A FEASIBILITY STUDY ON CANFLEX-RU 4-BUNDLE SHIFT SCHEME IN CANDU-6 REACTOR

HO CHUN SUK*, SOON YOUNG KIM, and CHANG KEUN JO
Korea Atomic Energy Research Institute
150 Dukjin, Yusong, Daejeon 305-353, Republic of Korea
*hcsuk@kaeri.re.kr

ABSTRACT

A feasibility of the 4 RUFIC[1] (Recovered Uranium Fuel in CANDU[2]) fuel bundle shift refuelling scheme for a CANDU-6 core was evaluated through the transition core simulation by changing from the existing 37-element natural uranium (NU) fuel to the 0.92 w/o RUFIC fuel and the 1200 full power day (FPD) equilibrium core simulation, where the CANFLEX[3]-RU fuel is called as RUFIC. The computer code system used in this work is WIMS-AECL/DRAGON/RFSP. The results of transition and equilibrium core fuelling simulations show that the variations of maximum channel power (MCP) and maximum bundle power (MBP) as a function of FPDs were maintained within the self-imposed operating limits which are currently employed in Wolsong reactors. The maximum channel power peaking factor (CPPF) is maintained below 1.14 in all FPDs, which is set as the minimal margin of 8 % for the refuelling in a Wolsong unit. Concerning the operating limits on the MCP, MBP, and CPPF, a 4-bundle shift refuelling scheme is feasible to refuel the RUFIC fuel bundles into an operating CANDU-6 reactor. 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 are 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 is above the SCC threshold. Considering the fact that fuel defects occur when both the results on the two envelops violate the SCC threshold curve simultaneously, no defect of RUFIC fuel bundles is expected in the 4-bundle shift refuelling scheme. And, it is revealed that there would be some improvement in the critical channel power (CCP) in a channel with the RUFIC fuel bundle.

---

1 RUFIC®(Recovered Uranium Fuel in CANDU) is a registered trademark of Korea Atomic Energy Research Institute (KAERI)I

2 CANDU® (Canada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited

3 CANFLEX® (CANDU FLEXible) is a registered trademark of Atomic Energy of Canada Limited (AECL) and the Korea Atomic Energy Research Institute (KAERI).

1. INTRODUCTION

The use of recovered uranium (RU) in CANDU reactors is an exciting new fuel development for the reactors' operators seeking significantly improved fuel cycle economics since the CANDU reactor design has the flexibility to use alternative fuel cycles other than natural uranium (NU). Atomic Energy of Canada Limited (AECL), British Nuclear Fuels plc (BNFL) and Korea Atomic Energy Research Institute (KAERI) have recognized jointly that the CANFLEX (CANdu FLEXible fuelling) fuel bundle incorporating RU provides "improved fuel performance" and "reduced fuel cycle costs", since the RU reprocessed from the irradiated nuclear fuel can be directly used in CANDU reactors without re-enrichment, where the CANFLEX-RU fuel is called RUFIC (Recovered Uranium Fuel in CANDU). The RUFIC program has been initiated to assess the use of RUFIC fuel in CANDU-6 reactors such as Wolsong units. The program has been made with a co-operative effort between KAERI, BNFL and AECL in order to develop technologies of all aspects of CANDU-6 design and operation with the RUFIC bundles, only with minimal modifications to the basic core design.

In the CANDU-6 reactors, an 8-bundle shift refuelling scheme is currently employed for the existing 37-element NU fuel. For the RUFIC fuel, it was, however, expected to find a simple scheme of the bundle shift refuelling into the core because of the significant reactivity increase. A previous work 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]. In the study, a 4-bundle shift scheme was introduced for the first introduction of the enriched fuel in a channel and a 2-bundle shift for all subsequent fuelling to the same channel. Considering that the discharge burnup of the RUFIC fuel is almost twice 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, therefore, to examine the feasibility of 4-bundle shift refuelling in both the transition core simulation by changing from the existing 37-element NU fuel to RUFIC fuel and 1200 full power day (FPD) simulation of a CANDU-6 equilibrium RUFIC core.

The computer codes used in this study are WIMS-AECL version 2-5d[2] for the lattice cell calculation, RFSP version IST-REL_3-01HP[3] for the fuelling simulation and the core flux/power calculation, DRAGON version 3.04[4] for the incremental cross section of the control devices, and AUTOREFUEL[5] for the selection of refuelling channels.

