Bruce A Restart Initial Core Loading*

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Abstract

Bruce A Nuclear Generating Station (NGS) Units 3 and 4 are to be restarted with cores containing completely fresh fuel. The reactor power will be 92.5% of the originally designed power, or 2492 MW of thermal power to coolant.

Depleted uranium fuel bundles, with an enrichment of 0.4% ^{235}U by weight, will be used to reduce fresh-core excess reactivity and to provide the required flattening for flux and power distributions in the operating period before refuelling.

The computer codes RFSP-IST, WIMS-IST and DRAGON have been used to define a new initial core loading (ICL) scheme for the "Bruce A Restart".

The study assessed 14 different ICLs, based on simulations of initial operating periods of about 60 days at 92.5% full power (FP) (the plutonium peak is near day 50). The chosen ICL was examined in more detail, with a simulation of 350 days of operation at 92.5% FP (including channel refuellings, which started at day 100).

The ICL scheme for the Bruce A Restart will use 714 depleted uranium fuel bundles per reactor. There will be from one to three depleted uranium bundles per channel in the 332 central fuel channels of the core. The bundles will be placed in bundle positions 8 (58 channels), 8 and 9 (114 channels), 9 and 10 (52 channels), and 8, 9 and 10 (108 channels).

The ICL scheme recommended above will allow Bruce A NGS Units 3 and 4 to safely operate at 92.5% FP with practically no loss in power output, and with comfortable operating margins and conservative allowances for calculation uncertainties.

* Funding for this work was provided by Bruce Power.

1. INTRODUCTION

Bruce A Nuclear Generating Station (NGS) Units 3 and 4 will be restarted with cores containing all fresh fuel. With fresh fuel, the initial core has a large amount of excess reactivity. Also, unlike the equilibrium-burnup core, the power shape cannot be controlled by differential fuelling. The traditional solution to these problems has been to strategically place depleted uranium fuel bundles in the core. These bundles have the dual purpose of reducing the excess reactivity of the core and of flattening the power distribution. Any remaining excess reactivity is offset by adding soluble poison (boron) to the moderator.

The original initial core loading (ICL) for Bruce A NGS had 432 depleted uranium fuel bundles per reactor, placed at bundle positions 8 and 9 (counting from the fuelling end) in the central 216 fuel channels. These bundles have an isotopic concentration of 0.4% ^{235}U by weight. Natural uranium contains 0.71% ^{235}U by weight.

CANDU® reactor safety analyses and licensing requirements have changed considerably over the last 25 years. Acceptance criteria for the “Bruce A Restart” ICL are now broader in scope and more constraining than those defined 25 years ago for the new reactor. The task of defining an ICL for Bruce A Restart is more challenging than for a new CANDU reactor, and is summarized in this paper.

2. A SHORT DESCRIPTION OF BRUCE A REACTORS

Bruce A NGS has 480 fuel channels per reactor. The core length of each fuel channel is equivalent to 12 standard 37-element CANDU fuel bundle lengths. Each fuel channel contains 13 such bundles, with half a bundle outside the active reactor core length at each channel end.

The reactor power will be 92.5% of the originally designed power, or 2492 MW of thermal power to coolant.

Figure 1 shows the locations of reactivity control units. There are 30 shut-off rods (SORs), four mechanical control absorbers (MCAs) and six zone control units, which are divided into 14 liquid compartments or zone controllers (ZCRs).

Figure 2 shows the division of the core into inner and outer core regions, based on differences in channel flows.

Figure 3 shows the seven power control zones of the west side, associated with the seven ZCRs numbered 1 to 7. Those of the east side are numbered from 8 to 14.

Figure 4 shows the neutron overpower protection system (NOP) reference power distribution, normalized to 100% full power (FP). This NOP reference power distribution is the same as the one that was in use before the plant lay-up.

Figure 5 shows the channel power peaking factor (CPPF) region. Channel power peaking factors are calculated for fuel channels only in this region.

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Figure 6 shows the revised fuelling scheme, which includes 2-bundle-shift fuelling in the innermost 68 channels, 8-bundle-shift fuelling in the outermost 134 channels and 4-bundle-shift fuelling in the remaining channels. Fuelling will be in the same direction as coolant flow ("with flow"), as opposed to "against flow" fuelling, used originally at Bruce A NGS.

3. METHODOLOGY AND ASSUMPTIONS

3.1 Acceptance Criteria

Acceptance criteria for the study include

- licensing requirements: compliance with the Licence Limits on maximum channel powers (CPs) and bundle powers (BPs) in both inner and outer core regions; low moderator boron concentration at the plutonium peak (for shutdown system 1 depth analysis).
- design requirements: capability to maintain the reactor subcritical following hot shutdown using only the MCAs.
- operating requirements: initial fuelling rate well within fuelling machine capability; high margin to the NOP trip set point; ZCR fills within the ideal 45–55% range.
- economic requirements: maximizing reactor output and minimizing fuel cost.

The Licence Limits for the inner core and outer core regions, applicable for 92.5% FP, are given in Table 1. Table 1 also lists the Compliance Limits derived from these Licence Limits: the Action Limit is used as an alarm for day-to-day monitoring purpose, and the Reporting Limit is a higher value which, if exceeded, represents a condition reportable to the CNSC. The margins between the Licence, Reporting and Action Limits are based on extensive analysis of power data generated by SORO, the computer code used for core-follow and fuel management at Bruce NGS.

3.2 Methodology

All simulations required for this work were carried out with the computer code RFSP-IST [1], version REL 3-01HP. The full 2-group diffusion calculation methodology of RFSP is used.

Reactivity device 2-group incremental cross-sections were calculated with the computer code DRAGON [2].

For a preliminary assessment of a given ICL, lattice cell cross-sections were obtained by interpolation from fuel tables generated with the cell code WIMS-IST [3], which used the nuclear data library ENDF/B-VI, version 1A. For a more definitive assessment, WIMS-IST was used in conjunction with the PERL utility gen_simp to generate data tables for the simple-cell model (SCM) [4] history-based methodology within RFSP-IST.

3.3 Assumptions

One of the most significant advances in the development of the computer code RFSP-IST in recent years has been the introduction of the "local parameter history-based" methodology in the code for lattice cell cross-section calculations [1]. With this methodology, lattice cell cross-sections depend not only on fuel irradiation (a limitation of the fuel-table approach), but also on the thermal-hydraulic local properties of the cell and the power history of the fuel bundle.

Unfortunately, the methodology, while fully workable with POWDERPUFS-V, a cell code incorporated in RFSP, is not currently feasible for using with WIMS-IST, because of the much longer computer time needed for a WIMS cell calculation compared to a POWDERPUFS-V calculation. This has been the reason behind the development of the SCM, an approximation to the WIMS cell calculation. With the possibility to use the "local parameter history-based" methodology with RFSP/SCM, RFSP/SCM results are considered more accurate than those obtained with the RFSP/WIMS fuel-table methodology.

By the same token, it is also assumed here that RFSP/SCM simulation errors would be less than SORO-generated errors. Thus, it is considered conservative to apply the Compliance Limits of Table 1, which were derived for SORO, to RFSP/SCM results.

