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A Study on RUFIC Core Refuelling Simulation Using 4-Bundle Shift Scheme in CANDU-6 Reactor

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Abstract

A feasibility of the 4 RUFIC fuel bundle shift refueling scheme was evaluated through the transition core simulation by changing from the existing 37-element natural uranium (NU) fuel to 0.92 w/o RUFIC (Recovered Uranium Fuel in CANDU) fuel and 1200 full power day (FPD) equilibrium core simulation for a CANDU-6 core. Considering that the discharge burnup of the RUFIC fuel is almost twice as that of the existing NU fuel, 4-bundle shift refuelling scheme is preferable for the RUFIC core from the standpoint of the in-core fuel management. The transition and equilibrium core fuelling simulation results showed that the variations of maximum channel power (MCP) and maximum bundle power (MBP) as a function of FPD were maintained within the self-imposed operating limits, which are currently employed in Wolsong reactors. Maximum channel power peaking factor (CPPF) was maintained below 1.14 in all FPDs, which is set as the minimal margin of 8 % for the refuelling in a Wolsong unit. As far as concerning the operating limits on the MCP, MBP, and CPPF, it is feasible to refuel the RUFIC fuel bundles in an operating CANDU-6 reactor with 4-bundle shift refuelling scheme. Also, data on element power and element power-increase upon fuelling as a function of burnup were extracted and compiled for fuel performance assessment. It is shown that all the fuel element powers were below the SCC threshold curve for normal operation and for power-increase, except that the power boost for some of the ring-4 (outermost ring) elements are above the SCC threshold. Considering the fact that fuel defects occur when both the two envelop results violate the SCC threshold curve simultaneously, no defect of RUFIC fuel bundles is expected in the 4-bundle shift refueling scheme.

1. Introduction

The CANDU reactor design has the flexibility to use alternative fuel cycles other than natural uranium (NU). These alternative fuel cycles utilize a variety of fissile materials, including slightly enriched uranium (SEU) from enrichment facilities, and recovered uranium (RU) or plutonium obtained from the reprocessing of an irradiated nuclear fuel. The choice depends on economics, resource conservation, as well as political considerations.

RU fuel as CANDU advanced reactor fuel is provided to extend fuel burnup due to a U-235 concentration slightly higher than that of the NU fuel. The typical enrichment of RU is 0.90 w/o U-235 in total uranium. Therefore, RU fuel offers a very attractive alternative to the use of NU in CANDU reactors, since fuel economy is expected to improve even more through the use of RU. RU fuel can be packaged in the CANFLEX fuel bundle, an advanced fuel design. The RU fuel is called as RUFIC (Recovered Uranium Fuel In CANDU). As one of the RUFIC program, with CANFLEX (CANdu FLEXible) bundle carrier, the RU fuel with 0.92 w/o U-235 in total uranium has been assessed to be implemented in CANDU-6 reactors. In a CANDU-6 reactor, the RU fuel with 0.92 w/o U-235 in total uranium is equivalent to SEU fuel with 0.90 w/o U-235 in total uranium. The RUFIC program is an international collaborating one between KAERI, AECL, and BNFL, and covers technology development of all aspects of fuel design and reactor operation with the RUFIC bundles along with minimal modifications to the basic core design.

In the CANDU-6 reactor, 8-bundle shift refuelling scheme is currently employed for the existing NU fuel. It is, however, expected that the use of the refuelling scheme has a difficulty to fuel the RUFIC fuel in the core due to the reactivity increase. Ngo-Trong in AECL had analyzed the fuel management study of a transition core for a CANDU 6 reactor with CANFLEX 0.9 w/o SEU fuel bundles[1]. He introduced the fuelling scheme that was a 4-bundle shift for the first introduction of the enriched fuel in a channel and a 2-bundle shift for all subsequent fuelling to the same channel. In this case, the average refuelling rate is more than 4 channels/day, which is about twice refueling rate of the 8-bundle shift scheme used in the natural uranium core. Considering that the discharge burnup of the RUFIC fuel is almost twice as that of the NU fuel, 4-bundle shift refuelling scheme is preferable for the RUFIC core from the standpoint of the in-core fuel management.

The objective of the study is to examine the feasibility of the 4-bundle shift refuelling scheme for the transition core simulation by changing from the existing 37-element NU fuel to 0.92 w/o RUFIC fuel and 1200 full power day (FPD) simulation of a CANDU-6 equilibrium RUFIC core.

The computer codes used for this study are:

- WIMS-AECL version 2-5d[2] with the nuclear libraries ENDF/B-VI for the lattice cell calculation;
- RFSP version IST-REL_3-01HP[3] for the fuelling simulation and the core flux/power calculation;
- Utility PROC16 for the post-processing of WIMS-AECL result to produce the fuel tables

for RFSP;

- DRAGON version 3.04[4] with the nuclear library ENDF/B-V for the incremental cross section of the control device;
- and AUTOREFUEL[5] for the selection of refuelling channels.

2. Description of RUFIC Fuel Refuelling Simulation

The fuel composition of the 0.92% RU is given in Table 2.1, and the burnup behaviors of RUFIC fuel and 37-element NU fuel are shown in Figure 2.1.