2. DECISION OF REFERENCE RUFIC FUEL

Prior to the refuelling simulations, a reference U-235 content in RUFIC fuel was firstly determined to be equivalent to CANFLEX-0.9 w/o SEU, whose nuclear characteristics are preferable to this work. In order to determine the reference U-235 content in RUFIC fuel, 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 2-5d 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 examined 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 ~14000 MWd/MTU, which is the discharge burnup of the CANFLEX-0.9 w/o SEU fuel, by using WIMS-AECL. 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 13645 MWd/MTU. It is, therefore, judged and taken that 0.92 w/o as 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 13625 MWd/MTU.

3. DESCRIPTION OF RUFIC FUEL REFUELLING SIMULATION

First of all, the time-average and instantaneous calculations on the RUFIC core were carried out with the RFSP code in order to obtain the starting time of the fuel 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-AVER module of RFSP was used to guess the average discharge burnup of such a mixed core with 37-element NU and RUFIC fuels.

The core 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. 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 shift 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. 3. During the transition period, only RUFIC fuel bundles were refuelled into the core by using a 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-AVER 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 numbers 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 the AUTOREFUEL code in order to select the next refuelling channel. Third, the core parameters are calculated with a newly refueled channel using SIMULATE module of RFSP. In order to calculate channel overpower distribution (that is, CPPF) with 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, the 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 the MCP and MBP operating limits, respectively, which are currently used in a 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 refuelling 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.

4. RESULTS OF REFUELLING SIMULATION

4.1 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 of 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. 4. 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 5 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 those in the pre-transition period and 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 a 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 6 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 to each other. As shown in Figure 7, the variation of the average zone fill is maintained in the range of 40% to 55% fully-filled at all time.

Figure 8 shows the total number of discharged 37-element NU fuel and RUFIC fuel bundles versus FPDs. Also this figure shows the 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/MTU and 14204.8 MWd/MTU, respectively.

Figures 9 and 11 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 10 and 12 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 in the period of the fuel transition in the core.

The heat flux distributions of typical channels, O06 and M19, in the CANDU-6 reactor are shown in Figures 13 and 14, respectively. Channel O06 and M19 are often used for critical channel power (CCP) analysis. These figures show that all heat flux distribution of channel with RUFIC fuel are skewed toward the coolant inlet end of the channel, as compared with those of 37-element NU fuel. In general, the peak heat flux in a channel with CANFLEX fuel bundle using the 4-bundle shift scheme has a tendency towards the upstream in the fuel channel [7]. It is revealed that there would be some improvement in the CCP in a channel with the RUFIC fuel bundle.

4.2 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.

Figures 15 to 17 show the variations of the MCP, MBP, and maximum CPPF, respectively as the results of the 1200 FPDs equilibrium core simulation with the 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 the 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. As shown in Figure 18, average zone level shows good behavior in the liquid zone control system in the simulation core. Throughout this 1200 FPDs refuelling simulation, it is found that the average discharge burnup was calculated to be about 14135.8 MWd/MTU and the refuelling rate to be about 2.06 channels/day.

Figures 19 and 20 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 calculated results on the two envelops 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, therefore, expected that there will be no defect of RUFIC fuel bundles in the 4-bundle shift refuelling scheme.

5. SUMMARY AND CONCLUSIONS

A feasibility of the 4 RUFIC fuel bundle shift refuelling scheme was examined by the CANDU-6 transition and equilibrium core simulations. The results of transition and equilibrium core fuelling simulations 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. The maximum CPPF versus the number of FPDs is maintained below 1.14, which is set as the minimal margin of 8 % for refuelling in the Wolsong reactor. Also, the average zone controller fill shows good behavior in the liquid zone control system at all times. As far as concerning the operating limits on the MCP, MBP, and CPPF, the 4 RUFIC fuel bundle shift refuelling scheme is, therefore, feasible to refuel the RUFIC fuel bundles into an operating CANDU-6 reactor.

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 are 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 results on the two envelops violate the SCC threshold curve simultaneously, no defect of RUFIC fuel bundles is expected in the 4-bundle shift refuelling scheme.

ACKNOWLEDGEMENT

This work is supported by the Mid- and Long-term Nuclear R&D Program of the Ministry of Science and Technology.

REFERENCES

[1] KAERI/AECL Joint CANFLEX Development Program Background Information Generated by AECL, CANFLEX-AECL-56, KAERI, November 2000.

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

[3] B. Arsenault, D. A. Jenkins and A. U. Rehman, “RFSP-IST User's Manual,” COG-98-272 Rev. 0, June 1999.

