A CANDU-6 IN-CORE FUEL MANAGEMENT STUDY ON CANFLEX-RU FUEL

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ABSTRACT

In the CANDU 6 reactor, an 8-bundle shift refuelling scheme is currently employed in natural uranium (NU) fuel management. This refuelling scheme has difficulty in its use for the CANDU in-core fuel management of a 0.92 w/o RUFIC (Recovered Uranium Fuel in CANDU) fuel as a 0.90w/o-equivalent SEU fuel because of the reactivity increase. Considering that the discharge burnup of the RUIFC fuel is almost twice that of the NU fuel, a 4-bundle shift refuelling scheme is preferable for the in-core fuel management of the RUFIC fuel in the CANDU-6 reactor. In this paper, 700 full power day (FPD) equilibrium RUFIC core simulations have been carried out by the 4-bundle shift refuelling scheme in order to find the optimized refuelling schemes for CANDU-6 cores. The computer code system used for this work is WIMS-AECL/DRAGON/RFSP/AUTOREFUEL.

The results of the 700 FPD equilibrium core simulations with the 4-bundle shift refuelling scheme showed that the variation of the maximum channel power (MCP) and maximum bundle power (MBP) as a function of FPD are maintained within the self-imposed operating limits, which are currently employed in a Wolsong reactor. Maximum channel power peaking factor (CPPF) with the number of FPD was maintained below 1.11. It is also found that all the fuel element ratings are below the stress corrosion cracking (SCC) defect threshold curves for a normal operation and power boost, except that the boosted powers of the outermost ring elements are above the SCC threshold in the burnup range of around 100 MWh/kgU. Evaluating only the operating limits for MCP, MBP, CPPF, and the behavior of the liquid zone control system, it is concluded that the 4-bundle shift refuelling scheme is feasible for the equilibrium core fuel management of the RUFIC fueled CANDU-6 reactor.

However, the transition RUFIC core simulations indicated that the 4-bundle shift refuelling scheme leads to some difficulties for the liquid zone control system. Therefore, an optimizing scheme for the transition core fuel management is being investigated by using 2- and 4-bundle shift schemes.

1. INTRODUCTION

The use of slightly enriched uranium (SEU) or recovered uranium (RU) in CANDU(1) 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).

In the CANDU-6 reactors, an 8-bundle shift refuelling scheme is currently employed for the existing 37-element NU fuel. For the RU or SEU fuel, it is expected, however, to find a simple scheme for bundle shift refuelling into the core because of the significant reactivity increase. Considering that the discharge burnup of the RUFIC fuel is almost twice that of the NU fuel, a 4-bundle shift refuelling scheme is preferable for the RUFIC core from the viewpoint of in-core fuel management.

A previous work has analyzed the fuel management study of a 1200 FPD equilibrium core for a CANDU-6 reactor with RUFIC fuel bundles[1]. In the study, a 4-bundle shift scheme was introduced for transition and equilibrium core fuel management. The results of the study were as follows: Concerning the operating limits on the MCP, MBP, and maximum CPPF, a 4-bundle shift refuelling scheme is feasible for refuelling the RUFIC fuel bundles into an operating CANDU-6 reactor. Also, considering element power and element power-increase upon fuelling as a function of burnrup, no defect of the RUFIC fuel bundles is expected in the 4-bundle shift refuelling scheme. However, even if the average zone controller fill shows a good behavior in the liquid zone control system at all times, some zone controller fill does appear to have been zone saturated at high (80%) or low (20%) levels.

The objective of the study is to re-evaluate the feasibility of 4-bundle shift refuelling for a CANDU-6 equilibrium RUFIC core without any violation included in the zone control system. 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 the refuelling channels.

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

2. DESCRIPTION OF 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. The distribution of the age map is very important for the refuelling simulation with the RUFIC fueled CANDU-6 core. When we used an age map as a 7×7 array of the "patterned-age" distribution, we failed the refuelling simulation. The distribution of an age map for the instantaneous calculation in this study is shown in Table 1. Table 1 shows that the distribution of the age map dos not have any pattern.

RUFIC refuelling simulations were carried out using the SIMULATE module of the RFSP and the AUTOREFUEL codes for the selection of refuelling channels. A time-dependent refuelling simulation was carried out for the RUFIC equilibrium core for 700 FPDs. Individual channels were selected for refuelling, and the flux and powers were calculated at the intervals of 1 FPD. 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 the CPPF limit, 1.14 was used, which is the minimal margin of 8 % for refuelling in the Wolsong unit. A core flux/power calculation with RFSP/WIMS-AECL codes, using the true two energy groups and the distributed-xenon formalism, were done with a spatial control at the end of the burnup period to validate the selected refuelling channels. If the above operating limits are not violated, refuelling continues for the next burnup period. Otherwise, changes to the refueled channel identities were made until all the refuelling criteria are simultaneously satisfied.