Before the RUFIC fuel refuelling simulation, time-average and instantaneous calculations were first carried out by using the RFSP code in order to obtain the starting time of refuelling simulation. The instantaneous calculation provides a snapshot of the core power and burnup distribution at some point in time. In this work, those calculations were also applied to a CANDU-6 reactor loaded with 37-element NU fuel bundle to analyze the transition core. RUFIC fuel refuelling simulations were carried out using SIMULATE module of RFSP and AUTOREFUEL codes for the selection of refuelling channels. Especially in the transition core analysis, TIME-AVERAGE module of RFSP was also used to guess the average discharge burnup of such a mixed core with 37-element NU and RUFIC fuels.

The simulation of a transition from 37-element NU fuel to RUFIC fuel is divided into three parts, that is, pre-transition, transition, and post-transition phases as shown in Fig. 2.2. In this study, the pre-transition period extended from 0 to ~300 FPD. During this period, the reactor was fuelled only with 37-element NU fuel bundles by using the 8-bundle fuelling scheme. The simulations of the pre-transition and transition periods were carried out iteratively using SIMULATE module of RFSP and AUTOREFUEL codes as shown in Fig. 2.3. During the transition period, only RUFIC fuel bundles were refuelled into the core by using 4-bundle shift refuelling scheme. The transition stage lasted until all of the 37-element NU fuels in the core had been replaced by RUFIC fuel bundle. The procedure of the calculation is as follows: First, the next refuelling channel is selected by AUTOREFUEL code using the last core state parameters. Second, the bundle power and burnup are calculated by using TIME-AVERAGE module of RFSP. The time average bundle power and burnup are used in SIMULATE module of RFSP in order to calculate maximum bundle power and burnup over the time average burnup. Because the number of 37-element NU and RUFIC fuel bundles in the core are daily changed and consequently the average exit burnup are daily changed. Also, those are used in AUTOREFUEL code in order to select the next refuelling channel. Third, the core parameters are calculated with newly refueled channel using SIMULATE module of RFSP. In order to calculate channel overpower distribution (that is, CPPF) in RFSP code, the reference channel power distribution in Reference 6 is employed, which was used for the design of the regional overpower protection system in the Wolsong reactor. Finally, the core state parameters such as channel and bundle powers, maximum CPPF, zone controller level, channel and bundle burnups, etc. are found from the output of SIMULATE module. In the post-transition phase, refuelling continued with RUFIC fuel until 1200 FPDs, in order to estimate the equilibrium RUFIC core characteristics. The simulations of the post-transition period are carried out with the same procedure of transition period.

As self-imposed operating limits employed in this work, 7070 kW and 895 kW were used as MCP and MBP operating limits, respectively, which are currently used in the Wolsong unit. For reference, license limits of the MCP and MBP of the Wolsong unit are 7300 kW and 935 kW, respectively. For maximum CPPF limit, 1.14 was used, which is the minimal margin of 8 % for refuelling in the Wolsong unit. Fuel channels chosen to be refueled were selected for a burnup period of 1 FPD. A core flux/power calculation with RFSP/WIMS-AECL codes, using the true two energy groups and the distributed-xenon formalism, were done with spatial control at the end of the burnup period to validate the selected refueling channels. If the above operating limits are not violated, the refuelling continues for the next burnup period. Otherwise, changes to the refueled channel identities were made until all refuelling criteria are simultaneously satisfied.

3. Results of Refuelling Simulation

3.1 Transition Core

In order to estimate parameters such as the peak power and channel refuelling rate for transition from 37-element NU fuel to RUFIC fuel, a time-dependent refuelling simulation was performed for 1200 FPDs for the CANDU 6 reactor. As a result, all the self-imposed operating limits mentioned in the previous Section (namely MCP not higher than 7070 kW, MBP not higher than 895 kW, a maximum CPPF not higher than 1.14) are met. The average zone fill is maintained in the range 40% to 55% fully-filled at all time. The average refuelling rate was calculated as 2.16 channels per day, which means fuelling rate is almost the same as that of the 37-element NU fuel in the normal operating of the CANDU-6 reactor.

The variation of the MCP during 1200 FPDs transition core simulation is shown in Fig. 3.1. This figure shows that all of the MCPs in transition and post-transition periods are maintained within the self-imposed operating limit of 7070 kW. Figure 3.2 shows the variation of the MBP during 1200 FPDs. The highest value of the maximum bundle power in the transition simulation is 895 kW. The MBPs in early transition period (301 FPD ~ 500 FPD) is higher than that in the pre-transition period and also that in the period after 500 FPD. Due to the difference of uranium enrichment between 37-element NU fuel and RUFIC fuel, it is indicated that bundle powers with RUFIC fuel are much higher than those of 37-element NU fuel in a core with low portion of RUFIC fuel bundles. All of the MBPs during transition simulation are maintained within the self-imposed operating limit of 895 kW.

Figure 3.3 shows the variation of the maximum CPPF during 1200 FPDs. The trend for this parameter is similar to that of the MCP. It is understandable since two parameters are related each other. The variation of the average zone fill is shown in Figure 3.4, from which it is maintained in the range 40% to 55% fully-filled at all time.

Figure 3.5 shows the total number of discharged 37-element NU fuel and RUFIC fuel bundles versus FPDs. Also this figure shows total number of RUFIC fuel bundles loaded. At the 933 FPD, all of the 37-element NU fuel bundles were discharged from the core. The RUFIC fuel bundles were discharged for the first time at the 718 FPD. The average discharge burnup of the 37-element NU fuel and RUFIC fuel bundles from 301 FPD to 1200 FPD were 9124.8 MWd/tU and 14204.8 MWd/tU, respectively.