[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.

[7] J. S. Jun, et. al., “The Preliminary Thermalhydraulic Analysis of CANFLEX-RU(0.9%) Fuel Bundle,” Proceeding of the KNS Spring Meeting, Suwon, May 1998 (in Korean).

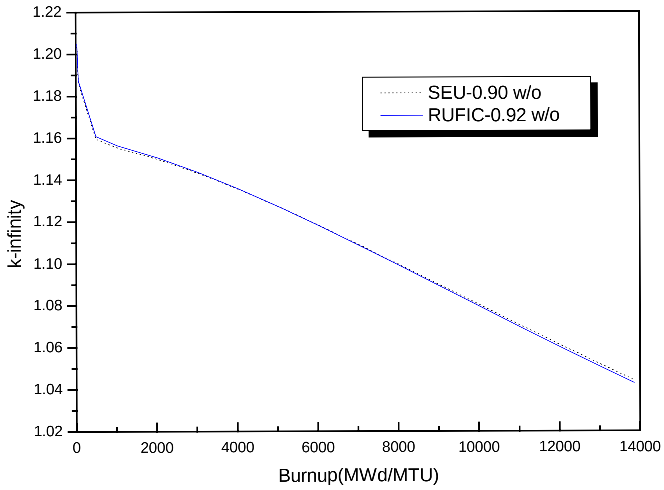


Figure 1. Comparison of Burnup Behaviors between RUFIC-0.92 w/o and CANFLEX-0.9 w/o SEU fuel

