A REFUELLING STRATEGY OF CANFLEX-RU FUEL IN CANDU REACTORS

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ABSTRACT

The refuelling strategy of CANFLEX-RU (=RUFIC, Recovered Uranium Fuel In CANDU) as a CANDU high-burnup fuel for CANDU 6 reactors is studied to determine the achievable characteristics of the fuel and reactor operations. In this study, 4-, 2-, and 3-bundle shifts of 0.92 w/o RUFIC fuel in a CANDU 6 reactor were individually evaluated through 1200 FPD refuelling simulations. The computer code system used is WIMS-AECL/DRAGON/ RFSP. The 4-bundle shift case shows that the peak maximum channel power of 7228 kW seems too high to maintain the available operating margins, whereas the 2-bundle shift case shows that a sufficient operating margin could be secured. However, since the channel-refuelling rate (channels/day) of the 2-bundle shift case is twice that of the 4-bundle shift, the 3-bundle shift of the RUFIC fuel was also studied. As a result, it is found that all the operating parameters in the 3-bundle shift case are achievable for the CANDU 6 reactor operation, and the channel-refuelling rate of 2.88 channels/day seems to be attractive compared to that of 4.32 channels/day in the 2-bundle shift case.

1. INTRODUCTION

A CANDU advanced fuel such as RU (Recovered Uranium from spent uranium oxide fuel) shall be necessarily developed to reduce the spent fuel arising of the natural uranium fuel used in the existing reactors and so as to improve the fuel cycle cost. RU fuel offers a very attractive alternative to the use of NU (Natural Uranium) and SEU (Slightly Enriched Uranium) in CANDU reactors, since fuel economy is expected to improve even more through the use of RU. Recycling RU fuel in PWR is particularly unattractive because of the following two reasons. First, it must be re-enriched to obtain the higher U-235 concentration for the PWR fuel. Second, the presence of a significant U-236 concentration in RU fuel makes it considerably less valuable because U-236 is a resonance absorber. On the other hand, recycling RU fuel in CANDU reactors is straightforward to simply blend the RU fuel with the tails from enrichment plants to a U-235 concentration slightly higher than that of the NU in order to compensate for the presence of U-236. A unique country such as Korea having both PWR and CANDU reactors can exploit the natural synergism between the two reactor types to minimize overall waste production, and maximize energy derived from the fuel by burning the spent fuel from its PWR reactors in CANDU reactors. RU fuel can be packaged in the CANFLEX fuel bundle as an advanced fuel design.

Equilibrium CANDU 6 reactor core with CANFLEX-RU (=RUFIC, Recovered Uranium Fuel In CANDU) fuel bundles was, therefore, analyzed in this work through 1200 FPD refuelling simulations using 4-, 2-, and 3-bundle shift fuelling schemes individually in order to examine the core parameters to be kept within the operating and licensing limit. Prior to the refuelling simulations, U-235 content in RUFIC fuel was determined to be equivalent to CANFLEX-0.9 w/o SEU. The computer codes used for this work are RFSP[1] version IST-REL_3-00HP for the fuelling simulation and the core flux/power calculation, and WIMS-AECL[2] version 2-5d with the nuclear libraries ENDF/B-VI for the lattice cell calculation. In addition to the codes for the core and lattice cell calculation, DRAGON[3] version 3.04 with the ENDF/B-V was also used for the calculation of the incremental cross section of the control devices in CANDU reactor. The current standard ENDF/B-VI library was not used because it is not available in a format used by the DRAGON code.