Figures 3.6 and 3.8 show the element power envelop (ramped power) with element burnup for 37-element NU fuel and RUFIC fuel, respectively. In the case of RUFIC fuel, the envelopes are much lower than the SCC threshold curve, as compared with 37-element NU fuel. Figures 3.7 and 3.9 show the element power-increase envelop (power boost) with burnup for 37-element NU fuel and RUFIC fuel, respectively. These figures show that there will not be any fuel defect of the 37-element NU fuel or RUFIC fuel bundles during the transition simulation.

3.2 Equilibrium Core

In this Section, a time-dependent refuelling simulation was carried out for the RUFIC equilibrium core for 1200 FPDs. The simulation was started from the equilibrium core state, which had been obtained from the instantaneous core calculation based on the time-average model, by fuelling the RUFIC bundle. Individual channels were selected for refuelling, and the flux and powers were calculated at the intervals of 1 FPD.

The variations of the MCP, MBP, and maximum CPPF are shown in Figures 3.10 ~ 3.12 during the 1200 FPDs equilibrium core simulation with 4-bundle shift refuelling scheme. As shown in the Figures, the calculated highest maximum channel and bundle powers are 7066 and 863 kW, respectively, and the calculated highest maximum CPPF is 1.119. It is found that the self-imposed operating limits of 7070 and 895 kW on the MCP and MBP limits, respectively, were met throughout the simulations using 4-bundle shift refuelling scheme. For the maximum CPPF results, minimum margin of 8 % for refuelling can be secured even if the 4-bundle shift refuelling scheme is employed. In Figure 3.13, average zone level is presented during the simulation, which shows a good behavior of the liquid zone control system. Throughout this 1200 FPDs refuelling simulation, it is found that the average discharge burnup was calculated as about 14135.8 MWd/tU and the refuelling rate as about 2.06 channels/day.

Figures 3.14 and 3.15 show the element power envelop and the element power-increase envelop for the RUFIC fuels loaded into the equilibrium core during 1200 FPDs. Observing that both the two envelop results are not violated against SCC threshold curve simultaneously, even if some points exceeded the SCC threshold curve in the element power increase envelop, it is expected that there will be no defect of RUFIC fuel bundles in the 4-bundle shift refuelling scheme.

4. Summary and Conclusions

A feasibility of the RUFIC fuel refuelling simulation using 4-bundle shift refuelling scheme was examined for transition and equilibrium core in a CANDU 6 reactor. The transition and equilibrium core fuelling simulation results showed that the variations of MCP and MBP as a function of FPD were maintained within the self-imposed operating limits, which are currently employed in a Wolsong reactor. Maximum CPPF versus the number of FPDs was maintained below 1.14, which was set as the minimal margin of 8 % for refuelling in the Wolsong reactor. Also, the average zone controller fill showed a good behavior of the liquid zone control system at all times. As far as concerning the operating limits on the MCP, MBP, and CPPF, it is, therefore, feasible to refuel the RUFIC fuel bundles into an operating CANDU-6 reactor with 4-bundle shift refuelling scheme.

Data on element power and element power-increase upon fuelling as a function of burnup were extracted and compiled for fuel performance assessment. It is also found that all the fuel element powers were below the SCC threshold curve for normal operation and for power-increase, except that the power boost for some of the ring-4 (outermost ring) elements were above the SCC threshold. Considering the fact that fuel defects occur when both the two envelop results violate the SCC threshold curve simultaneously, no defect of RUFIC fuel bundles is expected in the 4-bundle shift refuelling scheme.

Acknowledgement

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[2] J. Griffiths, “WIMS-AECL User's Manual,” RC-1176/COG-94-52 Rev. 3, February 1999.

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[4] G. Marleau, A. Hebert and R. Roy, “A User Guide for DRAGON, Version DRAGON 000331 Release 3.04,” IGE-174 Rev. 5, April 2000.

[5] H. B. Choi, “A fast-running fuel management program for a CANDU reactor,” Annals of Nuclear Energy, Vol. 27, pp. 1-10, 2000.

[6] Design Manual – Shutdown System No.1, 86-68200-DM-001, Appendix D, p.D-26, KOPEC, December 2001.

Table 2.1 Composition of the 0.92% Recovered Uranium

Isotope	Weight %
U-234	0.016
U-235	0.92
U-236	98.724
U-238	0.34

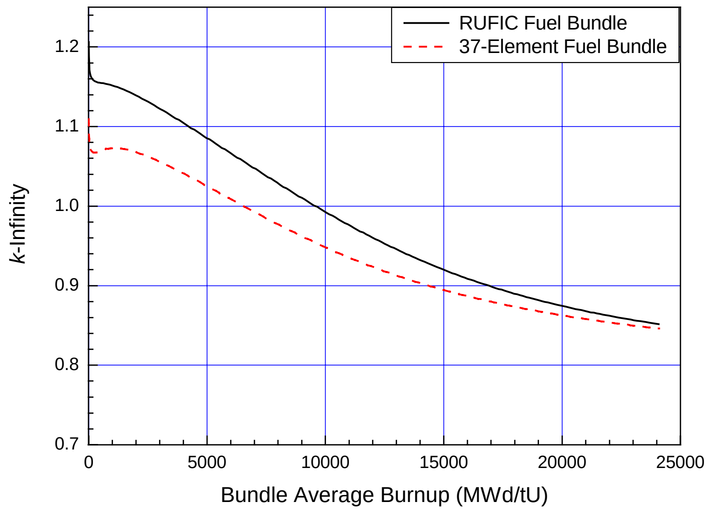

Figure 2.1 *k*-Infinity vs. Bundle Average Burnup for 37-Element NU and RUFIC Lattice Cell