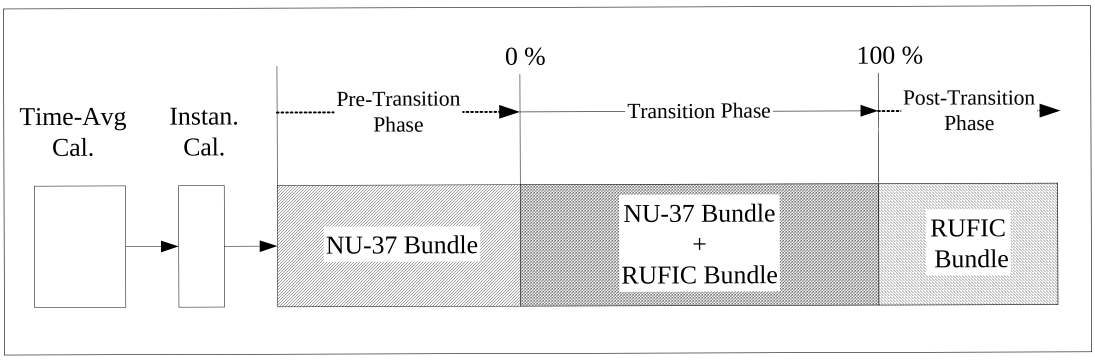


Figure 2. Concept of Transition Core Analysis

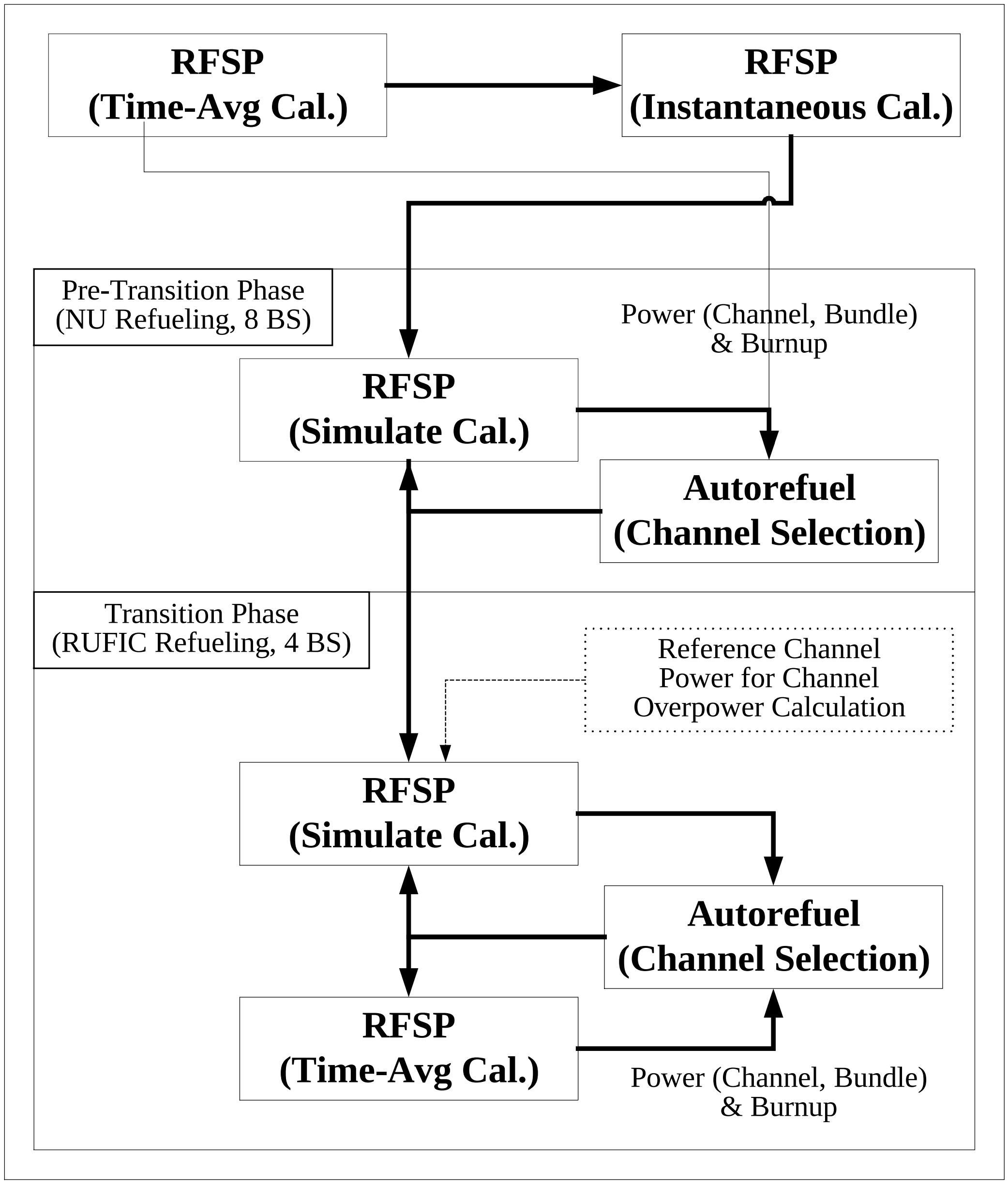


Figure 3. Flowchart for Transition Simulation from 37-Element NU Fuel to RUFIC Fuel