4. RESULTS

4.1 Search for a Best Possible Initial Core Loading

The search for a best possible ICL was conducted to meet the criteria defined in Section 3.1. Depleted uranium fuel bundles to be used for Bruce A Restart initial core loading will have the same isotopic composition as those of the original ICL. Except for the original ICL, which was examined in detail with both the 2-group "RFSP/WIMS fuel-table" and the 2-group RFSP/SCM methodologies for reference purposes, all other ICLs were assessed only with the RFSP/WIMS fuel-table methodology until the ICL was deemed acceptable. Then, it was also assessed by RFSP/SCM. The RFSP/SCM methodology is more accurate than the "RFSP/WIMS fuel-table" methodology, but the computer execution time is also at least ten times longer. For each ICL, the assessment period covers 50 to 60 new full-power days (NFPDs), so as to pass the plutonium peak by about 10 NFPDs (new FPD, or 92.5% FPD, or core burnup of 1 day at 92.5% FP). Hereafter, the "RFSP/WIMS fuel-table" methodology will be referred to simply as RFSP/WIMS.

The construction of an ICL scheme for assessment with RFSP-IST was not arbitrary. It was done with hints obtained from the results of the previous schemes, using appropriate extensions or adjustments. In all, 14 different ICLs were assessed with RFSP/WIMS.

Figure 7 shows the original ICL. Figure 8 shows the ICL scheme that responded best to acceptance criteria defined in Section 3.1. This ICL, now called "Option M", has been selected for the Bruce A Restart.

Of all 14 ICL schemes assessed, Option M has the lowest moderator boron concentration at the plutonium peak (1.25 ppm less than that of the original ICL), the lowest maximum CPs and BPs in both core regions, the lowest CPPFs. The MCA reactivity worth is about 10% higher than that of the original ICL.

Confirmation of Option M continues with RFSP/SCM simulations of reactor operation up to 350 NFPDs, which was estimated to be sufficiently close to the equilibrium fuelling state. Some detailed simulations of core characteristics at the plutonium peak were also performed. Identical simulations with RFSP/SCM were also done for the original ICL, from fresh core up to the onset of fuelling. The results of these simulations are given in the following sections.

4.2 Comparisons between Option M and the Original Initial Core Loading with RFSP/SCM Simulations

Figure 9 shows the variation of critical moderator boron concentration with core burnup for Option M and the initial ICL. The difference in boron concentration is largest at the fresh clean fuel condition, with the original ICL requiring 6.86 ppm and Option M requiring 5.02 ppm. At about 6 NFPDs, the boron concentration is lowest before the Pu peak, with the original ICL requiring 2.08 ppm and Option M requiring 0.44 ppm. At the Pu peak, the original ICL requires 3.56 ppm and Option M requires 2.31 ppm. Figure 9 also shows that, with the original ICL, fuelling should start no later than at about 140 NFPDs, while with Option M, fuelling should start no later than at about 120 NFPDs.

Figures 10–13 show variations, with core burnup, of the maximum CP in the inner core, the maximum BP in the inner core, the maximum CP in the outer core and the maximum BP in the outer core, respectively. The Reporting Limits are also shown on these figures for comparison. All four parameters are far below the Reporting Limits for Option M. The Reporting Limit on maximum BP in the outer core region is exceeded by the original ICL for about 50 NFPDs.

Figure 14 shows the variation of CPPF with core burnup. For Option M, the CPPF is less than 1.1, even less than the past operating average of 1.14 [5]. The CPPF is exceedingly high for the original ICL, before 40 NFPDs.

4.3 Core Properties at the Plutonium Peak

Moderator poison concentration is highest at the fresh clean fuel condition. However, this does not represent a safety concern requiring special investigation, since the reactor power is necessarily very low during the first few NFPDs for commissioning activities. The most critical period with a fresh core is at the Pu peak, with high moderator boron concentration for an extended period and the reactor operating at high power. Safety analysis at this particular core condition is outside the scope of this study, but certain parameters could be readily calculated for the selected Option M and the original ICL. Comparison of those parameters between the two loading schemes would provide further insight on the strength or weakness of the selected Option M.

The following parameters are calculated for Option M and the original ICL using RFSP/SCM, with the results reported in Table 2:

a. The SOR reactivity worth at the Pu peak, with the reactor at 92.5% FP steady state.

b. The critical moderator boron concentration at the Pu peak after a long shutdown, assuming a cold restart after the long shutdown.

c. The critical moderator boron concentration at the Pu peak after a long shutdown, assuming an instant power rise to 68% FP.

d. The whole core void reactivity, at the same core conditions as in (*c*).

e. The ZCR, MCA and SOR reactivity worths, at the same core conditions as in (*c*).

f. The moderator temperature reactivity changes from normal temperature, at the same core conditions as in (*c*).

Values given in Table 2 show that, with the exception of ZCR fill, the parameters are better with Option M than in the original ICL.

4.4 Hot Shutdown Reactivity Versus MCA Reactivity Worth At Different Core Burnups

Hot shutdown reactivity in Option M has been compared to MCA and ZCR reactivity worths at different core burnups, from a fresh core to 20 NFPDs. The results are shown in Table 3 for a hot shutdown from 92.5% FP, in Table 4 for a hot shutdown from 80% FP, in Table 5 for a hot shutdown from 70% FP and in Table 6 for a hot shutdown from 60% FP.

At 92.5% FP, the MCA reactivity worth magnitude is smaller than the hot shutdown reactivity for core burnup less than 15 NFPDs (except at the fresh and clean fuel condition) and larger for core burnup of 15 NFPDs or higher.

At 80% FP, the MCA reactivity worth magnitude is smaller than the hot shutdown reactivity for core burnup less than 10 NFPDs (excepted at the fresh and clean fuel condition). The two are about equal in magnitude at 10 NFPDs.

At 70 % FP, the MCA reactivity worth magnitude is smaller than the hot shutdown reactivity at 5 NFPDs, and larger at 10 NFPDs.

At 60 % FP, the MCA reactivity worth magnitude is larger than the hot shutdown for all core burnups.

The combined MCA plus ZCR (50 to 90% fill) reactivity worth magnitude is larger than the hot shutdown reactivity for all core burnups.

There is no need to make an assessment for core burnup larger than those given in the above tables, due to the general trend of rapid reduction of hot shutdown reactivity with fuel burnup, as obtained from a WIMS lattice cell calculation shown in Figure 15.

These results suggest the following reactor power profile for Bruce A Restart: no more than 60% FP from 0 to 5 NFPDs; no more than 70% FP from 5 to 10 NFPDs; and no more than 80% FP from 10 to 15 NFPDs. There is no restriction after 15 NFPDs.

Alternatively, the reactor could be operated at 92.5% FP for all core burnups, with operating procedures in place to limit the ZCR average fill to less than 50% full at all times up to 15 NFPDs.

4.5 Fuel Management Study To 350 NFPDs With Option M Initial Core Loading

Figure 9 shows that, for Option M, refuelling should start no later than at about 120 NFPDs to maintain the average ZCR fill near 50% and the critical moderator boron concentration (CMBC) at about 0.25 ppm, which is the maximum concentration assumed for the purpose of fuelling ahead. Past fuel management studies and operating experience show that the initial fuelling rate is substantially higher than the equilibrium fuelling rate. The time at the high fuelling rate could be many weeks. To help reduce this high fuelling rate to a more manageable level, it was decided to advance the start of refuelling to 100 NFPDs.