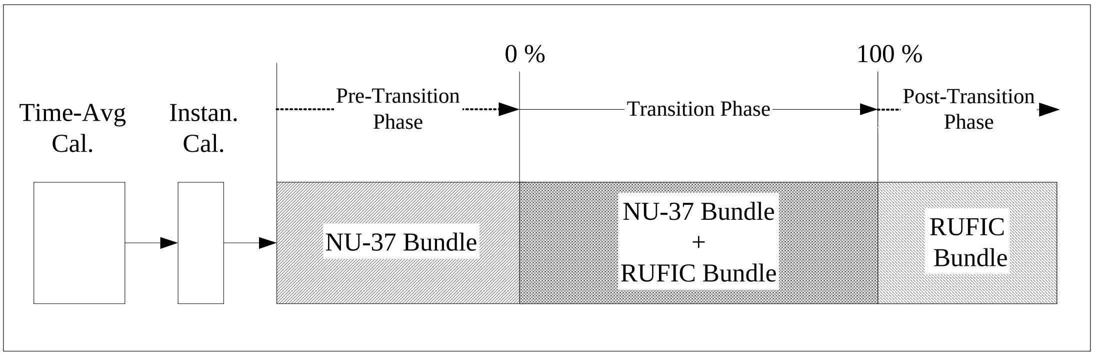

Figure 2.2 Concept of Transition Core Analysis

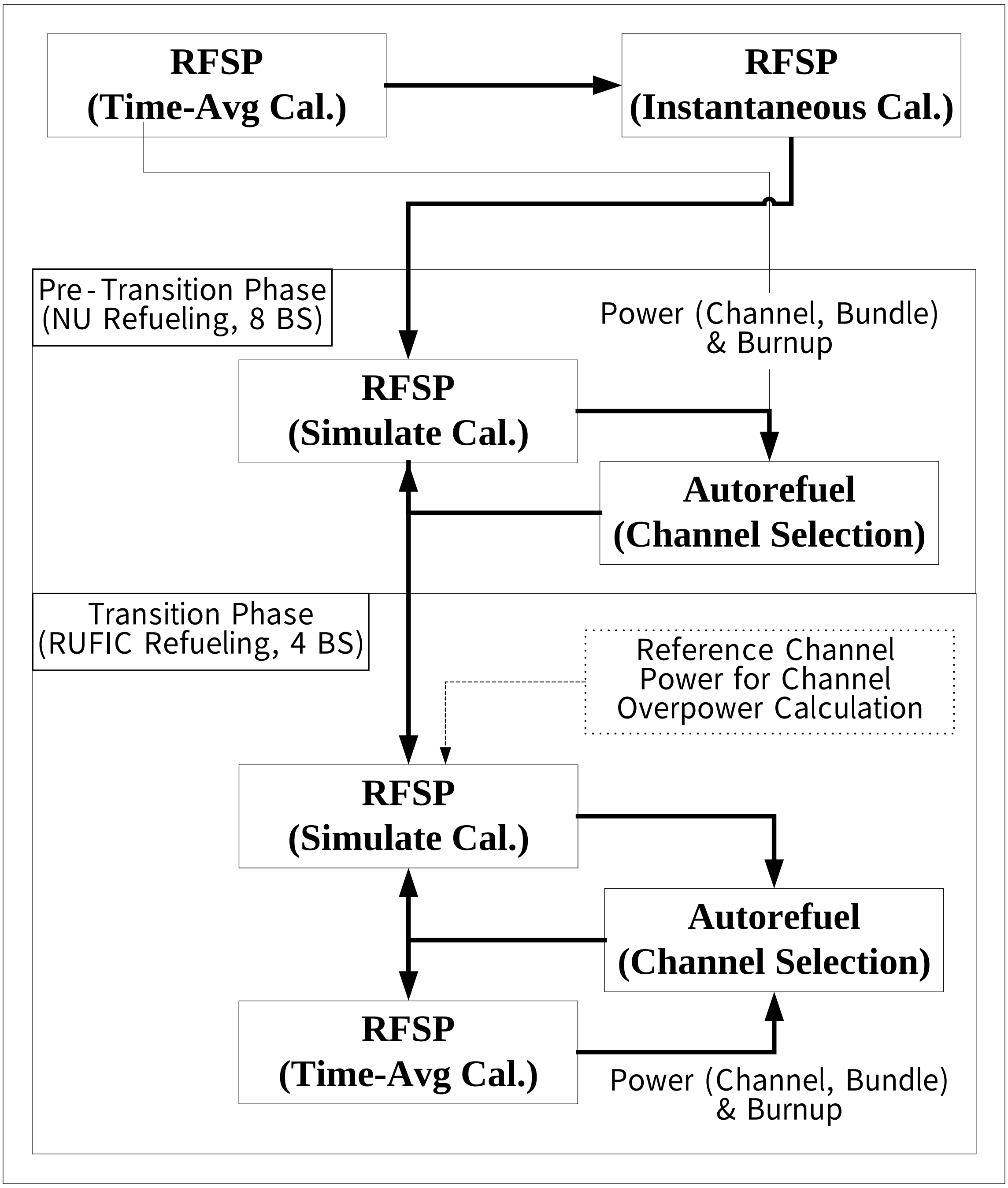

Figure 2.3 Flowchart for Transition Simulation from 37-Element NU Fuel to RUFIC Fuel

