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Optimization of CANFLEX-RU Fuel Bundle for CANDU-6

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Abstract

Considering the higher discharge burnup, lower channel refuelling rate, lower linear element rating(LER), lower coolant void reactivity and axial power shape, CANFLEX-RU fuel bundle is optimized for CANDU-6 by grading the fissile composition in the ring-wise of the bundle and by applying fuel management scheme appropriately. The fissile composition of the fuel bundle is graded as the recovered uranium (0.9 w/o U-235) in the outer and intermidiate elements, depleted Uranium (0.2 w/o U-235) in the center element, natural uranium (0.71 w/o U-235) in the inner elements. Enrichment is not rquired for these fuel. The fissile composition is optimized by lattice calculation and by time-averaged reactor simulation.

CANFLEX-RU optimized for CANDU-6 resulted to be the 15% lower channel refuelling rate, acceptable axial power profile and power envelope, 70% higher discharge burnup, 15% lower LER and not increase coolant void reactivity compared with the 37-element natural uranium bundle for CANDU-6.

1. Introduction

When advanced fuel cycles in existing CANDU reactors[1,2] are used, the CANFLEX (CANdu FLEXible fuelling) bundle[1] extends fuel burnup and enhances the operating margins compared with current CANDU-6 fuel. The advanced and economical fuel is characterized by the contents of higher fissile material compared with the fissile contents of natural uranium(NU).

CANFLEX-1.2 w/o slightly enriched uranium(SEU) gives 3 times higher discharge burnup (~ 21 MWD/kgU) compared with the natural uranium fuel(7 MWD/kgU). But the 1.2 w/o SEU fuel management become somewhat complicated when used in current CANDU-6 without hardware modification[3]. The 0.9 w/o SEU fuel is able to be 2 times higher discharge burnup compared with the NU fuel and haredware modification is not required. So, the 0.9 w/o SEU fuel is economically and technically attractive compared to 1.2% SEU fuel[4]. The recovered uranium(RU) from LWR spent fuel has an enrichment of around 0.9% U-235 in total uranium. The RU fuel is a potentially cheaper alternative to 1.2% SEU fuel in the CANDU reactors and is favorable in the strategic considerations.

Previous studies on the CANFLEX 0.9 w/o fuel-management and compatibility with 0.9% SEU CANFLEX in the Wolsung-1 core[5,6] showed 12.9 MWD/kgU discharge burnup, same channel refuelling rate, acceptable power history, a little power boosting at high burnup, 15% lower peak LER and sufficient controllability of reactivity devices without complicated fuelling management scheme and hardware modification of the reactor. The only disadvantage of this 0.9 w/o SEU fuel is slightly higher coolant void reactivity which is one of the key safety parameter for CANDU-type reactor. This is mainly due to the geometric characteristics of the CANFLEX bundle which has a larger surface to volume ratio and has higher thermal flux in the central region.

In this study, CANFLEX-RU fuel bundle is optimized to be more compatibe with the current CANDU-6. The fissile composition is graded on the ring-wise elements to suppress flux at the central region where reactivity mostly increases when coolant is voided, and appropriate fuelling scheme is studied with the optimized fuel bundle.

2. Optimization Criteria

Following criteria were set in optimizing CANFLEX-RU:

(1) No enrichment process involved:
The recovered uranium (0.9 -1.0 w/o U-235), depleted uranium (0.2 w/o U-235) and natural uranium (0.71 w/o U-235) fuel are selected to exclude enrichment cost. The possible combinations are listed in Table 1.

(2) Coolant void reactivity of the bundle is less than or equal to that of the current CANDU-6 fuel:
Grading lower fissile fuel in the inner region and higher fissile fuel in the outer region, it reduces coolant void reactivity.

(3) Lower peak LER than current CANDU-6's :
To extend fuel burnup, CANFLEX bundle was deigned to have more fuel elements with smaller diameter at the outer region(Figure 1). This CANFLEX fuel bundle geometry will suppresses peak LER below the current CANDU-6 fuel even when flux density increases at the outer region of the bundle for the reduction of coolant void reactivity.

