for the CANFLEX and standard bundles are 1402 °C and 1530 °C, respectively and occur both at 21 s. The lower maximum fuel centerline and sheath temperatures of the CANFLEX bundle are attributed to the lower stored heat caused by the lower maximum linear element power for the (ring power flattened) CANFLEX bundle as compared with the standard bundle.

The PT top sector temperature monotonously increases up to the time of PT/CT contact and then rapidly cools down due to the heat loss to the surrounding moderator. The PT heatup rate for the CANFLEX bundle is lower compared to the standard bundle. The PT contacts its CT at 18 s and 16 s with the average contact temperatures and pressures of 795 °C and 802 °C, and 4.3 MPa and 4.6 MPa for the CANFLEX and standard bundles, respectively. The maximum PT top sector temperatures at the time of each PT/CT contact for the CANFLEX and standard bundles are 806 °C and 817 °C, respectively.

3.1.2 Effect of CHF Enhancement

The 10% CHF increase resulting from the CHF enhancement pad attachment gives none or at most 2 °C decrease in the maximum fuel centerline, sheath and PT temperatures. This is because, following large break LOCA, the fuel channels located downstream of the break void quickly, sheath dryout occurs within 2 s from the break initiation and the 10% CHF increase is too immaterial to affect the sheath dryout behaviour.

3.2 Total Loss of Class IV Power Case

3.2.1 Effect of Bundle Ring Power Flattening

Figure 3 shows the temperature transients for the centerline and sheath of the top fuel element at mid-channel. The fuel centerline temperature increases due to the increased power caused by the positive void coefficient of CANDU reactor. The maximum fuel centerline temperatures for the CANFLEX and standard bundles are well below melting

(1909 °C and 2307 °C, respectively) and occur both at 5.8 s. Dryouts are predicted to occur for the CANFLEX and standard bundles at 4.8 s and 4.2 s, respectively. The maximum sheath temperatures for the CANFLEX and standard bundles are 676 °C and 778 °C, respectively and occur both at 5.7 s. As in the case of 30% RIH break case, the lower maximum fuel centerline and sheath temperatures of the CANFLEX bundle are attributed to the lower stored heat caused by the lower maximum linear element power for the (ring power flattened) CANFLEX bundle as compared with the standard bundle.

3.2.2 Effect of CHF Enhancement

It is shown in Figure 3 that the maximum fuel centerline temperatures for the hypothetic standard bundle with CHF enhancement pad attachments are the same as those for the standard bundle. However, the maximum sheath temperature for the hypothetic standard bundle is 705 °C (73 °C lower compared to the standard bundle) and occur at 5.7 s. Dryout for the hypothetic bundle occurs at 4.8 s, i.e., 0.6 s later compared to the standard bundle case. Unlike large break LOCA such as 30% RIH break case, the CHF enhancement affects both the timing of the onset of dryout and the maximum sheath temperature. This is because, for non-LOCA cases such as loss of class IV power accident, the onset of sheath dryout (and therefore CHF) is considered as a critical event directly related with the safety requirement for fuel integrity.

4. CONCLUSION

A recently developed advanced CANDU fuel bundle, CANFLEX has two major design improvements over the 37-element standard bundle: bundle ring power flattening and CHF enhancement. Effect of each of the two design changes of CANFLEX bundle on CANDU-6 reactor safety has been assessed for the two representative accident scenarios, 30% RIH break (a large break LOCA) and total loss of class IV power to all PHT pumps (non-LOCA) using CATHENA and SOPHT simulations.

The bundle ring power flattening increases the safety margin for both large break LOCA and non-LOCA, but the 10% CHF enhancement increases the safety margin for non-LOCA only.

5. REFERENCES

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TABLE 1
BUNDLE POWER DISTRIBUTION
AT PLUTONIUM PEAK (~60MW.h/kg(U))

Parameters	Standard	CANFLEX
Relevant Element Power Normalized to Bundle Average:		
Outer Element	1.131	1.058
Intermediate Element	0.9206	0.8707
Inner Element	0.8051	1.080
Center Element	0.7613	1.0325