2. DETERMINATION OF U-235 CONTENT IN RUFIC FUEL

In order to determine the U-235 content in RUFIC fuel to be equivalent to the CANFLEX-0.9 w/o SEU, three RUFIC fuels such as RUFIC-0.9163 w/o, RUFIC-0.9208 w/o, and RUFIC-0.9250 w/o were chosen through many depletion calculations using WIMS-AECL with ENDF/B-V library, which give the same reactivities as those of CANFLEX-0.9 w/o SEU fuel at initial, middle, and discharge burnup stages, respectively. Lattice properties of the three RUFIC fuels chosen were investigated and compared to those of the CANFLEX-0.9 w/o SEU fuel. The contents of U-234 and U-236 in the RUFIC fuels were kept as their averages contained in RU, 0.016 and 0.34 w/o, respectively. The three fuels were depleted until ~14,000 MWd/MTU, which is the discharge burnup of the CANFLEX-0.9 w/o SEU fuel, by using WIMS-AECL 2-5 with ENDF/B-VI library. As a result, it is found that the burnup behavior of the RUFIC-0.9208 w/o fuel is very similar to that of the CANFLEX-0.9 w/o SEU fuel, considering the reactivity and burnup aspects. The discharge burnup of RUFIC-0.9208 w/o fuel was calculated to be 13,645 MWd/MTU. It is, therefore, judged and taken that 0.92 w/o as a reference U-235 content in RUFIC fuel is practically and nearly approached to be equivalent to the CANFLEX-0.9 w/o SEU fuel. In Figure 1, k-infinity as a function of burnup is shown for the RUFIC-0.92 w/o fuel. At this time, the discharge burnup was estimated as 13,625 MWd/MTU.

3. TIME-AVERAGE CALCULATIONS

In CANDU 6 reactors, an 8-bundle shift refuelling scheme is currently employed, but the use of the refuelling scheme seems to be difficult in the RUFIC-fuelled core due to the reactivity increase. The fuelling schemes tried for this work are the 4-, 2-, and 3-bundle shift refuelling schemes. Time-average calculations for each refuelling scheme were carried out using RFSP code, and the major results are presented in Table 1 together with that for CANFLEX-NU-fuelled core that uses 8-bundle shift refuelling scheme. In this work of time-average calculation, the core was divided into 5 irradiation zones, over which the average fuel discharge irradiation is constant. These irradiation zones were chosen to make the reactor critical, and to provide an appropriate degree of flattening of the radial channel power distribution to enhance the flattening provided by the adjuster systems. The water level in the zone control department was set to 50 % full, representative of the normal operating conditions.

As shown in Table 1, the maximum channel power and maximum bundle power for 4-bundle shift refuelling scheme were calculated as 6534 and 772.1 kW, respectively. The maximum channel power and maximum bundle power for 2-bundle shift case were 6555 and 763.1 kW, respectively, and those for 3-bundle shift refuelling were 6553 and 763.7 kW, respectively. From the results, it is found that the maximum channel power and maximum bundle power are not quite different between them whatever refuelling schemes are employed. For the three refuelling cases, average discharge burnups were calculated as about 325 MWh/kgU, which corresponds to 1.9 times the average discharge burnups of CANFLEX-NU fuel, 175.1 MWh/kgU.

4. 1200 FPD REFUELLING SIMULATION

In order to estimate parameters such as the peak power and refuelling rate for RUFIC fuel bundle, a time-dependent refuelling simulation was performed for 1200 FPD for the CANDU 6 reactor. The simulation was started at the equilibrium core using the RUFIC fuel bundle. This equilibrium condition was obtained from the instantaneous core based on the time-average model as described in the previous section. Individual channels were selected for refuelling, and the flux and powers were calculated at 50-day intervals.

The results of maximum channel power as a function of burnup is presented in Figure 2 for CANDU 6 core with the RUFIC fuel bundles in 4-bundle shift during 1200 FPD refuelling simulation. As shown in Figure 2, the calculated highest maximum channel power is 7228 kW, which meets the requirement of the maximum channel power as the licensing limit of 7300 kW. It is, however, observed that some instances exceed the operating limit on the maximum channel power of 7070 kW, which is based upon the Technical Specifications of Wolsong Unit 3 and 4.

In Figure 3, the variation of maximum channel power with the number of FPD is presented when 2-bundle shift scheme is employed. The highest maximum channel power was calculated to be 6889 kW. As shown in Figure 3, both the licensing and operating limits on the maximum channel power comfortably met at all times for the 2-bundle shift scheme.