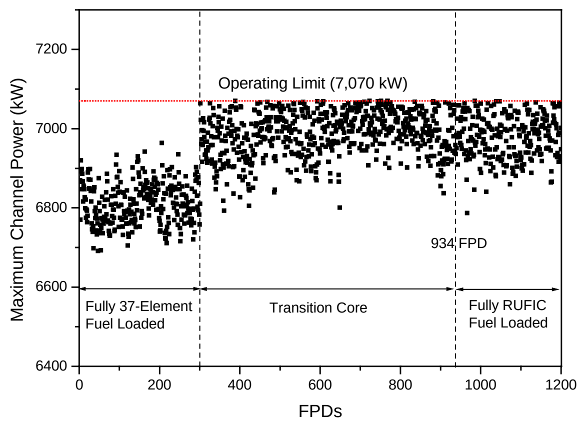


Figure 4. Maximum Channel Power during 1200 FPD Transition Core Simulation

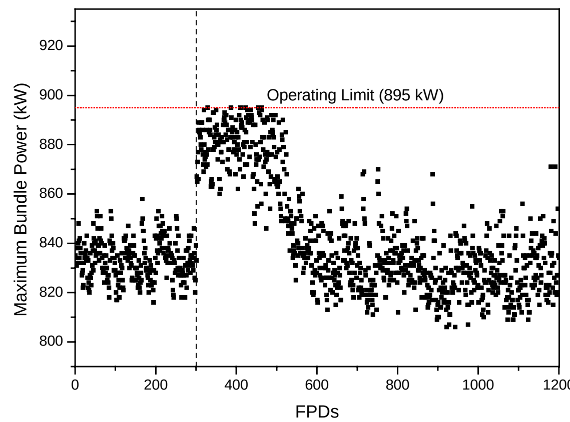


Figure 5. Maximum Bundle Power during 1200 FPD Transition Core Simulation

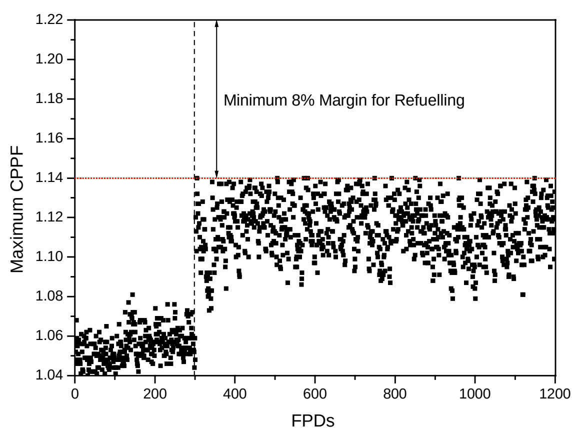


Figure 6. Maximum CPPF during 1200 FPD Transition Core Simulation

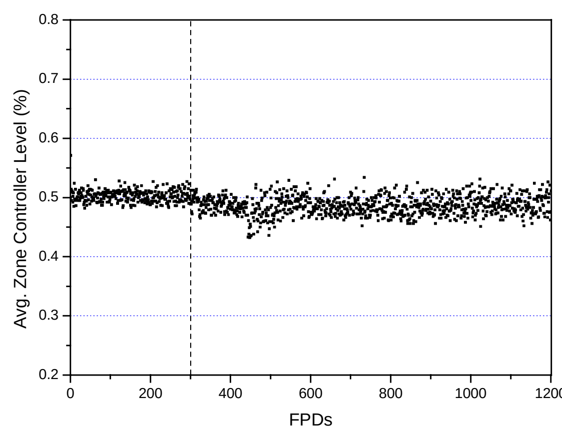


Figure 7. Average Zone Fill during 1200 FPD Transition Core Simulation

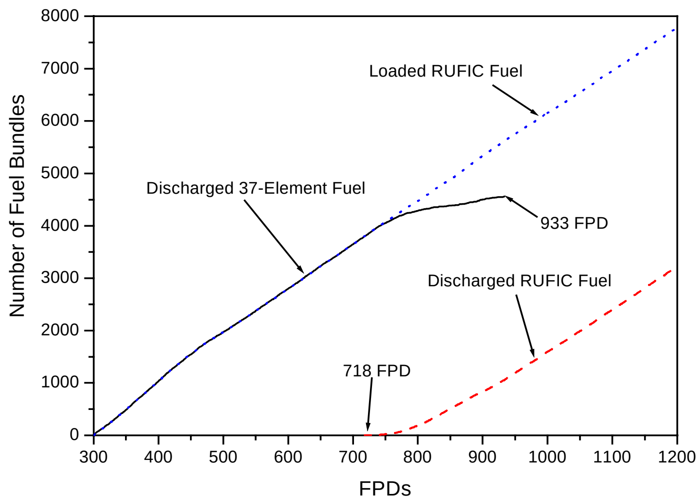


Figure 8. Total Number of Discharged 37-Element NU fuel and RUFIC Fuel Bundles and Loaded RUFIC Fuel Bundles with FPD

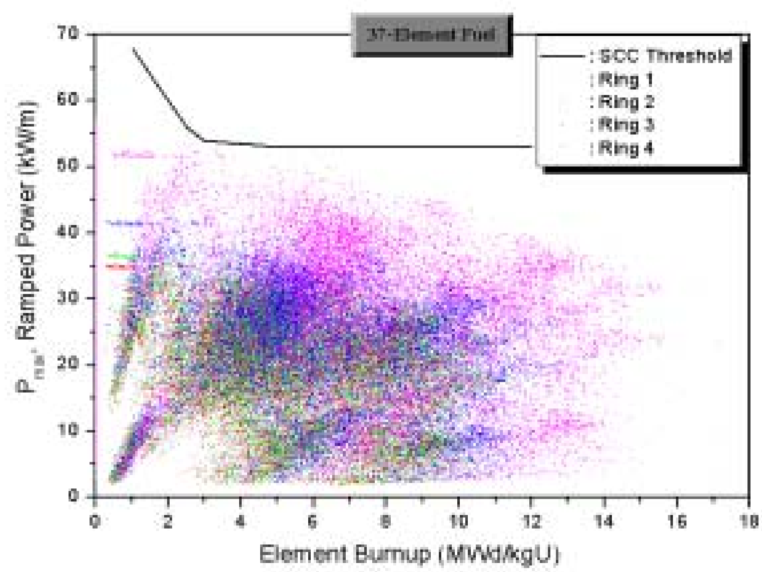


Figure 9. Element Power Envelopes of 37-Element NU fuel with element burnup (Transition Core)

