LOCA SAFETY MARGIN IMPROVEMENT OF CANFLEX-NU FUEL

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ABSTRACT

The CANFLEX-NU fuel has a lower peak linear heat generation rate and a higher critical heat flux compared to 37-rod standard fuel. The improvement on LOCA safety margin with use of CANFLEX-NU fuel was evaluated. The effect of relative power distribution in a bundle on initial core-wide fission product inventory distribution, the power pulse and the amount of fission product release by fuel failure following a large LOCA were analyzed and compared to those for 37-rod standard fuel. The margin for energetic fuel breakup due to power pulse is increased for CANFLEX-NU fuel. The amount of fission product release, and so the dose to the public, are reduced significantly compared to standard fuel due to the reduction of initial gap inventory and the number of failed fuel elements.

1. INTRODUCTION

The advanced fuel bundle CANFLEX-NU [1], which was developed by Korea and Canada jointly for use in CANDU nuclear power plants (NPP), has a lower peak linear heat generation by flattening the power distribution and a higher critical heat flux (CHF) by appending the buttons on the fuel element surface. These features of CANFLEX-NU fuel increase the operating margin in normal operation and the safety margin during the postulated accidents. The number of fuel elements in a bundle is increased to 43, which includes 8 large elements in center and inner ring and 35 small elements in intermediate and outer rings. Figure 1 shows the cross-section of CANFLEX-NU and 37-rod standard fuel bundle. The demonstration irradiation of this advanced fuel bundle was carried out successfully in Point Lepreau NPP [2 and 3] and is on-going in Wolsong 1 NPP. The safety analysis for full CANFLEX-NU core of CANDU 6 plant has been performed to identify the increase of safety margin during the postulated accidents. This paper shows the analysis results for a large loss-of-coolant-accident (LOCA) and provides the comparison with those for 37-rod standard fuel core.

2. CORE-WIDE FISSION PRODUCT INVENTORY DISTRIBUTION

2.1 The Effect of Relative Power Distribution within a Bundle

The full CANFLEX-NU core of CANDU 6 NPP will have 196,080 fuel elements in 380 fuel channels. Actually each element will have different power and burnup. In order to simplify the analysis, these 196,080 fuel elements were grouped according to its power and burnup. Since only the bundlewise power and burnup data are available from reactor physics simulation, the relative power and burnup distribution within a bundle must be assumed in the process of element grouping.

Figures 2 and 3 show the relative element linear power in a bundle according to bundle average burnup for CANFLEX-NU and 37-rod standard fuel [4]. For a standard fuel bundle, the order of relative element linear power of outer, intermediate, inner and center is not changed as depletion proceeds and the fuel elements of outer ring have maximum value at plutonium peak burnup (45 MWh/kgU). Therefore, the use of relative element linear power in a bundle at plutonium peak burnup for element grouping maximizes the number of fuel elements with high power, and then the fission product inventory in the gap between UO_2 pellet and sheath.

As shown in Figure 2, the initial order of relative element linear power of inner, outer, center and intermediate ring is changed to the order of inner, center, outer and intermediate ring at average discharge burnup (175 MWh/kgU) for CANFLEX-NU fuel. The fuel elements of outer ring have maximum value at plutonium peak burnup (45 MWh/kgU) and then decrease. However, the fuel elements of inner ring, which have highest power, have the minimum at plutonium peak burnup and the maximum at discharge burnup of 175 MWh/kgU. Therefore, a question, which power distribution in a bundle should be used in element grouping, is raised.

Two sets of element grouping according to power and burnup were made : one with relative power and burnup distribution at plutonium peak burnup and the other with relative power and burnup distribution at average discharge burnup. Table 1 shows the analysis results for total core gap inventory. The fuel element grouping is made for large and small elements separately because of the existence of two different element sizes for CANFLEX-NU fuel bundle. The gap inventory in large elements of center and inner ring is higher with power and burnup distribution at average bundle discharge burnup. However, the gap inventory in small elements of intermediate and outer rings is higher with power and burnup distribution at bundle plutonium peak burnup. Total core gap inventories calculated using the relative power and burnup distribution at plutonium peak burnup are slightly higher than those at average bundle discharge burnup. This means the contribution of fuel elements of outer ring is larger than that of inner ring. Therefore, the power and burnup distribution within a fuel bundle at plutonium peak burnup is used in the element grouping finally.