The initial fuelling rate was arbitrarily fixed at four channels per NFPD, about the same as that at equilibrium fuelling. This fuelling rate was maintained until the CMBC, with the average zone fill fixed at 50% full, reached the assumed level of 0.25 ppm. Afterward, the fuelling rate was adjusted to have the CMBC as close to 0.25 ppm as possible at all times.

Core flux/power distributions were updated every 2 NFPDs with an RFSP/WIMS simulation, which provided necessary information (fuel channel exit burnups, zone relative powers, channel overpowers, etc.) for the selection of channels to be refuelled in the next 2 NFPDs. For more accurate results, core flux/power distributions were updated every 10 NFPDs with an RFSP/SCM simulation.

Refuelled channels were manually selected. Factors guiding the choice of refuelled channels include maintaining relative zone powers as close to 92.5% FP as possible, low CPPF, low maximum CPs and BPs in both core regions, and high fuel exit burnup. For RFSP input data preparation simplicity, fuellings were assumed to be done daily, with all fuellings of the day completed simultaneously at midday.

For conservatism, all RFSP runs were performed without spatial control, with all ZCR fills fixed at 50%. The calculated maximum CPs, BPs and CPPF are expected to be higher without spatial control than with spatial control.

Figure 16 shows the change of fuelling rate with core burnup. Each column of Figure 16 represents the number of channels refuelled per 10-NFPD period. For most of the time, the fuelling rate is close to the equilibrium fuelling rate of 40 channels per 10 NFPDs. The maximum fuelling rate is 60 channels per 10 NFPDs. Figure 16 clearly suggests that it is possible to maintain the maximum fuelling rate at no more than 50 channels per 10 NFPD (or 25% more than the equilibrium fuelling rate) by starting the refuelling with that maximum rate instead of the lower rate of 40 channels per 10 NFPDs used in the study.

Figure 17 also shows the change of fuelling rate with core burnup, but here the fuelling rate is presented in terms of the total number of new fuel bundles used per period of 10 NFPDs. Note that fuel recycling was not assumed in this study. The maximum fuelling rate is 262 bundles per 10-NFPD period. The average of the last 10 periods is 170 bundles per period or about 3% higher than the equilibrium fuelling rate[*] of 165 bundles per period. The equilibrium core is not yet reached, but it is sufficiently close for assessment purposes.

RFSP/SCM-calculated maximum CPs and BPs are shown in Figures 18-21, for the entire 350-NFPD operating period. The corresponding Action and Reporting Limits are also shown in these figures for comparison.

The maximum CPs and BPs in both core regions are below the Reporting Limits at all time. Thus, there would be no urgent action at any time to lower the maximum CPs or the maximum BPs, which are considered “normal”. The maximum BPs in both core regions and the maximum CPs in the inner core region are also below the Action Limits at all time. These operating conditions are desirable, but not strictly required. The maximum CP in the outer core region is slightly higher than the corresponding Action Limit at one instance, namely at 180 NFPD. This is permissible, as long as compliance to the Reporting Limit is still observed and the subsequent refuellings did not make the situation worse, which is effectively the case, as shown in Figure 20.

Figure 22 shows the evolution of CPPF with core burnup. The highest CPPF for the period from 0 to 350 NFPDs is about 1.10, with an average of less than 1.09. For comparison, the average CPPF used in the NOP coverage assessment of Reference 5 is 1.14.

[*] The equilibrium fuelling rate was calculated by means of a time-average calculation by one of the authors (CNT) for another safety analysis for Bruce A Restart, using the same operating conditions as those assumed here for the long-term operation of the reactor.

5. CONCLUSIONS

A careful search for an ICL for the Bruce A Restart that would meet defined acceptance criteria resulted in a new ICL, named Option M. Based on an evaluation period of 350 days at 92.5% FP, which would bring the core sufficiently close to the equilibrium fuelling condition, the maximum CPs and BPs of both core regions are lower than the Compliance Limits by comfortable margins. The initial fuelling rate, in terms of the number of refuelled channels per refuelling period, could be maintained to within 125% of the equilibrium fuelling rate. The CPPF is considerably below the average value at equilibrium fuelling used in the last edition of the safety report [5]. The critical moderator boron concentration at the plutonium peak is reduced by about 1.25 ppm as compared to the original ICL. The MCA reactivity worth is slightly improved, also as compared to the original ICL.

Option M requires 714 depleted uranium fuel bundles per reactor, placed in the 332 central fuel channels of the core. The bundles will be placed in bundle positions 8 (58 channels), 8 and 9 (114 channels), 9 and 10 (52 channels), and 8, 9 and 10 (108 channels).

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Table 1

CP/BP Limits at a Reactor Power of 92.5% FP

Parameter	Action Limit (kW)	Reporting Limit (kW)	Licence Limit (kW)
Inner Core Maximum CP	6500	6606	6838
Outer Core Maximum CP	5834	5929	6247
Inner Core Maximum BP	896	921	969
Outer Core Maximum BP	792	814	857

Table 2

Bruce A Restart—Option M and Original Initial Core Loading
Core Properties at the Plutonium Peak—RFSP/SCM Simulations

Property	Original	Option M
Plutonium Peak (NFPD)	47	51
Critical Moderator Boron Concentration at Pu Peak* (ppm)	3.56	2.31
SOR Reactivity Worth at Pu Peak* (mk)	-33.38	-34.25
Critical Moderator Boron Concentration at Pu Peak after a Long Shutdown** (ppm)	7.46	6.07
Critical Moderator Boron Concentration at Pu Peak after a Long Shutdown, with the Reactor Power Raised instantly to 68% FP (ppm)	7.61	6.30
Whole Core Void Reactivity*** (mk)	20.33	19.62
ZCR Reactivity Worth (0% full to 100% full)*** (mk)	-5.85	-5.60
MCA Reactivity Worth (Out to In)*** (mk)	-5.72	-6.38
SOR Reactivity Worth (Out to In)*** (mk)	-34.54	-35.42
Moderator Temperature Reactivity Change (71 °C to 91 °C)*** (mk)	1.38	1.18
Moderator Temperature Reactivity Change (71 °C to 36 °C)*** (mk)	-2.88	-2.52

* From 92.5% FP steady state.
** Assuming a cold restart after a 30-day shutdown at the plutonium peak.
*** Assuming an instant power rise to 68% FP after a 30-day shutdown at the plutonium peak.

Table 3

Bruce A Restart—Option M Initial Core Loading
Hot Shutdown from 92.5 %FP—RFSP/SCM Simulations

	Core Burnup (NFPD)				
	0	5	10	15	20
Hot Shutdown* Reactivity (mk)	4.78	6.63	5.92	5.21	4.19
MCA Reactivity Worth (mk)	-4.84	-5.24	-5.36	-5.47	-5.56
MCA plus ZCR (50% to 90 % full) Reactivity Worth (mk)	-6.69	-7.18	-7.31	-7.42	-7.53

* Hot shutdown reactivity calculated with fuel and coolant temperatures at 257 °C and moderator temperature at 30 °C.