(4) Lower channel refuelling rate than current CANDU-6's:
Channel refuelling rate (number of refuelling machine visit to channel per day) is determined by refuelling scheme (number of bundle per one refuelling in a channel) and bundle refuelling rate (number of bundle refuelled per day). The extended burnup fuel has more excess reactivity than the NU fuel, hence the bundle refuelling rate become smaller than that of NU fuel bundle. But this excess reactivity restricts the number of bundles to be refuelled in a channel to keep the core reactivity and power distribution under control. Previous studies[1-4] showed that, when the extended burnup fuel is applied in CANDU-6 reactor, the channel refuelling rate is nearly same as or slightly higher than that of the current CANDU-6 fuel despite of reduced bundle refuelling rate. Optimizing CANFLEX-RU to have lower excess reactivity than RU fuel in all the elements, it would be possible to apply 6 bundle shift fuelling scheme rather than 4 bundle.
This reduced channel refuelling rate gives an operational advantage of reducing depreciation cost of fuelling machine.

(5) More compatibility of axial/radial power shape with current CANDU-6:
It is expected that the core-wise power distribution become closer to that of current CANDU-6 with NU fuel, when operated with the 6 bundle shift fuelling scheme.

(6) Better Power envelope than that of the RU fuel in all the CANFLEX elements :
With 6 bundle shift refuelling scheme, axial power profile along the channel is expected to have less power hump at the higher burnup region and consequently the power envelope become more resilient.

3. Methodology

(1) Lattice Design:

Figure 1 illustrates the geometry of the 43-element CANFLEX bundle, which has two sizes of elements : smaller diameter elements on the outside two rings and larger diameter elements of an inner ring and a central pin. To reduce coolant void reactivity, DU and NU fuel rods were positioned in the inner region of the bundle and RU fuel rods were positioned in the outer region.

The Lattice cell code WIMS-AECL with Winfrith library (CRNL- 1.1, WNRE version, 88-11-07)[7] was used to analyze the fuel properties which were then fed into reactor simulation code RFSP[8] via the linkage code WIMFMDP[9] for core-wise calculation. The transport calculation in WIMS-AECL was done with the 2-dimensional collision probability method, in 33 energy groups, which were subsequently condensed to two energy groups by using Benoist method for diffusion coefficients, B1 theory for leakage and a critical spectrum to provide the parameters for the RFSP calculation.

(2) Incremental Cross Sections:

In the RFSP code, the reactivity devices and structural materials are represented by incremental cross sections which are added to the cell-averaged macroscopic cross sections at the device locations. The incremental cross sections are simply the difference between the cell-averaged macroscopic cross sections of a lattice cell with and without the device. The incremental cross sections of CANFLEX-0.9 w/o SEU were used for the present study.

(3) Reactor Model:

The Wolsong-1 reactor has 380 fuel channels. Figure 2 shows the schematics of the face and top views of the reactor respectively. Fluxes and powers were calculated in three dimensions using 44, 36 and 24 mesh points in the x-, y- and z-directions respectively. The RFSP code calculates the 3-dimensional flux and power distribution for the core by solving the finite-difference neutron diffusion equations in two energy groups.

(4) Time-average Core Calculation:

In the time-average calculation, the properties of the lattice cell are averaged over the fuel dwell-time at each position in the core. The resultant flux and powers are indicative of what would be seen "on average" in the core. In reality there would be perturbations about the time-averaged distribution, due to refuelling, control rod action and so on. The time-average channel power distribution serves as a reference, which the fuel engineers try to achieve during refuelling.
In setting up the time-average model, the core is divided into several irradiation zones, over which the average fuel discharge irradiation is constant. These irradiation zones are chosen to make the reactor critical (or to maintain some excess reactivity to account for parasitic absorption in the core, which is not explicitly modelled), to provide an appropriate degree of flattening of the radial channel power distribution, and to enhance the flattening provided by the adjuster rods. The average water level in the zone control compartments was set to 50% full, representative of the normal operating conditions.