3. RESULTS OF EQUILIBRIUM CORE REFUELLING SIMULATION

Figures 1 to 3 show the variations of the MCP, MBP, and maximum CPPF, respectively as the results of the 700 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 7069 kW and 860 kW, respectively, and the calculated highest maximum CPPF is 1.11. It is found that the self-imposed operating limits of 7070 kW and 895 kW for the MCP and MBP limits, respectively, were met throughout all the simulations using the 4-bundle shift refuelling scheme. For the maximum CPPF results, a minimum margin of 8 % for refuelling can be secured even if the 4-bundle shift refuelling scheme is employed. As shown in Figure 4, the average zone level shows a good behavior for the liquid zone control system in the simulation core. Also, the minimum and maximum zone levels show a good behavior within the limiting value 0.2 and 0.8, respectively. Throughout this 700 FPDs refuelling simulation, it is found that the average discharge burnup was calculated to be about 13813.1 MWd/MTU and the refuelling rate to be about 2.06 channels/day.

Data on element power and element power-increase upon fuelling as a function of burnup were extracted and compiled for a fuel performance assessment. Figures 5 and 6 show the element power envelope and the element power-increase envelop for the RUFIC fuels loaded into the equilibrium core during 700 FPDs. It is also found that all the fuel element powers are below the SCC threshold curve for a 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 for the two envelops violate the SCC threshold curve simultaneously, no defect of the RUFIC fuel bundles is expected in the 4-bundle shift refuelling scheme.

4. TRANSITION CORE REFUELLING SIMULATION

A previous work has analyzed the fuel management study of a 1200 FPD transition core by changing from the existing 37-element natural uranium (NU) fuel to the 0.92 w/o RUFIC fuel for a CANDU-6 reactor [1]. In the study, a 4-bundle shift scheme was introduced for fuel management. And, the procedure of the transition core refuelling simulation is shown in Figure 7. The results of the transition core fuelling simulations showed that the variations of MCP and MBP as a function of FPDs were maintained within the self-imposed operating limits which are currently employed in Wolsong reactors. The maximum CPPF was maintained below 1.14 in all the FPDs. Also, it was shown that all the fuel element powers were below the SCC threshold curve for a normal operation and for a power-increase, except that the power boost for some of the ring-4 (outermost ring) elements was above the SCC threshold. Considering the fact that fuel defects occur when both the results for the two envelopes violate the SCC threshold curve simultaneously, no defect of the RUFIC fuel bundles is expected in the 4-bundle shift refuelling scheme.

Even if the MCP, MBP, and maximum CPPF were maintained within the self-imposed operating limits, zone controller fills do appear to have been zone saturated at high (80%) or low (20%) levels as shown in Figure 8. Consequently, the transition RUFIC core simulations indicated that the 4-bundle shift refuelling scheme leads to some difficulties for the liquid zone control system. Therefore, an optimizing scheme for the RUFIC transition core fuel management is being investigated and simulated carefully by using 2- and 4-bundle shift schemes.

5. SUMMARY AND CONCLUSIONS

A feasibility of the 4 RUFIC fuel bundle shift refuelling scheme was examined by a CANDU-6 equilibrium core simulation. The results of 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 was maintained below 1.11. Also, the average, minimum and maximum zone controller fills show a good behavior in the liquid zone control system at all times. As far as the operating limits on the MCP, MBP, and CPPF are concerned, the 4-bundle shift refuelling scheme for the RUFIC equilibrium core is, therefore, feasible to refuel the SEU fuel bundles into an operating

CANDU-6 reactor. Also, no defect of the RUFIC fuel bundles is expected in the 4-bundle shift refuelling scheme for an equilibrium core.

The 4-bundle shift refuelling scheme leads to some difficulties for the liquid zone control system in the transition core fuelling simulation. Therefore, an optimizing scheme for the RUFIC transition core fuel management is being investigated and simulated carefully by using 2- and 4-bundle shift schemes.