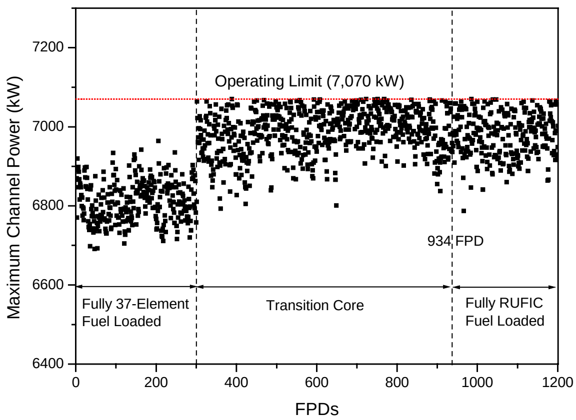

Figure 3.1 Maximum Channel Power during 1200 FPD Transition Core Simulation

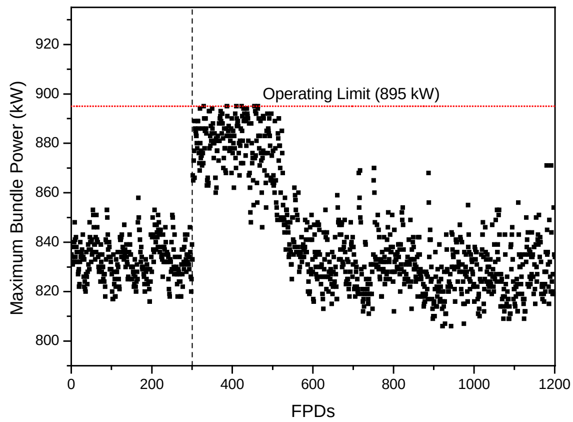

Figure 3.2 Maximum Bundle Power during 1200 FPD Transition Core Simulation

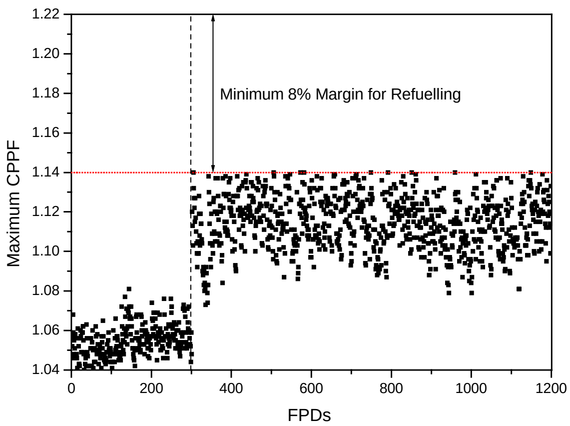

Figure 3.3 Maximum CPPF during 1200 FPD Transition Core Simulation

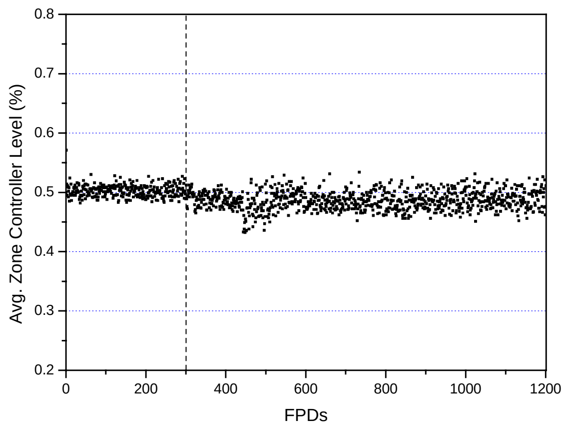

Figure 3.4 Average Zone Fill during 1200 FPD Transition Core Simulation

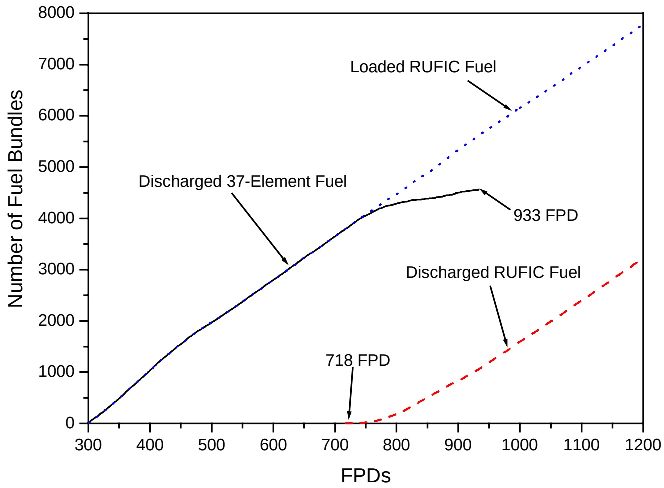

Figure 3.5 Total Number of Discharged 37-Element NU fuel and RUFIC Fuel Bundles and Loaded RUFIC Fuel Bundles with FPD