4. Results and Discussion

Table 2 summarizes the results of the lattice calculation with various combination of fuel fissile contents. It was concluded that fuel bundle with central rod of DU, inner ring of NU and intermediate and outer rings of RU shows most compatible characteristics satisfying the requirements such as void reactivity, LER and discharge burnup.

With the optimized CANFLEX-RU fuel bundle, the time-average calculation was performed to search optimum refuelling scheme. It is found that 6 bundle fuelling scheme is appropriate from the maximum channel and bundle power of time-average core, and actual channel refuelling rate of 1.7 channel/day and discharge burnup is 12 MWd/kgU. The results of the time-average simulation were summarized in Table 3. Figure 3 compares the axial power profiles of a typical channel from various fuel management studies. As expected, the axial power profile of optimized CANFLEX-RU is more compatible with that of CANDU-6 NU case. This axial power profile ensures monotonic declining of power envelope as burnup increases, which is desirable in the fuel performance point of view.

In summary, the CANFLEX-RU optimized for the CANDU-6 shows 15% lower channel refuelling rate, acceptable axial power profile, acceptable power envelope, 70% higher discharge burnup ,15% lower LER and no increase of coolant void reactivity compared with the CANDU-6's 37-element NU fuel bundle.

The optimized CANFLEX-RU fuel bundle is considered as one of the most favorable candidates for the application of high burnup fuel cycle for the CANDU-6. The detailed simulation of time dependent core is planned to generate actual power envelope for fuel performance analysis.

5. References

1) Lane, A.D., Rheem, K.S. et al, "AECL/KAERI Joint Study of the Potential for Use of CANFLEX Fuel in CANDU Reactors", AECL-MISC- 296, 1990 June.

2) Hastings, I.J. and Lane, A.D., "CANFLEX - An Advanced Fuel Bundle for CANDU", Nuclear Engineering International, 1989 December.

3) Younis, M.H., and Boczar, P.G., "Equilibrium Fuel Management Simulations for 1.2% SEU in a CANDU-6", Proc. Tenth Annual Conf., Canadian Nuclear Society, Ottawa, Ontario, also AECL-9986, 1989.

4) Boczar, P.G. and van Dyk, M.T., "Improved Locations of Reactivity Devices in Future CANDU Reactors Fuelled with NU or SEU Fuels" , AECL-9194, 1987 February.

5) Lee, Y.O., Boczar, P.G. et al., "Recovered Uranium in CANDU: A Strategic Opportunity", International Nuclear Congress, Toronto, Canada, 1993 October.

6) Lee, Y.O. Boczar, P.G. et al., "A Fuel bundle to Facilitate the Use of Enrichment and Fuel Cycles in CANDU Reactors", presented at the IAEA Technical Committee Meeting on Advances in Heavy Water Reactors, Toronto, Canada, 1993 June.

7) Donnelly, J.V. "WIMS-CRNL, a User's Manual for the Chalk River Version of WIMS", AECL-8955, 1986 January.

8) Jenkins, D.A. and Rouben, B.,"Reactor Fuelling Simulation Program - RFSP: User's Manual for Microcomputer Version", TTR- 321, AECL-CANDU.

9) Donnelly J.V. and van Dyk, M.T., "FMDP Fuel Table Preparation from WIMS-CRNL Burnup Calculations", APRP-RP-120, 1985 August.

Table 1: Average U-235 contents in Various Combination of Grading

Case	Center	Inner	Intermidiate	Outer	Average U-235 w/o
1	RU	RU	RU	RU	0.90
2	DU	RU	RU	RU	0.88
3	DU	DU	RU	RU	0.73
4	DU	NU	RU	RU	0.84