2.2 Comparison of Fission Product Inventory Distribution between CANFLEX-NU and Standard Fuel Core

Figure 4 shows the fuel element distribution as a function of linear power for full 37-rod standard and 43-rod CANFLEX-NU equilibrium core [4]. The relative power distribution within the bundle at plutonium peak burnup was used in the fuel element grouping for both cases (Figure 5). Due to flattening power distribution within the fuel bundle, the number of fuel elements with very high linear power is reduced for CANFLEX-NU core.

The fuel elements of whole core (36,480 large elements and 159,600 small elements) are grouped into 24 burnup and 29 linear power groups. Table 2 shows the fission product inventory distribution in grain, grain boundary and gap. The generation of fission product is a function of power and burnup. The distribution of fission product in UO_2 pellet (grain and grain boundary) and in gap between pellet and sheath is governed mainly by the temperature level in UO_2 pellet. Total fission product inventory of CANFLEX-NU core is almost the same as standard fuel core because the total core power is the same. However, the amount of fission product inventory in the gap is significantly reduced for CANFLEX-NU core due to reduction of the fuel elements with high power. The gap inventory is very important since it could be released to the coolant directly by sheath failure.

3. POWER PULSE

Power pulse analyses were performed for reactor inlet header (RIH), reactor outlet header

(ROH) and pump suction (PS) breaks. Figure 6 shows the power transient following a 40% RIH break. CANFLEX-NU fuel results in a higher power pulse due to higher void reactivity compared to standard fuel. However, Figure 7 shows that the initial stored energy of hot pin is lower due to lower initial temperature distribution. The total energy including the initial and transient stored energy is lower for CANFLEX-NU fuel. Therefore, the margin for energetic fuel breakup due to power pulse is increased for CANFLEX-NU fuel. Table 3 compares the stored energy between CANFLEX-NU and standard fuel.

4. FISSION PRODUCT RELEASE FOLLOWING A LARGE LOCA

From the break survey on each of the three break locations (RIH, ROH and PS), 35% RIH, 100% ROH and 55% PS breaks were selected as the critical break sizes. Detailed thermalhydraulic analyses with circuit and single channel models were done for these critical breaks.

The transient fuel behavior analysis requires as input the power transient from physics and thermalhydraulic boundary conditions such as coolant pressure, coolant temperature and sheath-to-coolant heat transfer coefficient. Fuel failure thresholds, maximum linear power for which the fuel element is predicted not failing following a large LOCA, were determined for fuel element burnup range from 10 MWh/kgU to 240 MWh/kgU. Simple and conservative criteria were used to determine whether a fuel element fails or not. The number of fuel elements expected to fail was estimated by adding the number of elements in each burnup group where the power is equal to or greater than the fuel failure thresholds.

The transient fuel behavior analyses were performed for three critical break sizes. Table 4 shows the number of failed fuel elements following a large LOCA with all safety systems available. For CANFLEX-NU fuel core, the fuel failure occurs only for 100% ROH break and the number of failed fuel elements are reduced significantly since the number of fuel elements with high linear power is reduced by power flattening as shown in Figure 4. Therefore, the amount of fission product release into coolant becomes very small due to reduction of failed fuel elements and gap inventory compared to standard fuel core. Table 5 shows the comparison of accumulated fission product release between CANFLEX-NU and standard fuel core following a 100% ROH break.

5. CONCLUSION

A large LOCA safety analysis was done for full CANFLEX-NU core of CANDU 6 plant to evaluate the safety margin improvement. The following major conclusions were reached from this study :

- Total core gap inventories calculated using the relative power and burnup distribution at plutonium peak burnup are slightly higher than those at average bundle discharge burnup.
- The amount of initial core-wide fission product inventory in gap is significantly reduced for CANFLEX-NU core due to reduction of the fuel elements with high power.
- CANFLEX-NU fuel results in a higher power pulse due to higher void reactivity compared to standard fuel. However, the total energy including the initial and transient stored energy is lower for CANFLEX-NU fuel. Therefore, the margin for energetic fuel breakup due to power pulse is increased for CANFLEX-NU fuel.
- The amount of fission product release, and so the dose to the public, are reduced significantly compared to standard fuel due to the reduction of initial gap inventory and the number of failed fuel elements.