Table 4

Bruce A Restart—Option M Initial Core Loading
Hot Shutdown from 80%FP—RFSP/SCM Simulations

	Core Burnup (NFPD)		
	0	5	10
Hot Shutdown Reactivity* (mk)	4.10	6.06	5.38
MCA Reactivity Worth (mk)	-4.83	-5.24	-5.37
MCA plus ZCR (50% to 90% full) Reactivity Worth (mk)	-6.69	-7.18	-7.32

* Hot shutdown calculated with fuel and coolant temperatures at 257 °C and moderator temperature at 30 °C.

Table 5

Bruce A Restart—Option M Initial Core Loading
Hot Shutdown from 70%FP—RFSP/SCM Simulations

	Core Burnup (NFPD)	
	5	10
Hot Shutdown Reactivity* (mk)	5.60	4.95
MCA Reactivity Worth (mk)	-5.25	-5.39
MCA plus ZCR (50% to 90% full) Reactivity Worth (mk)	-7.18	-7.32

* Hot shutdown calculated with fuel and coolant temperatures at 257 °C and moderator temperature at 30 °C.

Table 6

Bruce A Restart—Option M Initial Core Loading
Hot Shutdown from 60%FP—RFSP/SCM Simulations

	Core Burnup (NFPD)	
	5	10
Hot Shutdown Reactivity* (mk)	5.15	4.53
MCA Reactivity Worth (mk)	-5.25	-5.38
MCA plus ZCR (50% to 90% full) Reactivity Worth (mk)	-7.18	-7.33

* Hot shutdown calculated with fuel and coolant temperatures at 257 °C and moderator temperature at 30 °C.

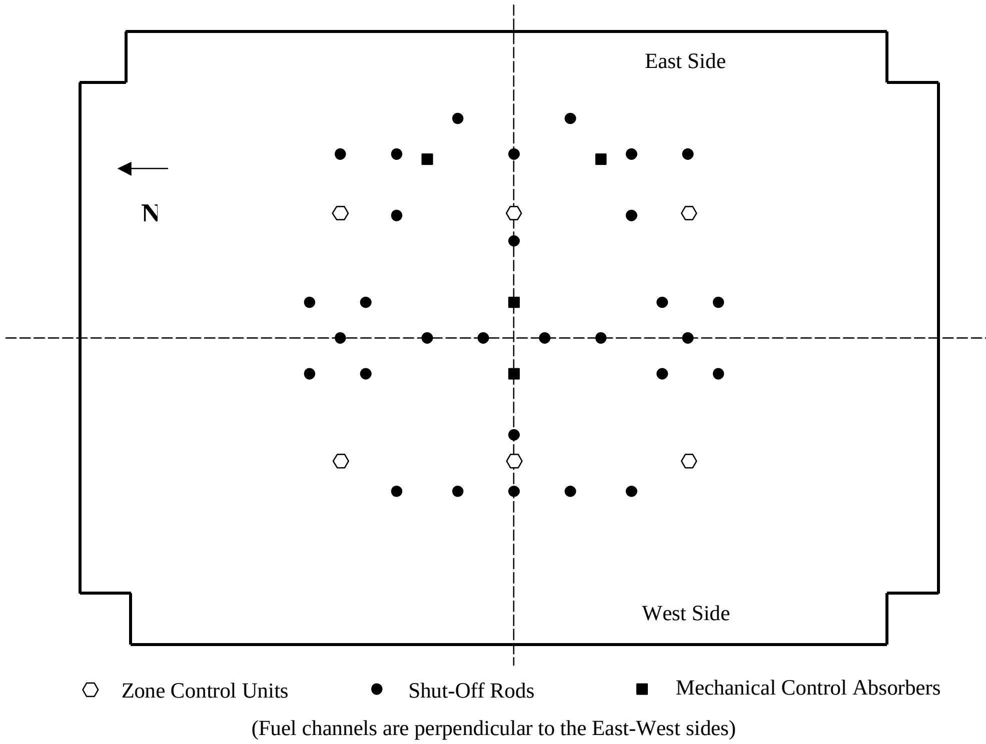

Figure 1: Bruce A Reactor Reactivity Control Unit Locations (Vertically Mounted Units)