In Figure 4, the variation of maximum channel power as a function of FPD is shown for the 3-bundle shift refuelling scheme. The highest maximum channel power is calculated to be 7012 kW. Figure 4 indicates that both the licensing and operating limits on the maximum channel power comfortably met at all times for the 3-bundle shift refuelling scheme.

Figures 5 through 7 present the maximum bundle powers versus FPDs, respectively, in the 4-, 2-, and 3-bundle shift cases during the 1200 FPD simulation. As shown in the Figures, all the maximum bundle power results in the three fuelling cases were within the operating limits of 898 kW that is taken in the Technical Specifications of Wolsong Unit 3 and 4.

Results of the fuelling and burnup simulations are summarized in Table 2 for each refuelling scheme. In this work, refuelling time calculations were also performed, and the results for each refuelling scheme were compared with the refuelling time of the existing 8-bundle shift scheme. From Table 2, it is found that all the average refuelling times of the three fuelling schemes are shorter than the average refuelling time of the CANDU 6 core with CANFLEX-NU fuel in 8-bundle shift, even if their channel-refuelling rates (channel/day) are larger than or equal to the channel-refuelling rate of 8-bundle shift scheme.

5. SUMMARY AND CONCLUSIONS

The feasibility of the RUFIC fuel bundle refuelling in a CANDU 6 reactor was reviewed through 1200 FPD refuelling simulations for each of 4-, 2-, and 3-bundle shift schemes. The simulations calculated maximum channel, bundle power, and CPPF for each case of refuelling schemes employed. As far as the license limits on the maximum channel and bundle power are concerned, it is feasible to fuel a CANDU 6 reactor with the RUFIC fuel bundles by 4-, 2-, or 3-bundle shift. But, considering the operating limits on the maximum channel power of 7070 kW and maximum bundle power of 898 kW, it is expected that some difficulties in reactor control arise if 4-bundle shift scheme is employed. In case of 2-bundle shift refuelling, peak maximum channel and bundle powers were comfortably maintained within the operating limits, and the value of peak maximum CPPF was the lowest among the CPPF calculation results obtained from the three refuelling cases. On the other hand, 2-bundle shift refuelling causes a much higher channel-refuelling rate (channels/day) than the 4-bundle shift refuelling which seems to be disadvantageous to economical aspects. For 3-bundle shift scheme employed to overcome the disadvantage of using the 2-bundle shift, the maximum channel and bundle power results were shown to be relatively good, which are within the operating limits, showing the lower channel-refuelling rate than that of the 2-bundle shift case. Contrary to expectations of long average refuelling time due to the use of the 4-, 2-, or 3-bundle shift scheme, it is found that all the average refuelling times in the three fuelling cases are shorter than the average refuelling time of the CANDU 6 core with CANFLEX-NU fuel refuelled by 8-bundle shift. Up to date, it is, therefore, concluded that 2-bundle or 3-bundle shift are the proper refuelling schemes to CANDU 6 core with the RUFIC fuel bundles.

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Table 1. MAJOR RESULTS OF RFSP TIME-AVERAGE CALCULATION

Model	RUFIC (4-BS*)	RUFIC (2-BS*)	RUFIC (3-BS*)	CANFLEX-NU (8-BS*)
Total Reactor Power, MW	2061.4	2061.4	2061.4	2061.4
Maximum Channel Power, kW	6534	6555	6553	6584
Maximum Bundle Power, kW	772.1	763.1	763.7	800.9
k_{eff}	0.999981	0.999999	1.000029	1.00088
Adjuster Rod Worth, mk	15.8	14.7	14.7	16.8
Zone Worth, mk	7.3	7.1	7.1	6.5
Exit Burnup, MWh/kgU				
average	325.6	325.9	325.9	175.1
inner zone	335.3	336.1	336.1	196.4
outer zone	320.9	321.0	321.0	164.0
Reactivity Decay Rate, mk/day	-0.574	-0.568	-0.570	-0.391