ACKNOWLEDGEMENT

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Table 1. The Distribution of Age Map for Instantaneous Calculation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									0.5737	0.8553	0.0947	0.7974	0.3211	0.5553								
B						0.5079	0.1974	0.7158	0.9605	0.2421	0.4789	0.2079	0.7263	0.9711	0.2526	0.4895	0.2316					
C					0.6658	0.9079	0.5974	0.1211	0.3605	0.6368	0.8789	0.6079	0.1316	0.3711	0.6474	0.8895	0.6289	0.1500				
D				0.7842	0.0684	0.3105	0.000	0.5184	0.7553	0.0421	0.2789	0.0105	0.5289	0.7658	0.0526	0.2895	0.0342	0.5474	0.7868			
E			0.9474	0.1868	0.4632	0.7053	0.3974	0.9184	0.1605	0.4368	0.6763	0.4079	0.9289	0.1711	0.4474	0.6868	0.4289	0.9500	0.1895	0.4658		
F			0.3500	0.5868	0.8684	0.1105	0.8000	0.3237	0.5579	0.8395	0.0789	0.8105	0.3342	0.5684	0.8500	0.0895	0.8316	0.3526	0.5895	0.8711		
G		0.2053	0.7237	0.9684	0.2500	0.4868	0.2368	0.7526	0.9974	0.2763	0.5158	0.2237	0.7395	0.9842	0.2632	0.5026	0.2184	0.7342	0.9789	0.2579	0.4974	
H		0.6053	0.1289	0.3684	0.6447	0.8868	0.6342	0.1579	0.3947	0.6737	0.9158	0.6211	0.1421	0.3816	0.6579	0.9026	0.6158	0.1368	0.3763	0.6526	0.8974	
J	0.2974	0.0079	0.5263	0.7632	0.0500	0.2868	0.0395	0.5526	0.7947	0.0763	0.3184	0.0263	0.5395	0.7763	0.0632	0.3053	0.0211	0.5342	0.7711	0.0579	0.3000	0.0158
K	0.6921	0.4053	0.9263	0.1684	0.4447	0.6842	0.4342	0.9553	0.1947	0.4737	0.7132	0.4211	0.9395	0.1816	0.4579	0.7000	0.4158	0.9342	0.1763	0.4526	0.6947	0.4132
L	0.0974	0.8079	0.3316	0.5658	0.8474	0.0868	0.8368	0.3579	0.5947	0.8763	0.1184	0.8237	0.3447	0.5816	0.8632	0.1053	0.8184	0.3395	0.5763	0.8579	0.1000	0.8158
M	0.4947	0.2211	0.7368	0.9816	0.2605	0.5000	0.2263	0.7421	0.9868	0.2658	0.5053	0.2342	0.7500	0.9947	0.2737	0.5132	0.2026	0.7211	0.9658	0.2474	0.4842	0.2158
N	0.8947	0.6184	0.1395	0.3789	0.6553	0.9000	0.6237	0.1447	0.3842	0.6605	0.9053	0.6316	0.1553	0.3921	0.6711	0.9132	0.6026	0.1263	0.3658	0.6421	0.8842	0.6132
O	0.2947	0.0237	0.5368	0.7737	0.0605	0.3026	0.0289	0.5421	0.7789	0.0658	0.3079	0.0368	0.5500	0.7921	0.0737	0.3158	0.0053	0.5237	0.7605	0.0474	0.2842	0.0184
P		0.4184	0.9368	0.1789	0.4553	0.6974	0.4237	0.9421	0.1842	0.4605	0.7026	0.4316	0.9526	0.1921	0.4711	0.7105	0.4026	0.9237	0.1658	0.4421	0.6816	
Q		0.8211	0.3421	0.5789	0.8605	0.1026	0.8263	0.3474	0.5842	0.8658	0.1079	0.8342	0.3553	0.5921	0.8737	0.1158	0.8053	0.3289	0.5632	0.8447	0.0842	
R			0.7474	0.9921	0.2711	0.5105	0.2105	0.7289	0.9737	0.2553	0.4921	0.2000	0.7184	0.9632	0.2447	0.4816	0.2289	0.7447	0.9895	0.2684		
S			0.1526	0.3895	0.6684	0.9105	0.6105	0.1342	0.3737	0.6500	0.8921	0.6000	0.1237	0.3632	0.6395	0.8816	0.6263	0.1474	0.3868	0.6632		
T				0.7895	0.0711	0.3132	0.0132	0.5316	0.7684	0.0553	0.2921	0.0026	0.5211	0.7579	0.0447	0.2816	0.0316	0.5447	0.7816			
U					0.4684	0.7079	0.4105	0.9316	0.1737	0.4500	0.6895	0.4000	0.9211	0.1632	0.4395	0.6789	0.4263	0.9447				
V						0.1132	0.8132	0.3368	0.5711	0.8526	0.0921	0.8026	0.3263	0.5605	0.8421	0.0816	0.8289					
W									0.9579	0.2395	0.4763	0.2132	0.7316	0.9763								