Figure 1. A 43-Element CANFLEX Fuel Bundle

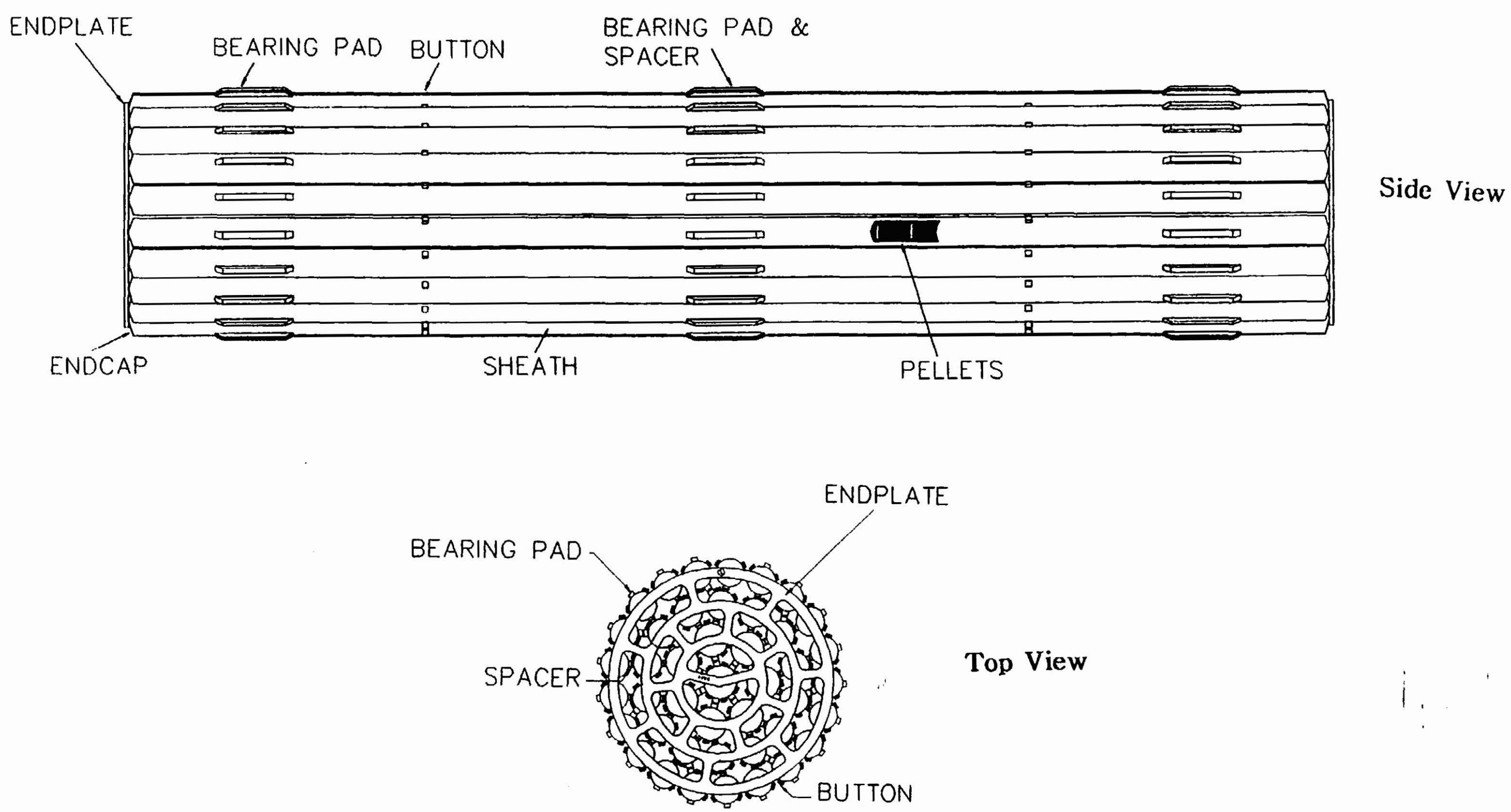

Figure 2 : Temperature Transients at Axial Node 7 of 7.3 MW (O6) Channel; Fuel Centerline, Sheath & PT Temperatures at the Top of Standard (solid line) & CANFLEX (dotted line) Bundles (30% RIH Break LOCA Case)

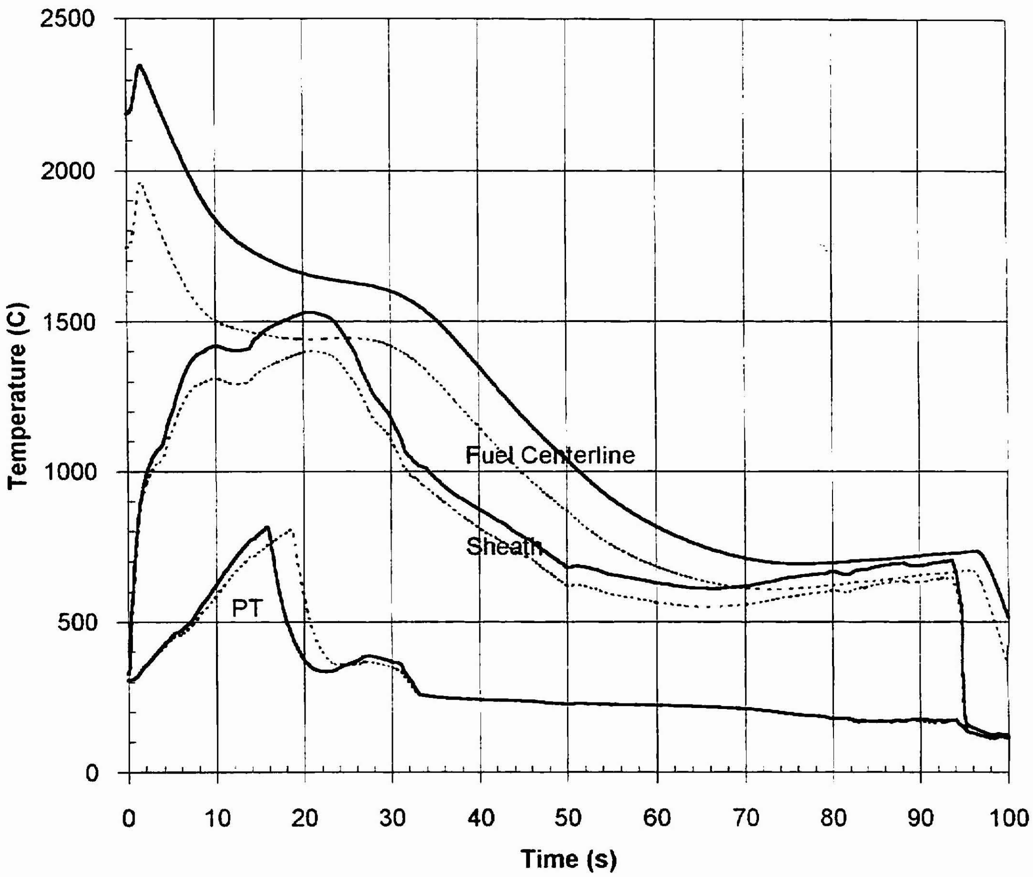

Figure 3 : Fuel Centerline & Sheath Temperature Transients of Top Outer Element at Axial Node 7 of 7.3 MW (O6) Channel (Total Loss of Class IV Power Case)