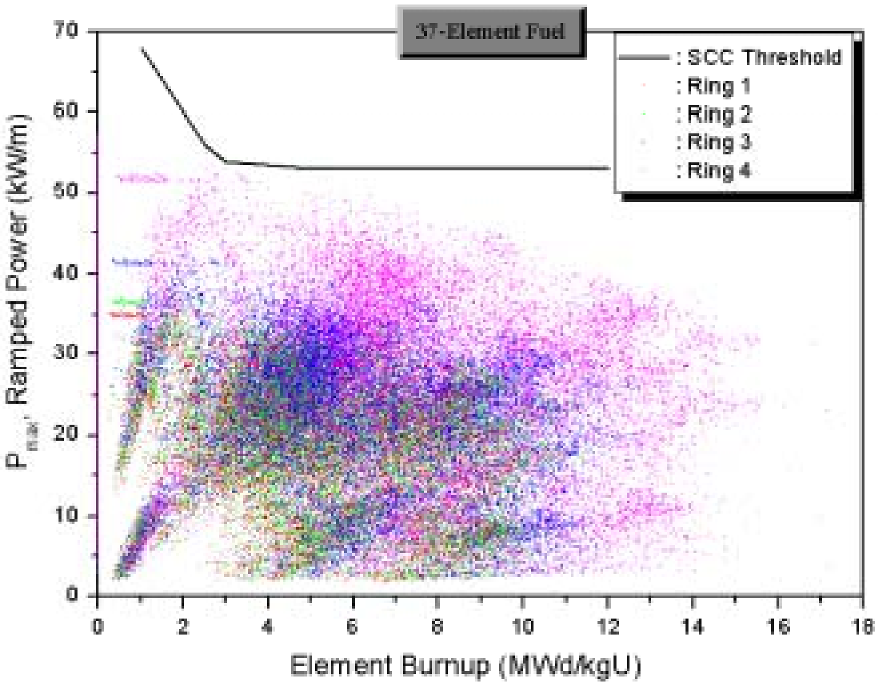

Figure 3.6 Element Power Envelopes of 37-Element NU fuel with element burnup (Transition Core)

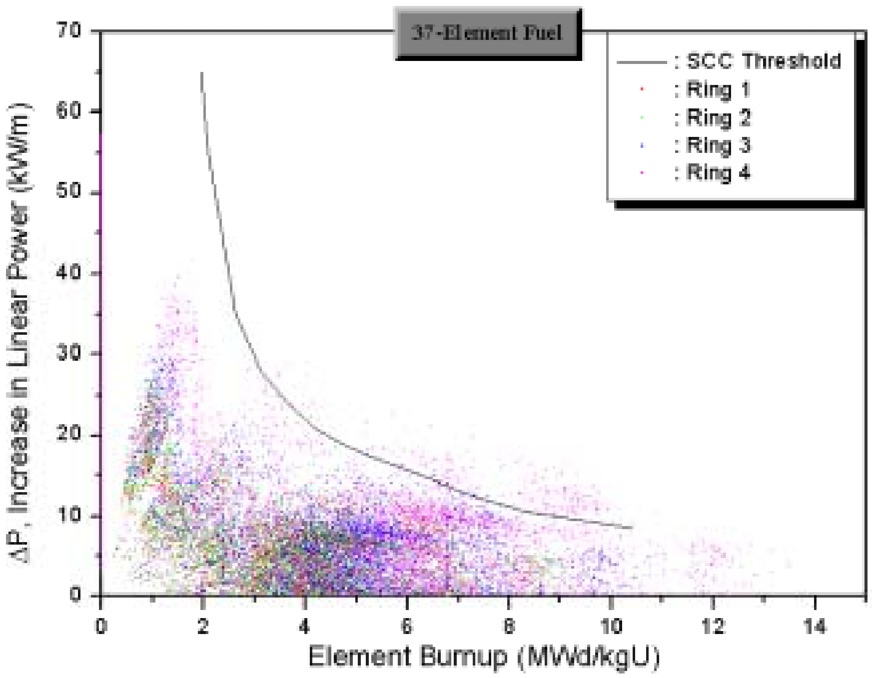

Figure 3.7 Element Power-Increase Envelopes of 37-Element NU fuel with element burnup (Transition Core)