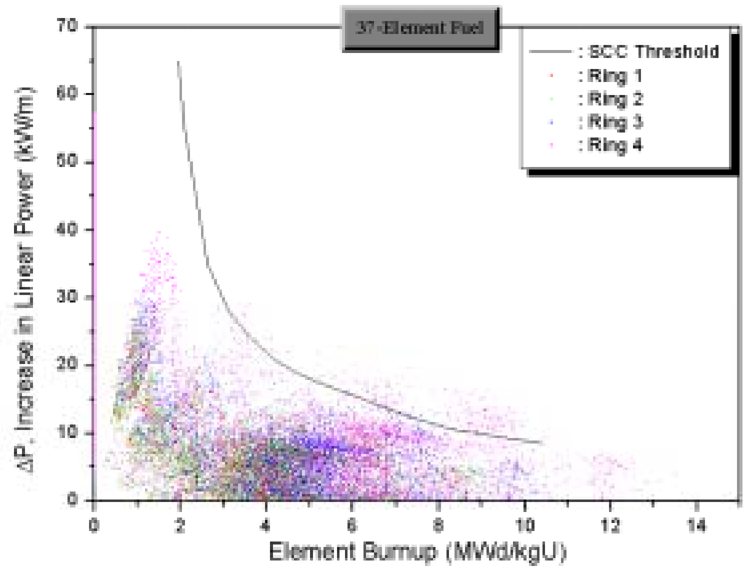


Figure 10. Element Power-Increase Envelopes of 37-Element NU fuel with element burnup (Transition Core)

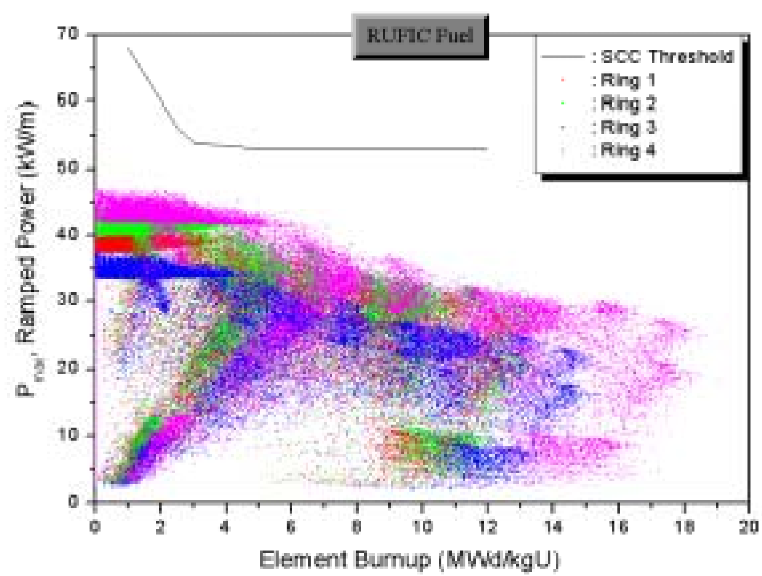


Figure 11. Element Power Envelopes of RUFIC fuel with element burnup (Transition Core)

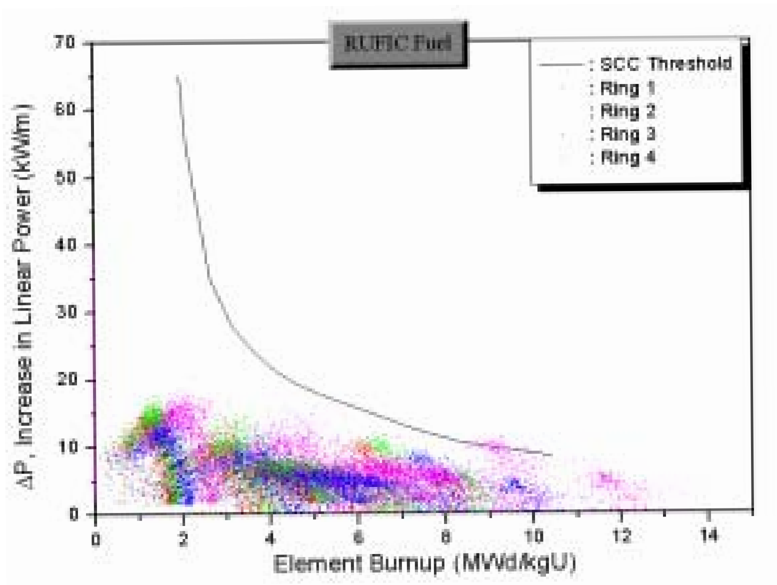
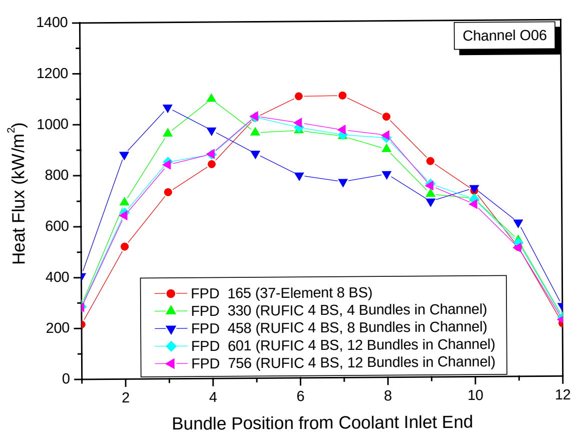