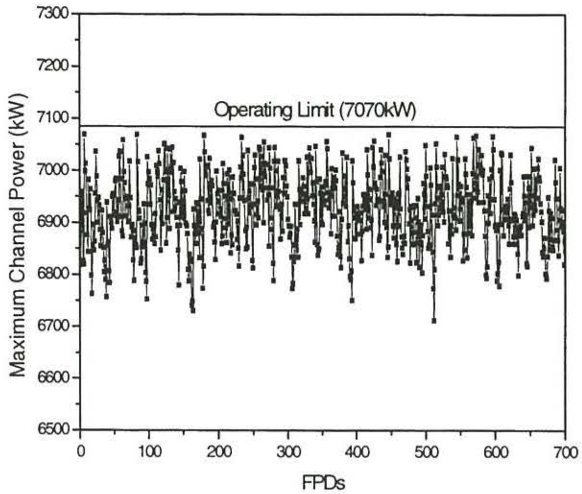

Figure 1. Maximum Channel Power during 700 FPD Equilibrium Core Simulation

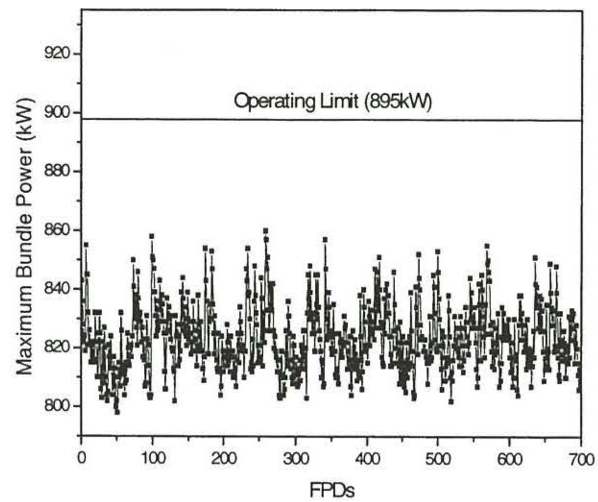

Figure 2. Maximum Bundle Power during 700 FPD Equilibrium Core Simulation

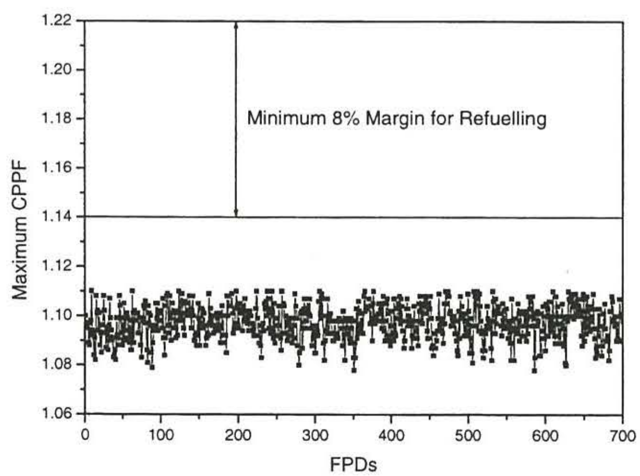

Figure 3. Maximum CPPF during 700 FPD Equilibrium Core Simulation