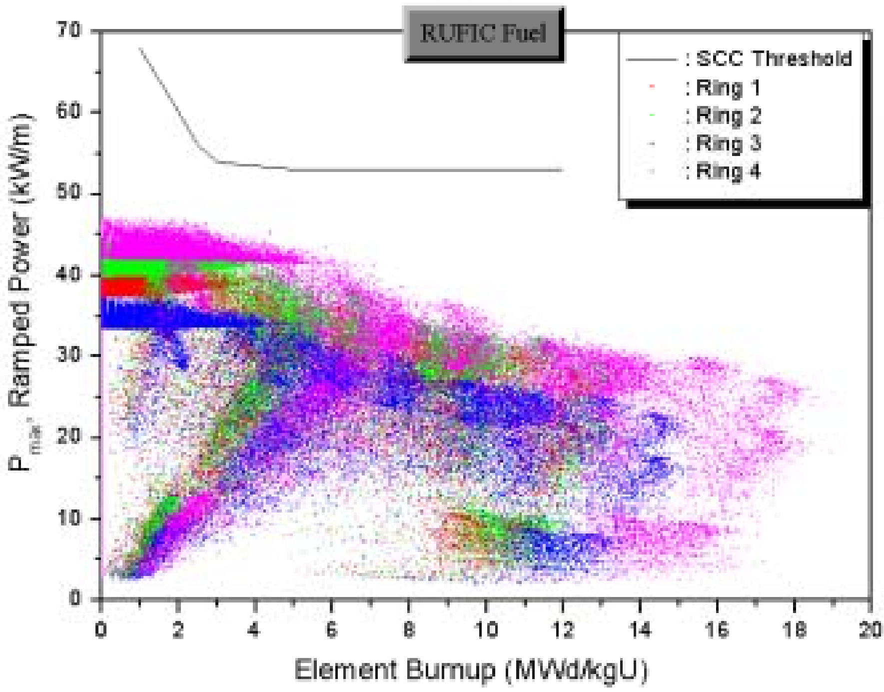

Figure 3.8 Element Power Envelopes of RUFIC fuel with element burnup (Transition Core)

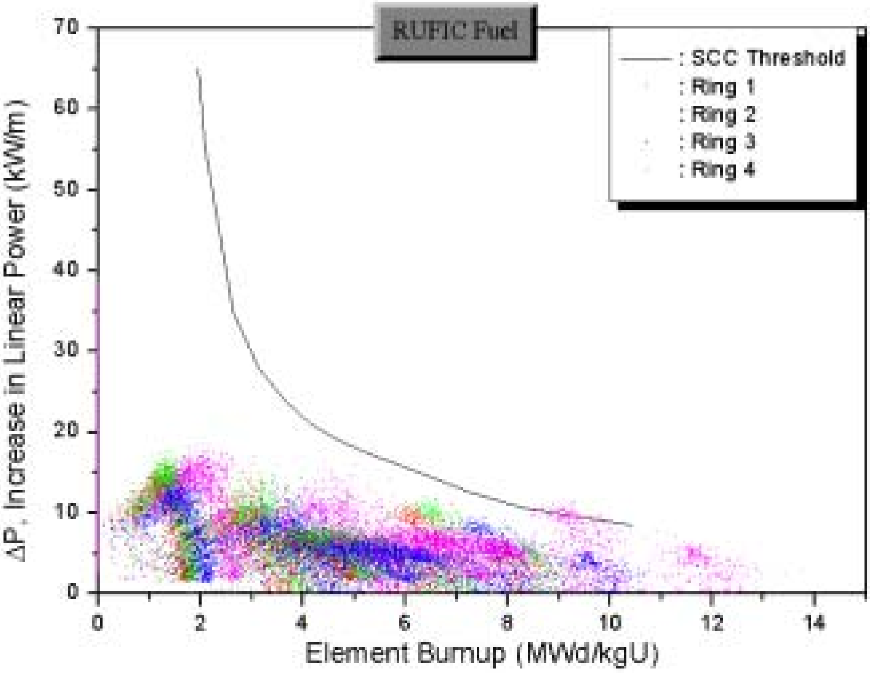

Figure 3.9 Element Power-Increase Envelopes of RUFIC fuel with element burnup (Transiton Core)