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3. P.J. Valliant et al, "PLGS CANFLEX Demonstration Irradiation: Highlights of In-Bay Inspections and Hot-Cell Examinations," 7th International CNS CANDU Fuel Conference, Kingsten, September 23-27, 2001.
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Table 1 Total Core Gap Inventory (TBq) for Full CANFLEX-NU Core

Isotope	Relative Power and Burnup Distribution at Plutonium Peak Burnup (~45 MWh/kgU)			Relative Power and Burnup Distribution at Average Discharge Burnup (~175 MWh/kgU)		
	Large Elements (Center & Inner Ring)	Small Elements (Intermediate & Outer Ring)	Total	Large Elements (Center & Inner Ring)	Small Elements (Intermediate & Outer Ring)	Total
I-131	562.6	2314.6	2877.1	730.1	1960.2	2690.2
I-132	1173.4	4460.0	5633.4	1518.7	3787.9	5306.6
I-133	427.8	1640.6	2068.4	554.5	1390.5	1945.0
I-134	98.5	378.1	476.6	127.7	320.2	447.9
I-135	226.2	868.8	1095.1	293.4	736.1	1029.5
KR-87	14.6	56.2	70.9	19.0	47.6	66.6
KR-88	30.8	118.4	149.2	40.0	100.2	140.2
KR-89	5.4	21.1	26.6	7.1	17.9	25.0
XE-133M	7.3	28.1	35.4	9.5	23.8	33.3
XE-133	758.5	3043.1	3801.6	985.4	2578.2	3563.6
XE-135M	2.8	10.9	13.7	3.6	9.2	12.8
XE-135	37.3	143.5	180.7	48.3	121.6	169.9
XE-137	8.2	31.5	39.7	10.6	26.7	37.3
XE-138	15.8	60.8	76.6	20.5	51.4	72.0

Table 2 Initial Fission Product Inventory Distribution in Fuel

Isotope	Full CANFLEX-NU Fuel Core (TBq)				Full Standard Fuel Core (TBq)			
	Gap	GBR	GRN	Total	Gap	GBR	GRN	Total
I-131	2877	147346	2017321	2167544	22530	185057	1901577	2109164
I-132	5633	231069	3179912	3416614	44354	290704	2987434	3322492
I-133	2068	361106	4976130	5339304	19569	454309	4718384	5192262
I-134	477	404106	5570489	5975071	4771	508400	5297319	5810491
I-135	1095	339084	4673505	5013685	10688	426596	4438315	4875599
KR-87	71	132731	1829763	1962564	718	166989	1740817	1908523
KR-88	149	187542	2585305	2772996	1503	238540	2510938	2750981
KR-89	27	243428	3355886	3599340	270	306261	3193755	3500286
XE-133M	35	10198	140519	150753	346	13528	146420	160295
XE-133	3802	329354	4525319	4858475	35737	413868	4275442	4725047
XE-135M	14	58036	800071	858121	141	73015	761332	834489
XE-135	181	38691	533212	572084	1765	48677	505883	556325
XE-137	40	328874	4533830	4862744	401	413758	4314611	4728770
XE-138	77	331561	4570772	4902410	789	449378	4945307	5395474