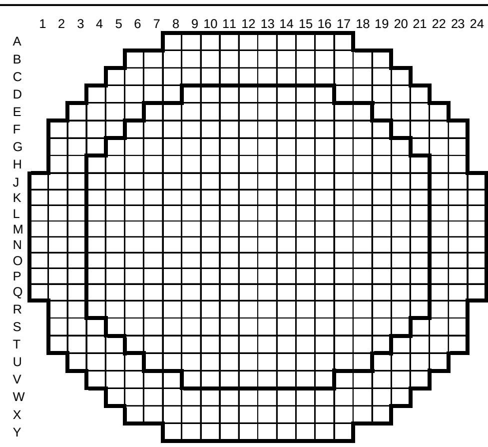

Figure 2: Division of the Core into Inner and Outer Core Regions

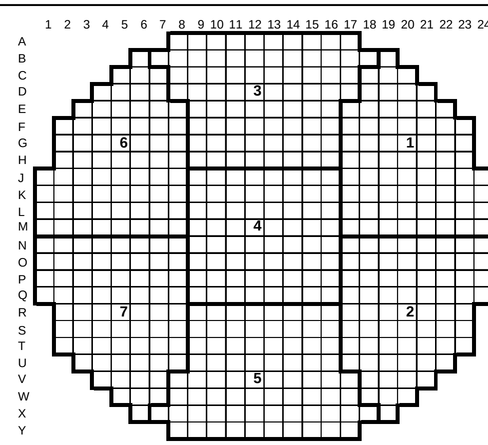

Figure 3: Division of the Core into Seven Power Control Zones

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A								3450	3701	4000	4210	4221	4221	4210	4000	3701	3450							
B						3400	4012	4295	4650	4950	5050	5069	5069	5050	4950	4650	4295	4012	3400					
C					3800	4456	4984	5324	6145	6122	5976	5816	5816	5976	6122	6145	5324	4984	4456	3800				
D				3770	4476	5170	5906	6070	6429	6410	6250	6054	6054	6250	6410	6429	6070	5906	5170	4476	3770			
E			3782	4748	5380	5660	6026	6268	6360	6397	6268	6065	6065	6268	6397	6360	6268	6026	5660	5380	4748	3782		
F		3500	4382	5399	5690	5858	5943	6209	6317	6404	6317	6133	6133	6317	6404	6317	6209	5943	5858	5690	5399	4382	3500	
G		4100	5012	5721	5970	5853	5927	6174	6293	6416	6372	6256	6256	6372	6416	6293	6174	5927	5853	5970	5721	5012	4100	
H		4626	5641	6009	6014	5884	5960	6168	6287	6410	6397	6342	6342	6397	6410	6287	6168	5960	5884	6014	6009	5641	4626	
J	3936	4852	5592	5960	6065	5960	6031	6180	6299	6404	6435	6410	6410	6435	6404	6299	6180	6031	5960	6065	5960	5592	4852	3936
K	4144	5117	5554	5927	6070	6048	6087	6221	6323	6410	6454	6467	6467	6454	6410	6323	6221	6087	6048	6070	5927	5554	5117	4144
L	4304	5324	5540	5911	6065	6139	6174	6274	6360	6429	6461	6305	6305	6461	6429	6360	6274	6174	6139	6065	5911	5540	5324	4304
M	4455	5466	5531	5911	6070	6244	6280	6342	6404	6448	6404	6221	6221	6404	6448	6404	6342	6280	6244	6070	5911	5531	5466	4455
N	4437	5466	5535	5922	6099	6355	6379	6410	6442	6474	6404	6209	6209	6404	6474	6442	6410	6379	6355	6099	5922	5535	5466	4437
O	4286	5324	5545	5933	6104	6282	6354	6404	6461	6499	6435	6268	6268	6435	6499	6461	6404	6354	6282	6104	5933	5545	5324	4286
P	4153	5173	5559	5938	6099	6157	6203	6305	6385	6454	6454	6404	6404	6454	6454	6385	6305	6203	6157	6099	5938	5559	5173	4153
Q	3993	4937	5573	5949	6104	6070	6104	6227	6323	6410	6385	6354	6354	6385	6410	6323	6227	6104	6070	6104	5949	5573	4937	3993
R		4635	5573	5949	6093	5992	6048	6180	6244	6280	6305	6240	6240	6305	6280	6244	6180	6048	5992	6093	5949	5573	4635	
S		4000	5050	5690	6048	5965	6048	6082	6104	6133	6168	6157	6157	6168	6133	6104	6082	6048	5965	6048	5690	5050	4000	
T		3400	4437	5324	5695	5970	5970	5982	5998	6014	6037	3059	6059	6037	6014	5998	5982	5970	5970	5695	5324	4437	3400	
U			3757	4682	5286	5626	5900	5906	5911	5922	5938	5949	5949	5938	5922	5911	5906	5900	5626	5286	4682	3757		
V				3755	4625	5173	5578	5578	5853	5863	5874	5879	5879	5874	5863	5853	5578	5578	5173	4625	3755			
W					3500	4138	4881	5230	5545	5554	5564	5583	5583	5564	5554	5545	5230	4881	4138	3500				
X						3276	3918	4248	4560	4767	5050	4861	4861	5050	4767	4560	4248	3918	3276					
Y								3200	3600	3950	4000	4153	4153	4000	3950	3600	3200							