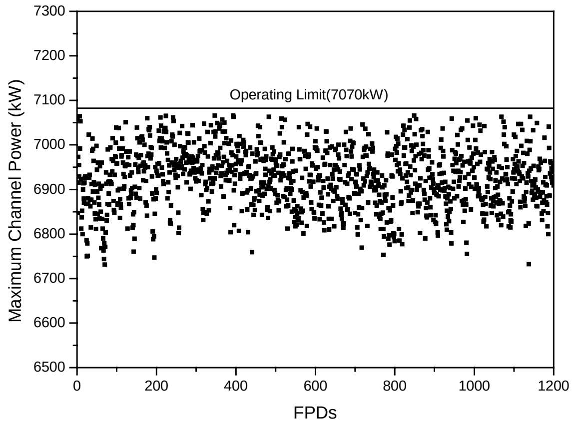

Figure 3.10 Maximum Channel Power during 1200 FPD Equilibrium Core Simulation

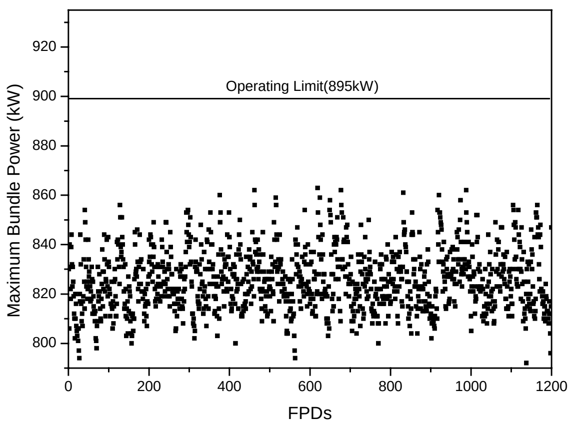

Figure 3.11 Maximum Bundle Power during 1200 FPD Equilibrium Core Simulation

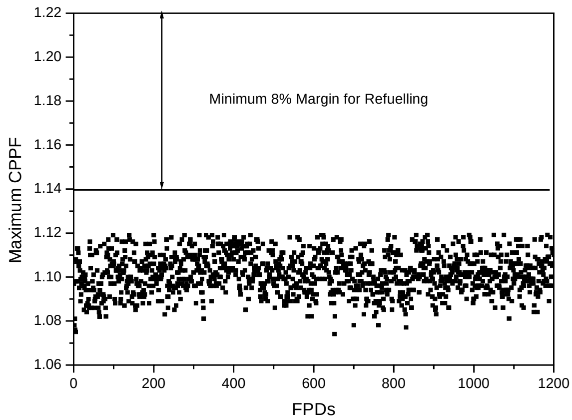

Figure 3.12 Maximum CPPF during 1200 FPD Equilibrium Core Simulation

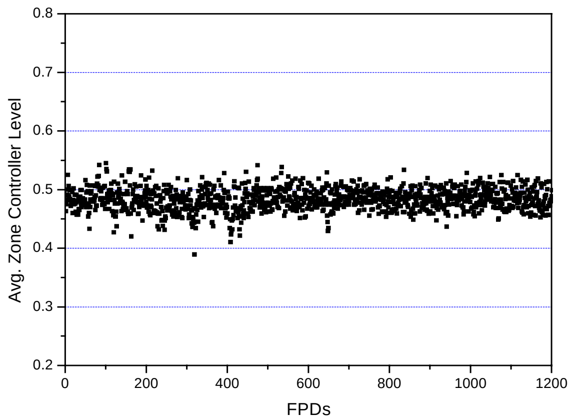

Figure 3.13 Average Zone Fill during 1200 FPD Equilibrium Core Simulation

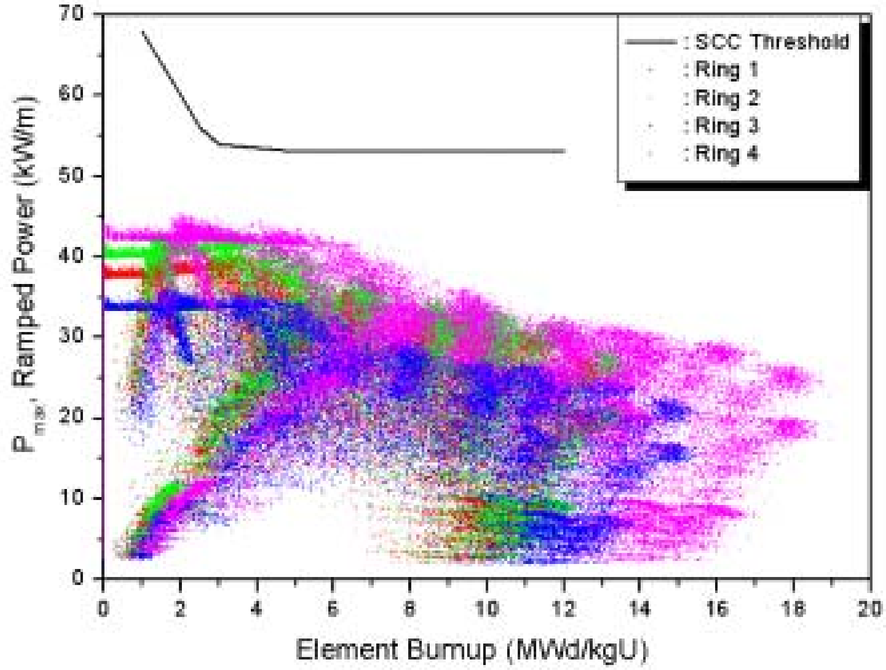

Figure 3.14 Element Power Envelopes of RUFIC fuel with element burnup (Equilibrium Core)

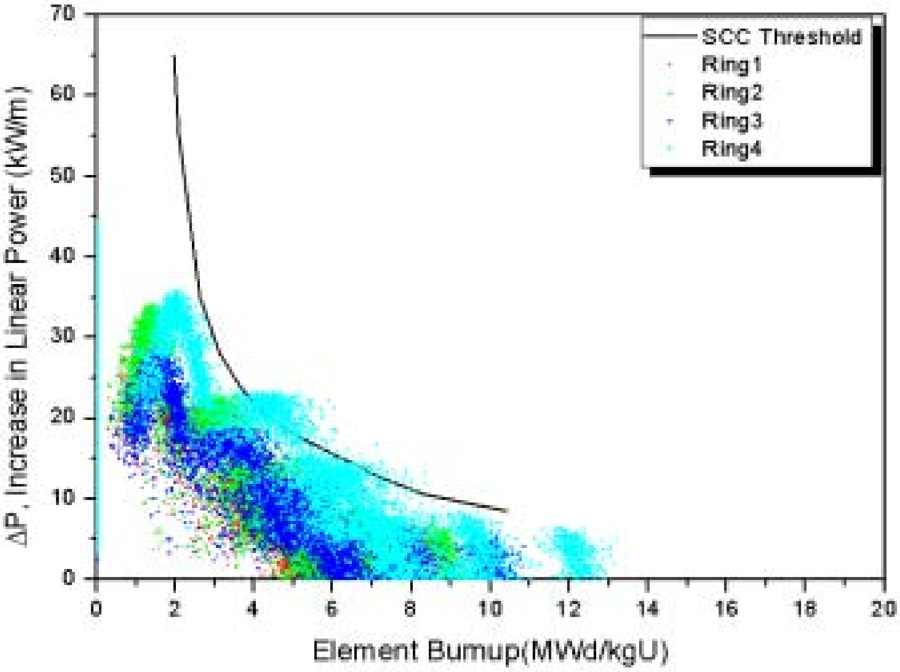

Figure 3.15 Element Power-Increase Envelopes of RUFIC fuel with element burnup (Equilibrium Core)