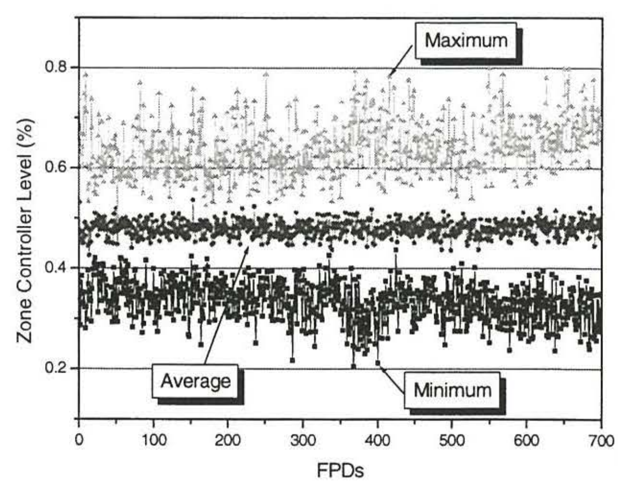

Figure 4. Zone Controller Fill during 700 FPD Equilibrium Core Simulation

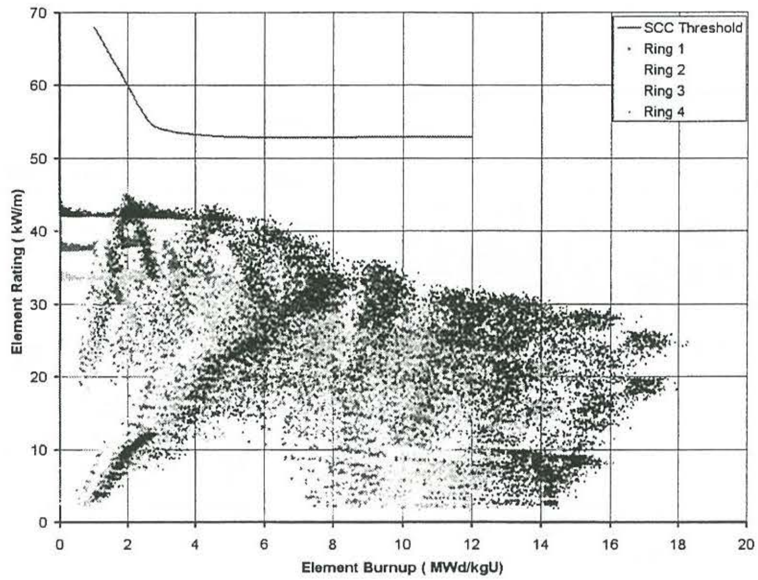

Figure 5. Element Power Envelopes of RUFIC fuel with element burnup (Equilibrium Core)

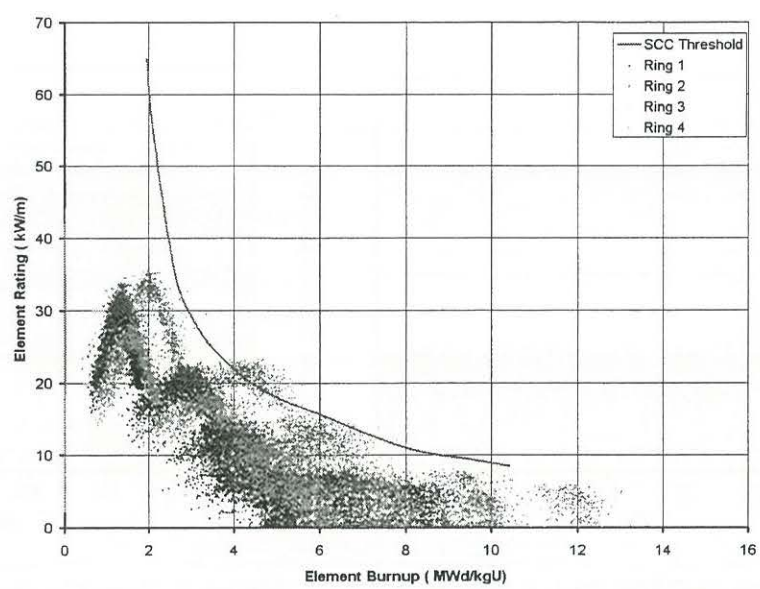

Figure 6. Element Power-Increase Envelopes of RUFIC fuel with element burnup (Equilibrium Core)