GBR : Grain Boundary, GRN : Grain Bound

Table 3 Initial and Peak Stored Energy of Hot Pin for 40% RIH Break

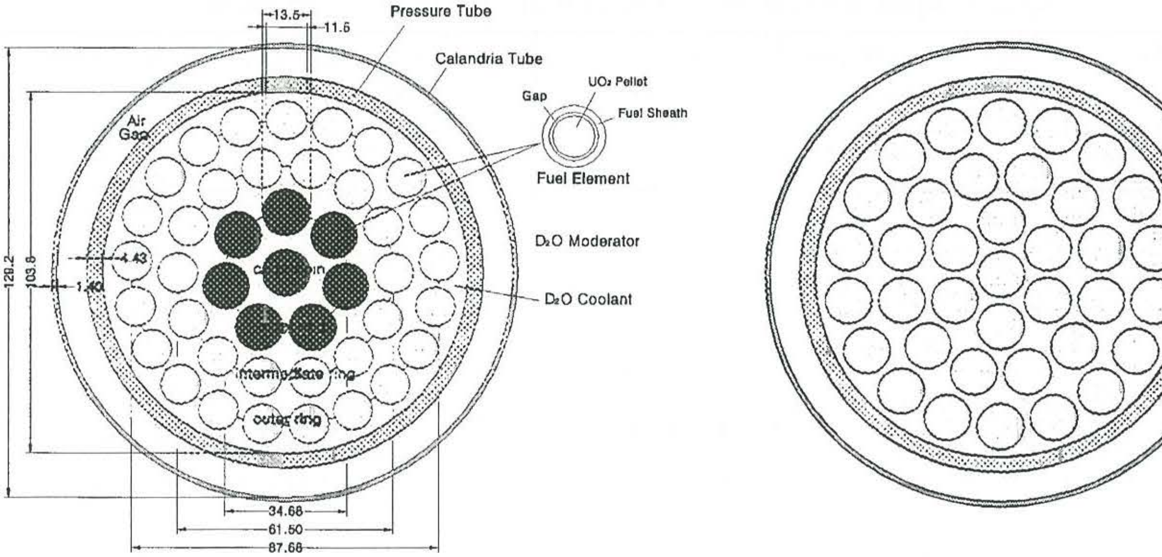
Fuel	Initial Stored Energy (J/g)	Peak Pulse Energy (J/g)	Peak Total Energy (J/g)	% Margin to Breakup
CANFLEX-NU	349	175	524	37.6
Standard	494	162	656	21.9

Table 4 Number of Failed Fuel Elements

Break	Standard Fuel	CANFLEX-NU
100% ROH	1975	120 (Small Element)
55% PS	634	0
35% RIH	634	0

Table 5 Accumulated Fission Product Release Following a 100% ROH Break

Isotope	Full CANFLEX-NU Fuel Core (TBq)	Full Standard Fuel Core (TBq)
I-131	92	5526
I-132	135	9997
I-133	93	5927
I-134	71	3705
I-135	72	3754
KR-87	22	588
KR-88	32	960
KR-89	38	802
XE-133M	2	119
XE-133	126	9917
XE-135M	9	212
XE-135	9	569
XE-137	52	1093
XE-138	53	1201