Table 2: Summary of Lattice Calculation

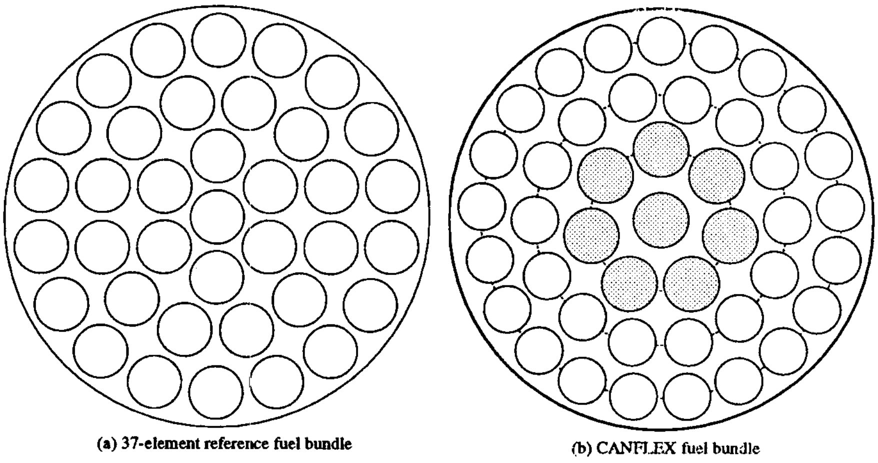
Case	Discharge Burnup (MWd/KgU)	Coolant Void Reactivity (mk) (Eq. Burnup)	Peak (kW/m) at Bundle Power of 935 kW
1	12.9	14.2	47
2	12.5	13.9	48
3	7.7	12.2	54
4	11.8	13.5	50
37-element NU			
	7.0	13.5	59

Table 3: Summary of Time-average Simulation for case-1 CANFLEX-RU

Tima-average Simulation	Results
keff	1.000120
Maximum Bundle Power (kW)	812
Maximum Channel Power (kW)	6206
Average Burnup (MWD/Kg)*	11.80
Feed Rate (Bundle/day)	19.2
(Channel/Day)	1.7
Adjuster Rod Worth (mk)	15.30
Zone-Control Worth (mk)	7.10

*) Assuming U-mass per bundle as 18.6 kg

Figure 1: Schematic Diagram of 37-element and CANFLEX



(a) 37-element reference fuel bundle

(b) CANFLEX fuel bundle

Figure 2: schematics of the face and top views of CANDU-6 Reactor

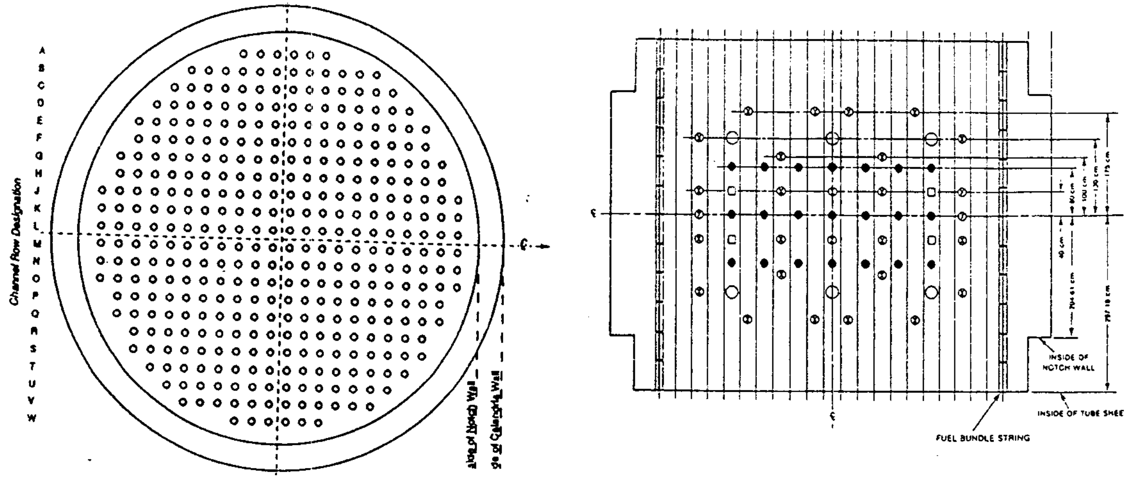


Figure 3: Time-average Axial Power Profiles of Optimized CANFLEX-RU