Figure 4: NOP Reference Power Distribution Normalized to 100% FP

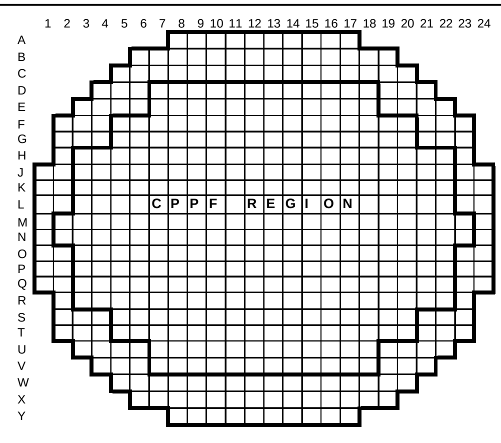

Figure 5: The CPPF Region

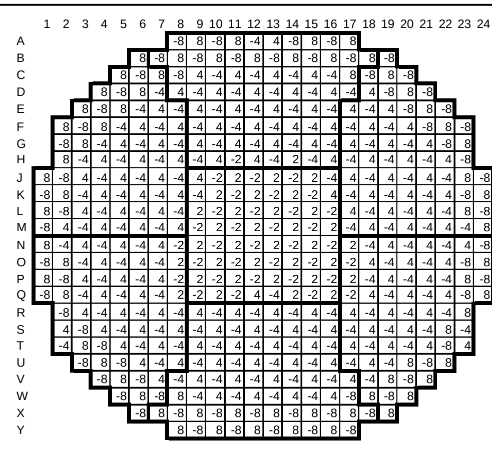

Figure 6: Revised Fuelling Scheme Map

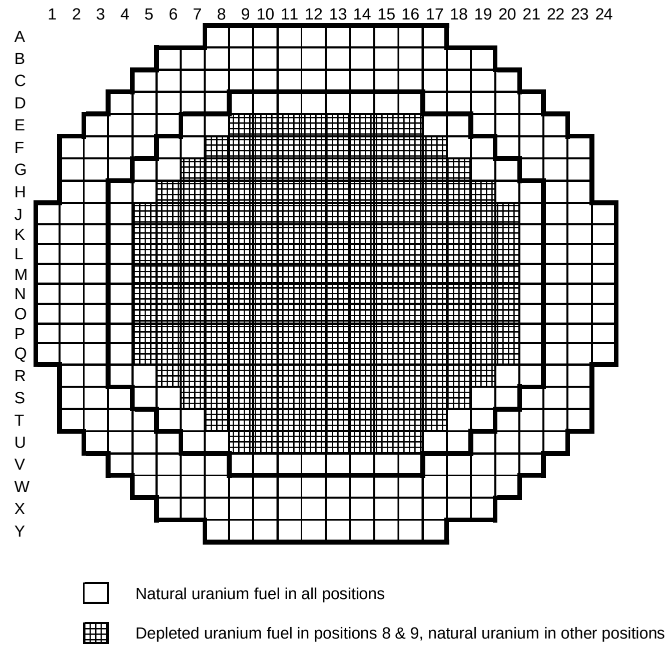

Figure 7: Original Initial Core Loading

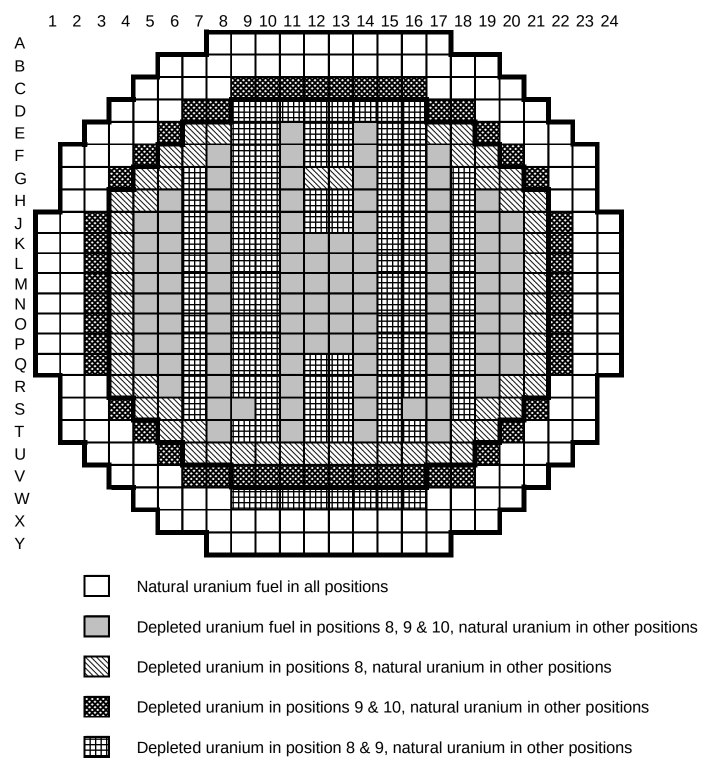

Figure 8: Initial Core Loading Option M

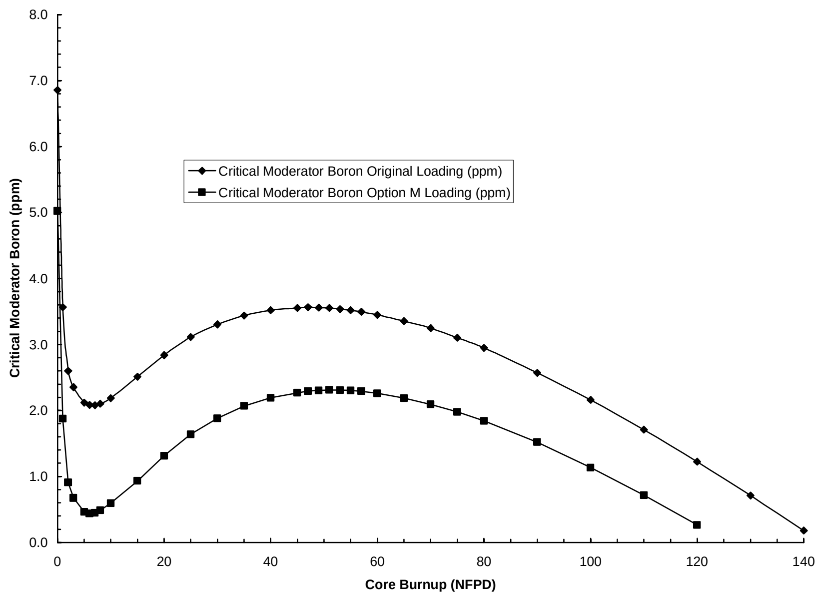

Figure 9: Option M and original initial core loading—critical moderator boron concentration versus core burnup.

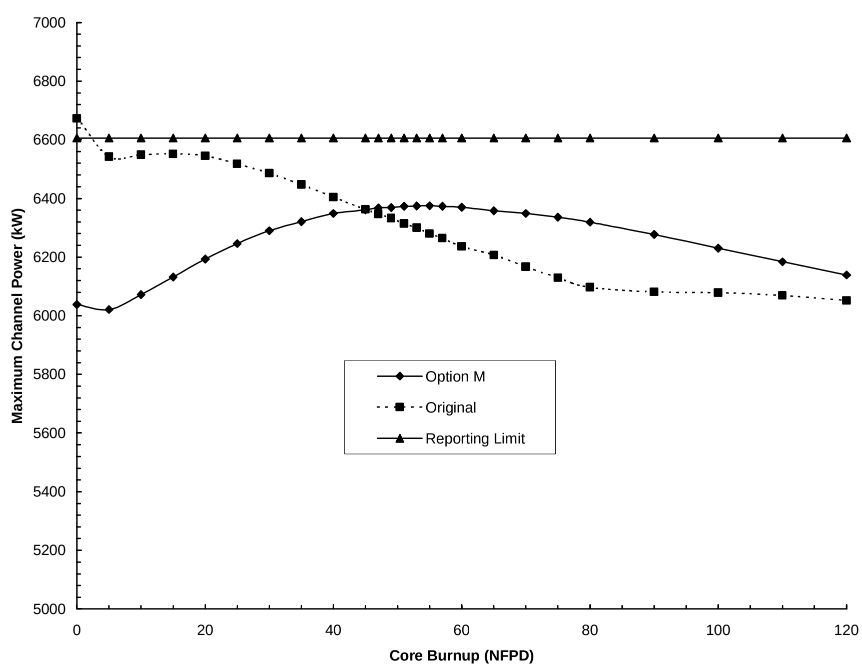

Figure 10: Comparison between maximum channel powers in the inner core region from Option M and original initial core loading—RFSP/SCM simulations.

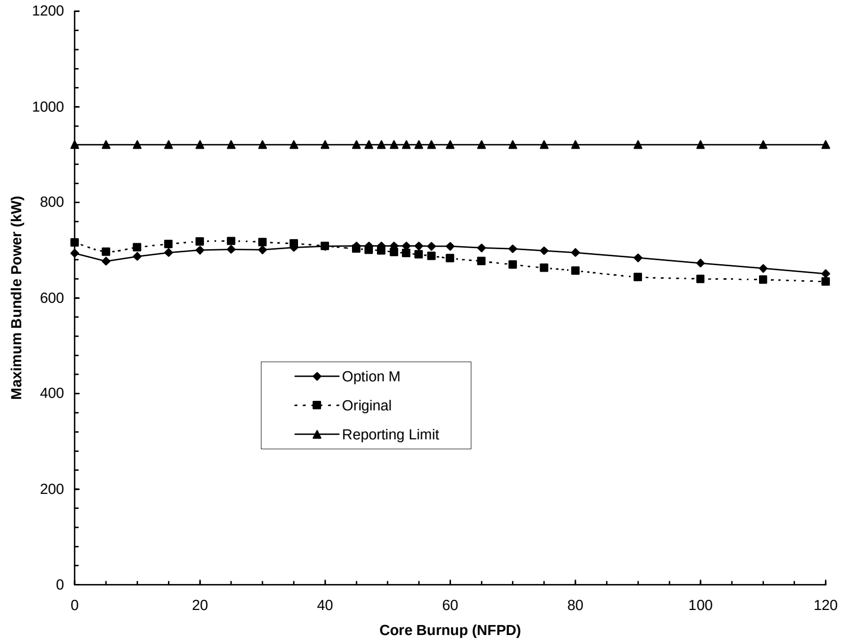

Figure 11: Comparison between maximum bundle powers in the inner core region from Option M and original initial core loading—RFSP/SCM simulations.

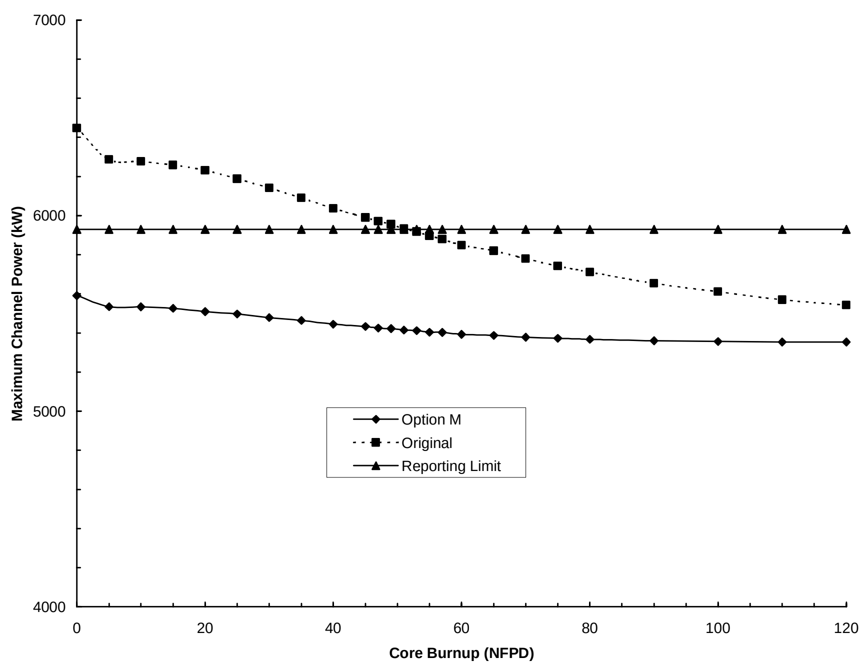

Figure 12: Comparison between maximum channel powers in the outer core region from Option M and original initial core loading—RFSP/SCM simulations.