CANFLEX-NU   37-ROD STANDARD

Figure 1 Cross-section of CANFLEX-NU and 37-Rod Standard Fuel Bundle

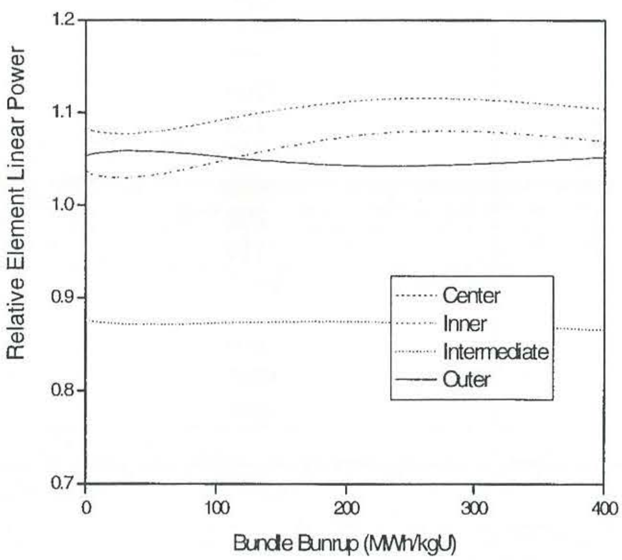


Figure 2 Relative Element Linear Power for CANFLEX-NU Fuel Bundle

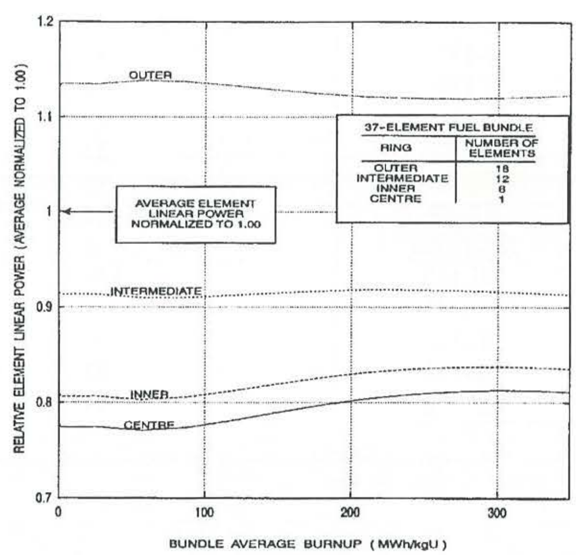


Figure 3 Relative Element Linear Power for Standard Fuel Bundle

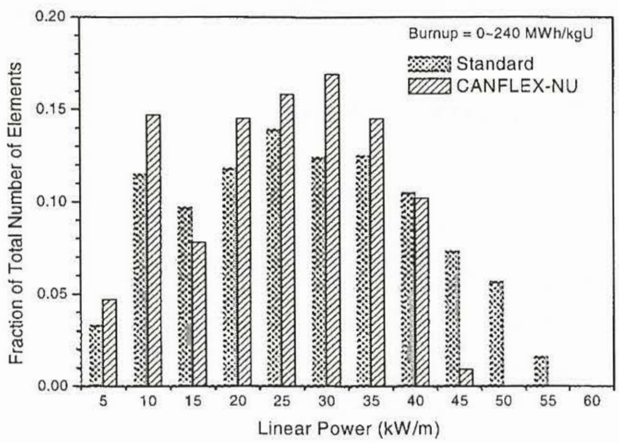


Figure 4 Fuel Element Distribution

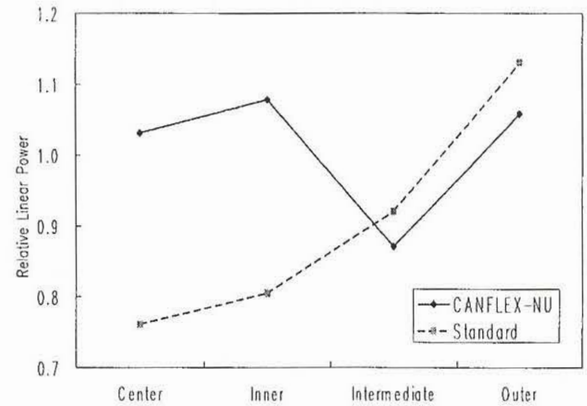


Figure 5 Relative Element Linear Power at Plutonium Peak Burnup

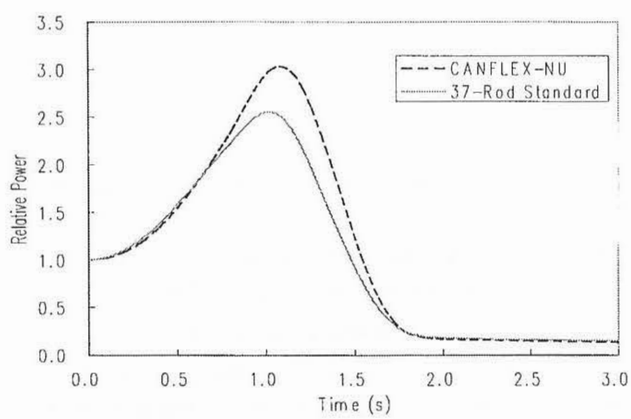


Figure 6 Power Transient following a 40% RIH Break O6,

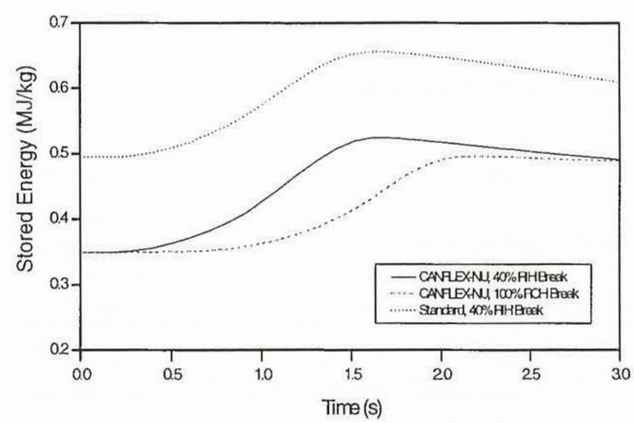


Figure 7 Stored Energy for Channel

Bundle 7, Hot Pin