Figure 12. Element Power-Increase Envelopes of RUFIC fuel with element burnup (Transiton Core)



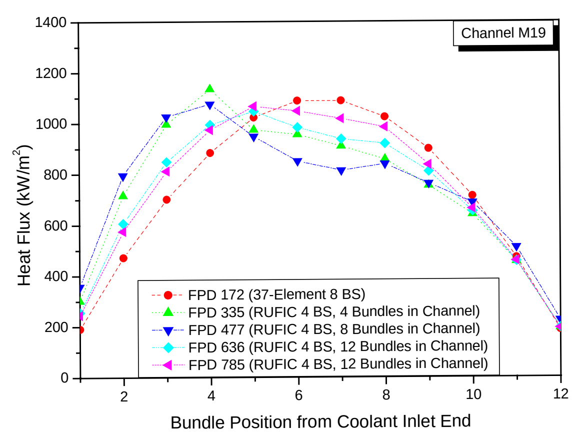


Figure 13. Heat Flux Distribution in Fuel Channel O06

Figure 14. Heat Flux Distribution in Fuel Channel M19

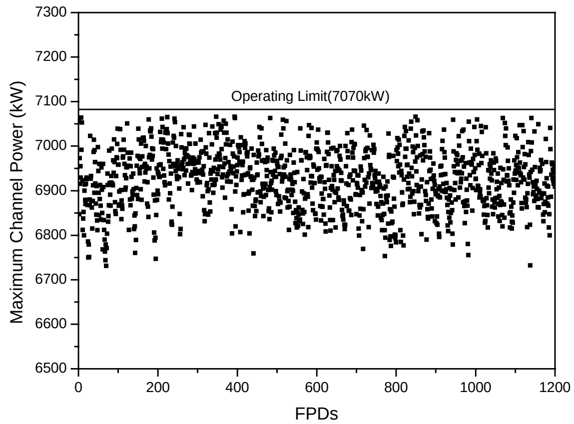


Figure 15. Maximum Channel Power during 1200 FPD Equilibrium Core Simulation

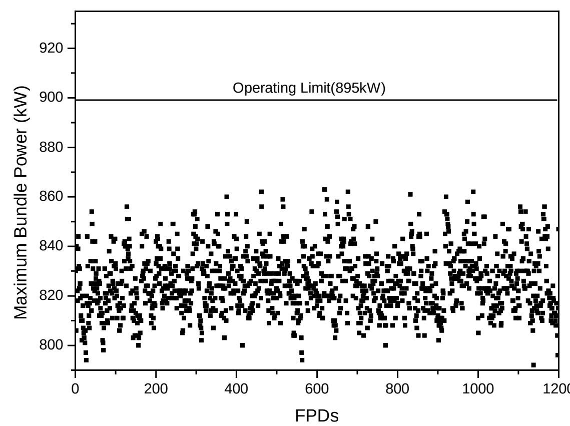


Figure 16. Maximum Bundle Power during 1200 FPD Equilibrium Core Simulation