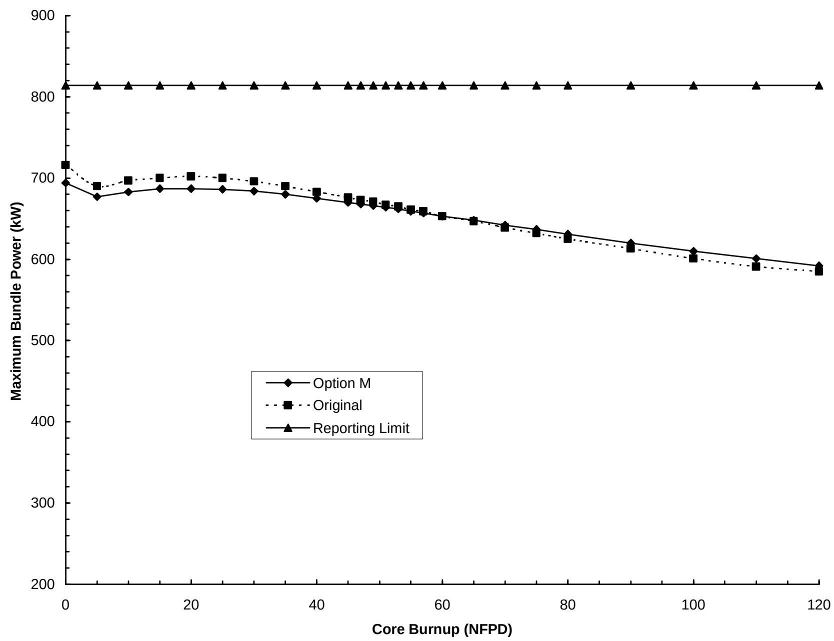

Figure 13: Comparison between maximum bundle powers in the outer core region from Option M and original initial core loading—RFSP/SCM simulations.

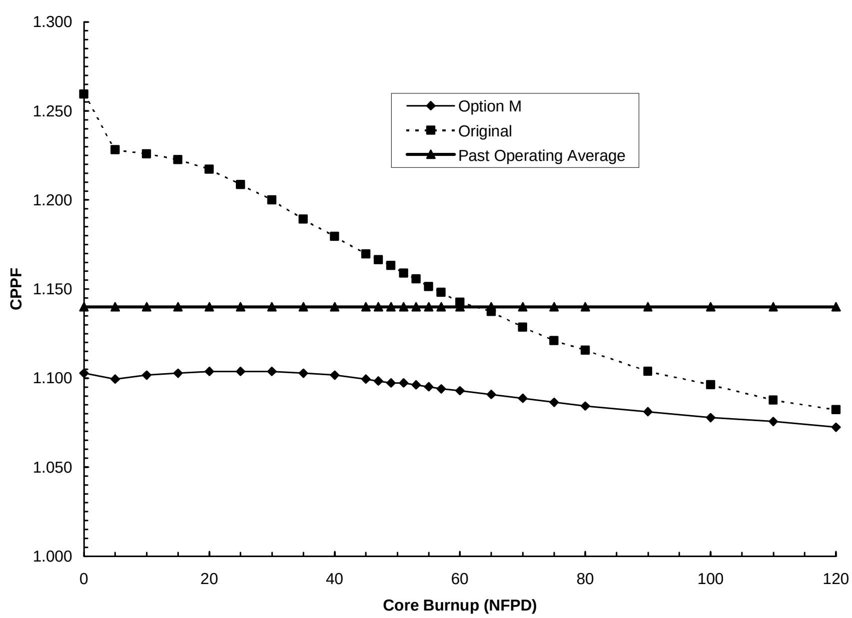

Figure 14: Comparison between the CPPF from Option M and original initial core loading—RFSP/SCM simulations.

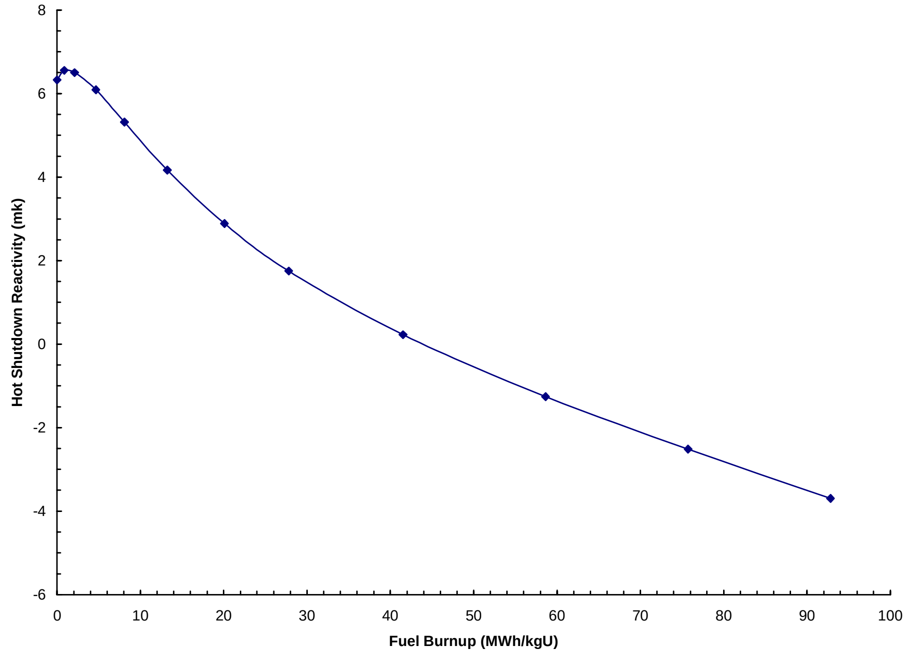

Figure 15: Hot shutdown reactivity vs fuel burnup—WIMS cell calculations.