* BS : Bundle Shift

Table 2. SUMMARY RESULTS OF 1200 FPD REFUELLING SIMULATIONS

	RUFIC (4-BS*)	RUFIC (2-BS)	RUFIC (3-BS)	CANFLEX-NU (8-BS)
Peak Max. Channel Power (kW)	7228	6889	7012	6840
Peak Max. Bundle Power (kW)	873	805	850	862
Peak Max. CPPF	1.1750	1.0940	1.1350	1.114
Avg. Refuelling Rate (channels/day)	2.15	4.32	2.88	2.16
Avg. Refuelling Time** (minutes/day)	185	276.5	223.4	278.5

*BS : Bundle Shift

**<u>Refuelling Time</u>

- Travel to and from reactor : 6 min
- New fuel loading .
  - ready FM : 8.28 min.
  - load 2 bundles : 3.1425 min.
  - close FM : 8.63 min.
- Discharge irradiated fuel
  - ready FM : 18.09 min.
  - load 2 bundles : 3.8325 min.
  - close FM : 7.64 min.
- Channel refuelling
  - ready FM : 19.09 min.
  - fuel 2 bundles : 2.565 min.
  - close FM : 24.27 min.

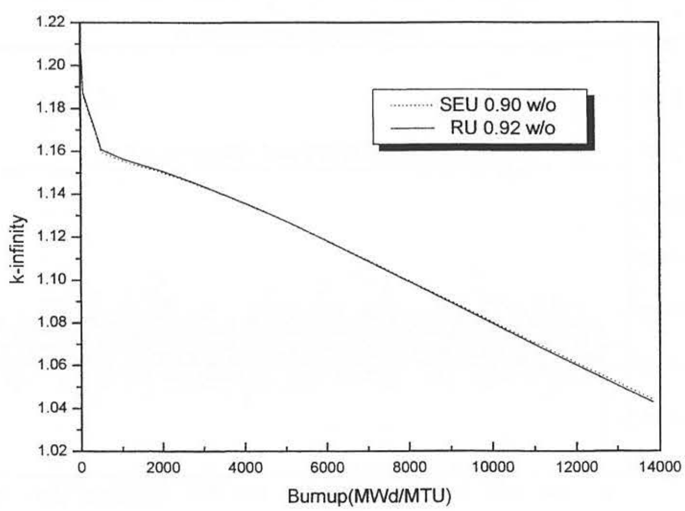

FIGURE 1. COMPARISON OF BURNUP BEHAVIORS BETWEEN RUFIC-0.92 W/O AND CANFLEX-0.9 W/O SEU FUEL

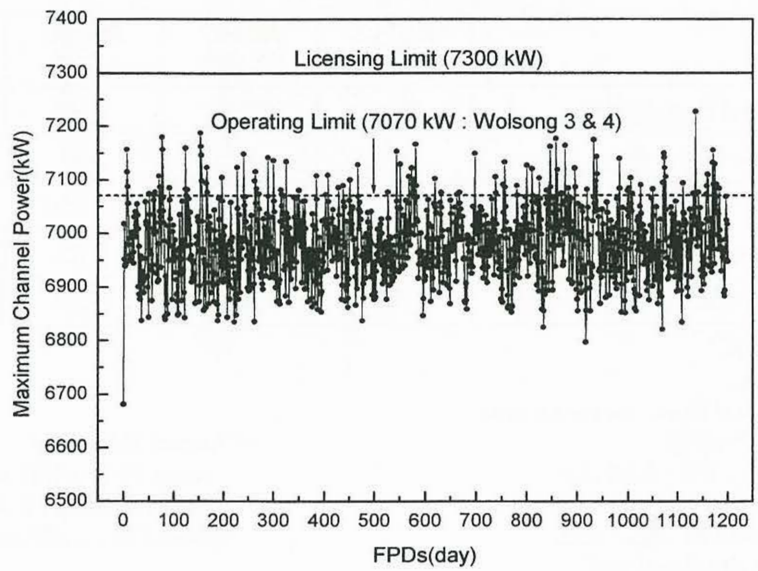

FIGURE 2. MAXIMUM CHANNEL POWER DURING 1200 FPD SIMULATION WITH 4-BUNDLE SHIFT REFUELLING SCHEME

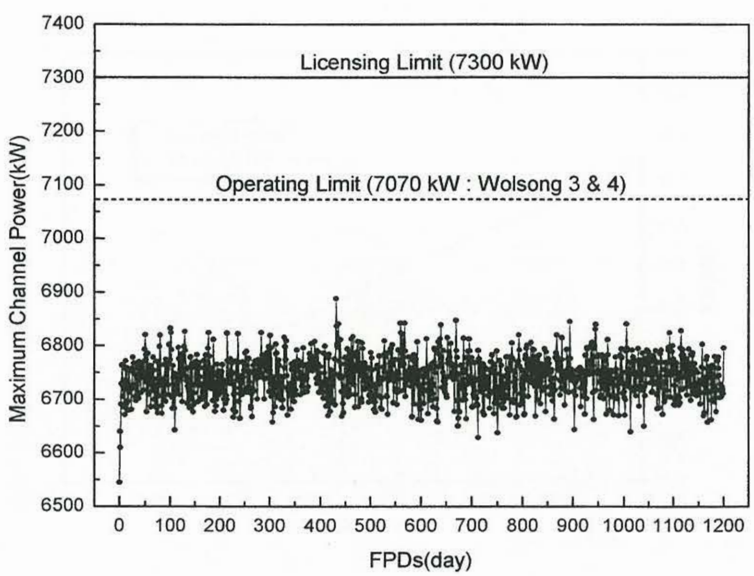

FIGURE 3. MAXIMUM CHANNEL POWER DURING 1200 FPD SIMULATION WITH 2-BUNDLE SHIFT REFUELLING SCHEME