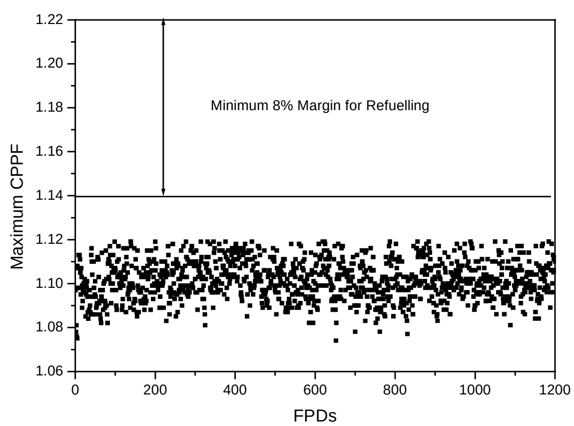


Figure 17. Maximum CPPF during 1200 FPD Equilibrium Core Simulation

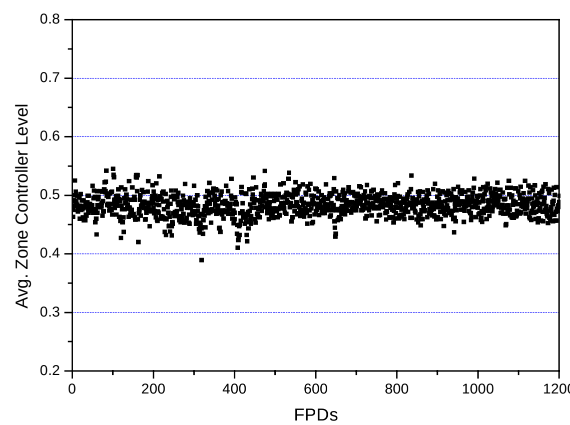


Figure 18. Average Zone Fill during 1200 FPD Equilibrium Core Simulation

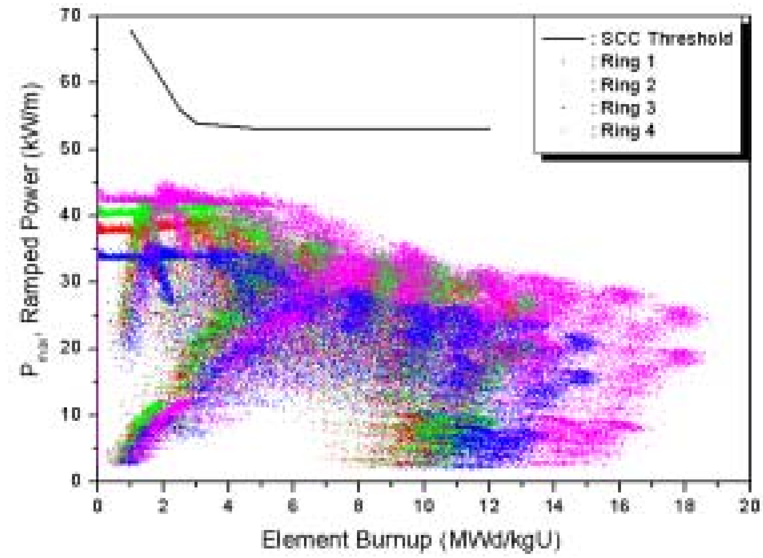


Figure 19. Element Power Envelopes of RUFIC fuel with element burnup (Equilibrium Core)

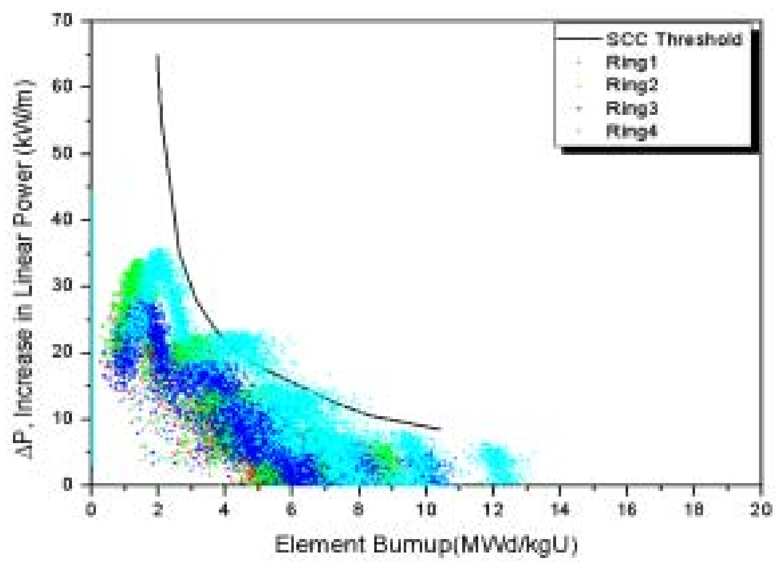


Figure 20. Element Power-Increase Envelopes of RUFIC fuel with element burnup (Equilibrium Core)