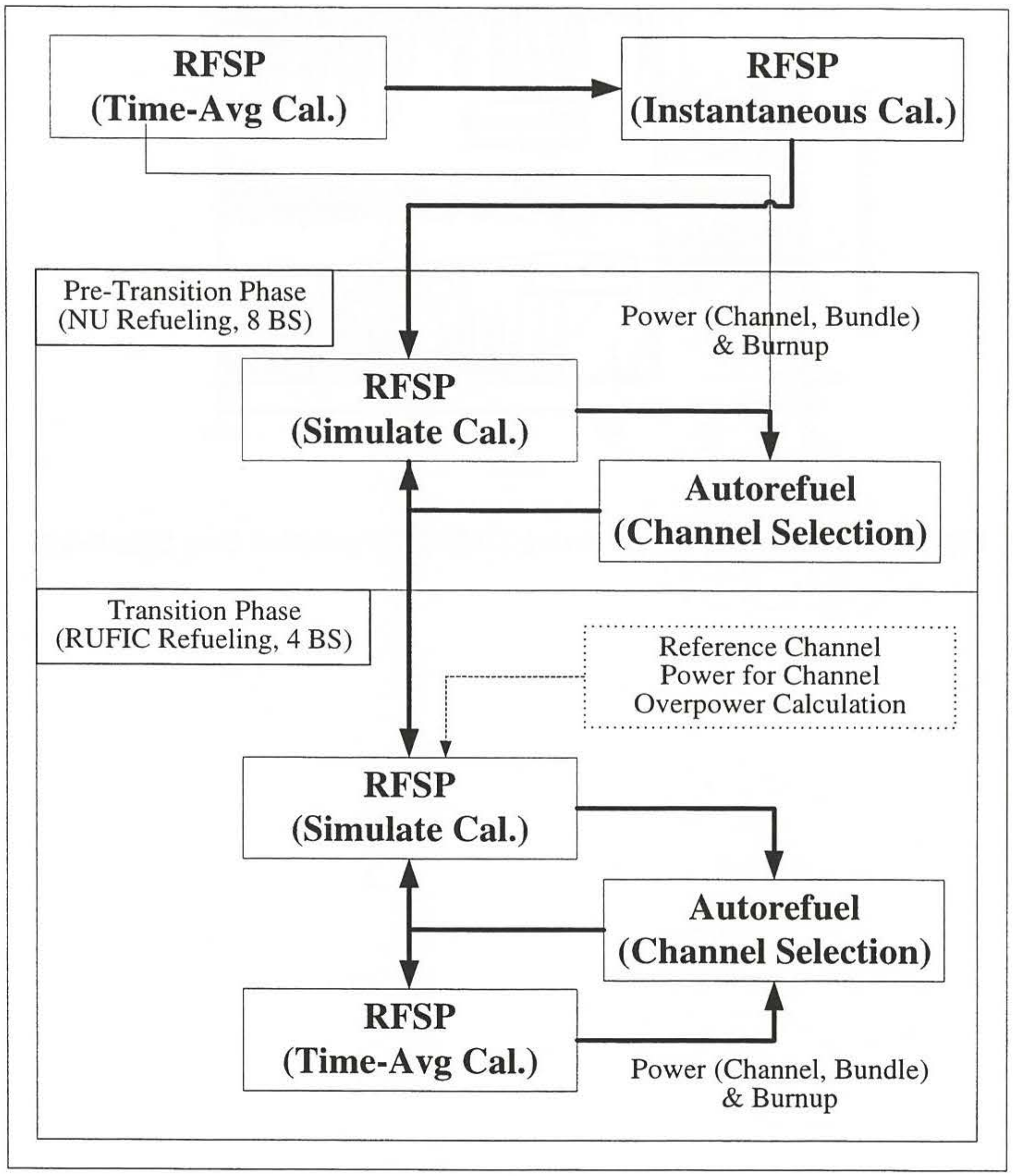

Figure 7. Flowchart for Transition Simulation from 37-Element NU Fuel to RUFIC Fuel

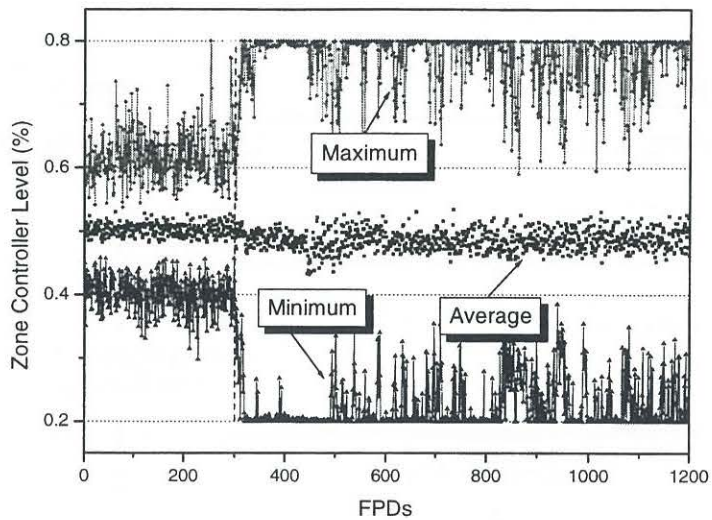

Figure 8. Zone Controller Fill during 1200 FPD Transition Core Simulation