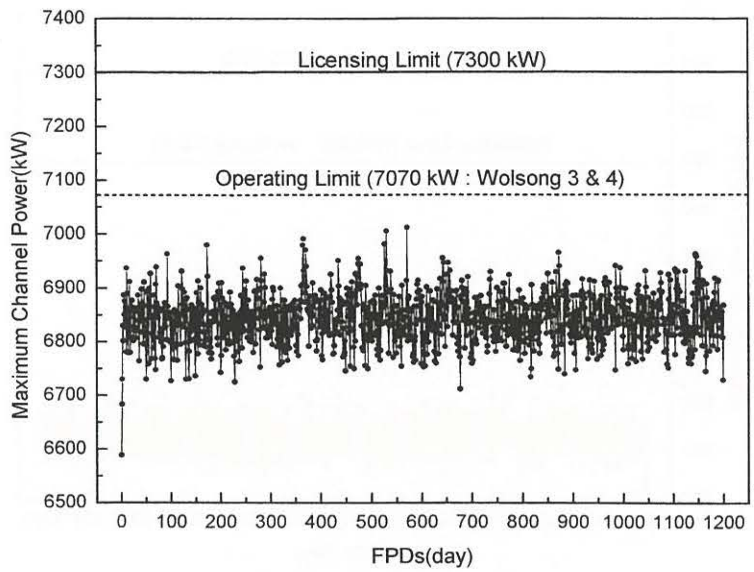

FIGURE 4. MAXIMUM CHANNEL POWER DURING 1200 FPD SIMULATION WITH 3-BUNDLE SHIFT REFUELLING SCHEME

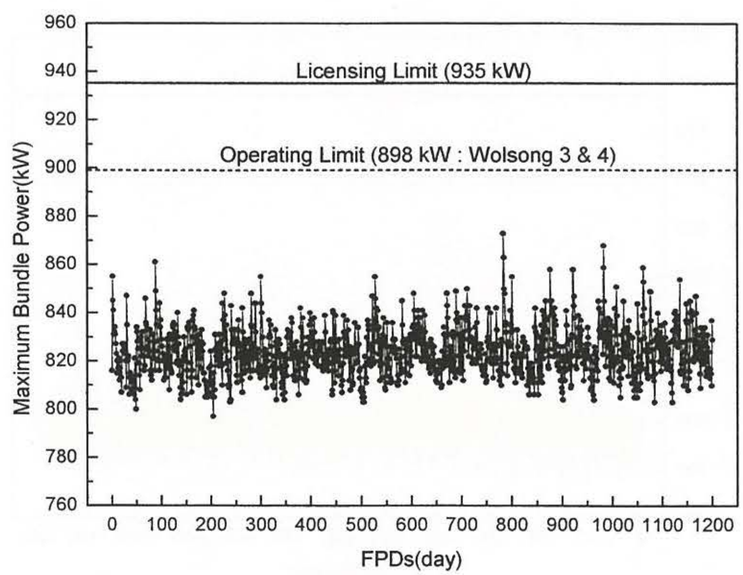

FIGURE 5. MAXIMUM BUNDLE POWER DURING 1200 FPD SIMULATION WITH 4-BUNDLE SHIFT REFUELLING SCHEME

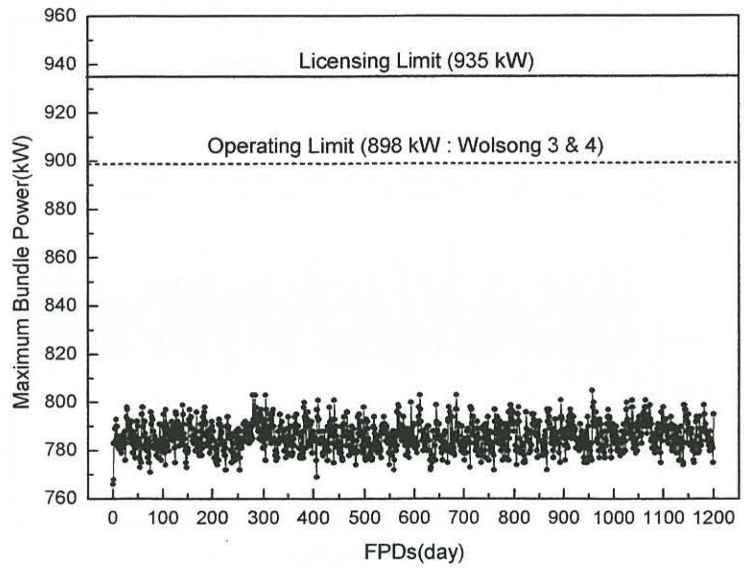

FIGURE 6. MAXIMUM BUNDLE POWER DURING 1200 FPD SIMULATION WITH 2-BUNDLE SHIFT REFUELLING SCHEME

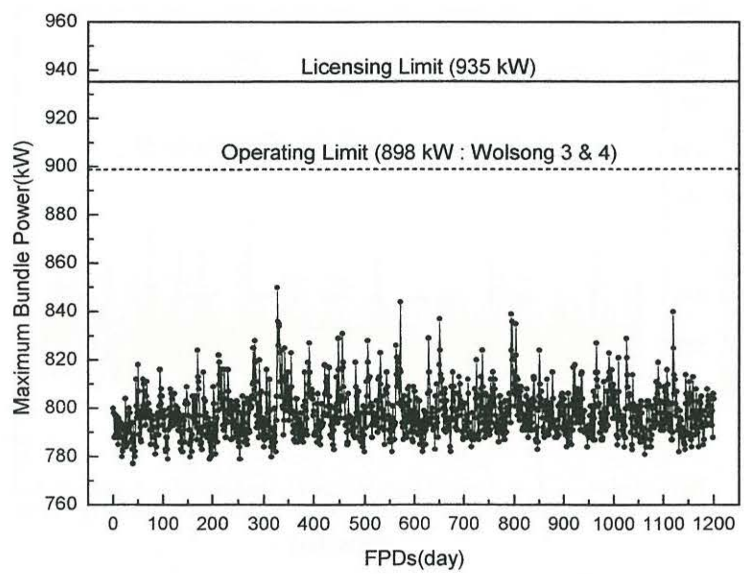

FIGURE 7. MAXIMUM BUNDLE POWER DURING 1200 FPD SIMULATION WITH 3-BUNDLE SHIFT REFUELLING SCHEME