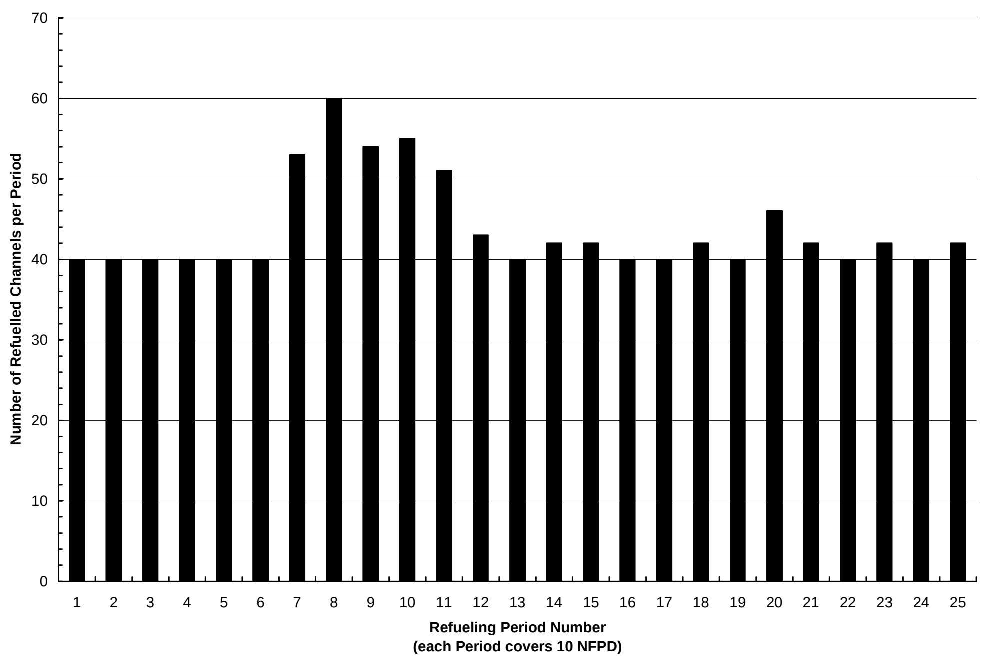

Figure 16: Option M fuelling rate (refuelled channels per 10-NFPD period) versus core burnup—RFSP/SCM simulations.

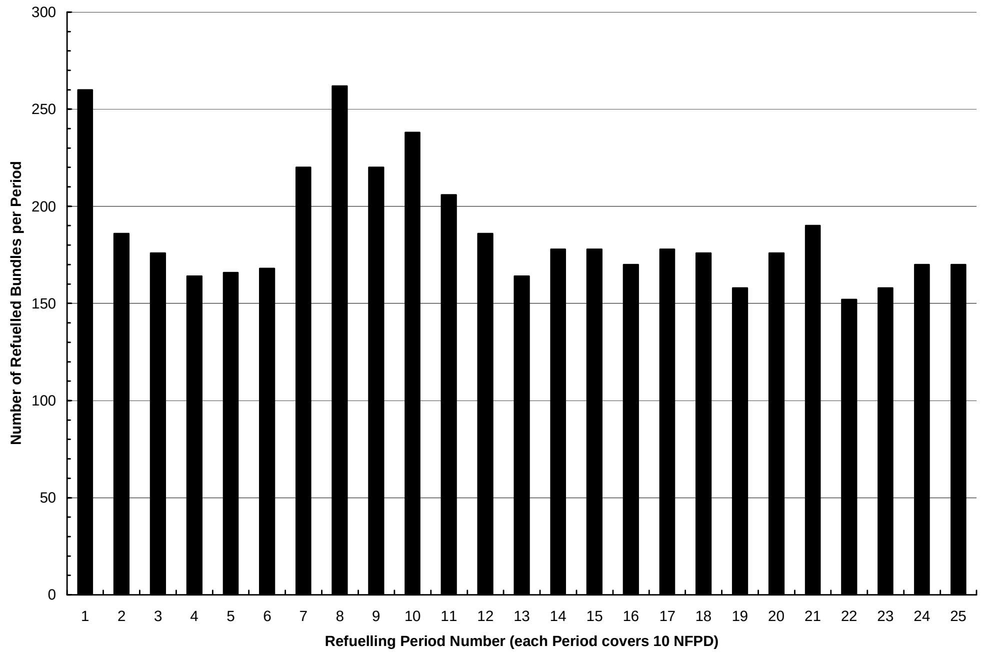

Figure 17: Option M fuelling rate (refuelled bundles per 10-NFPD period) versus core burnup—RFSP/SCM simulations.

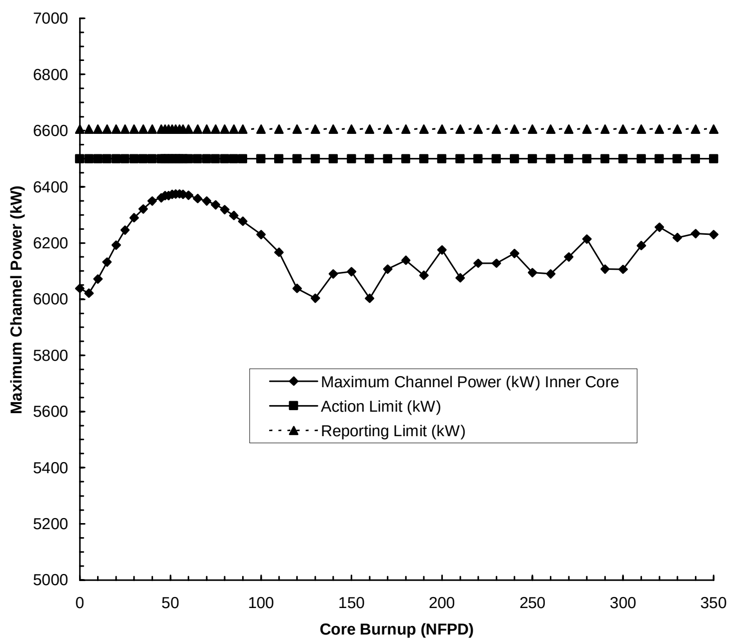

Figure 18: Option M maximum channel power in the inner core region versus core burnup—RFSP/SCM simulations.

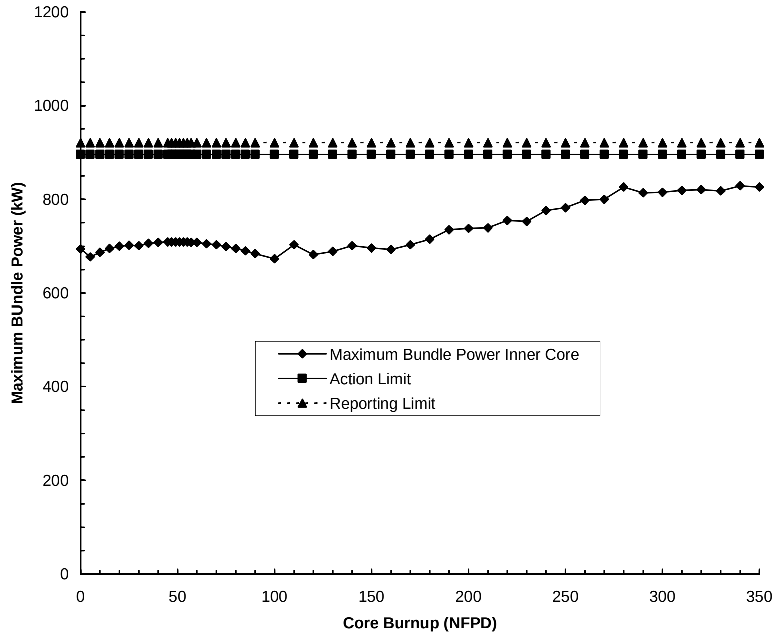

Figure 19: Option M maximum bundle power in the inner core region versus core burnup—RFSP/SCM simulations.

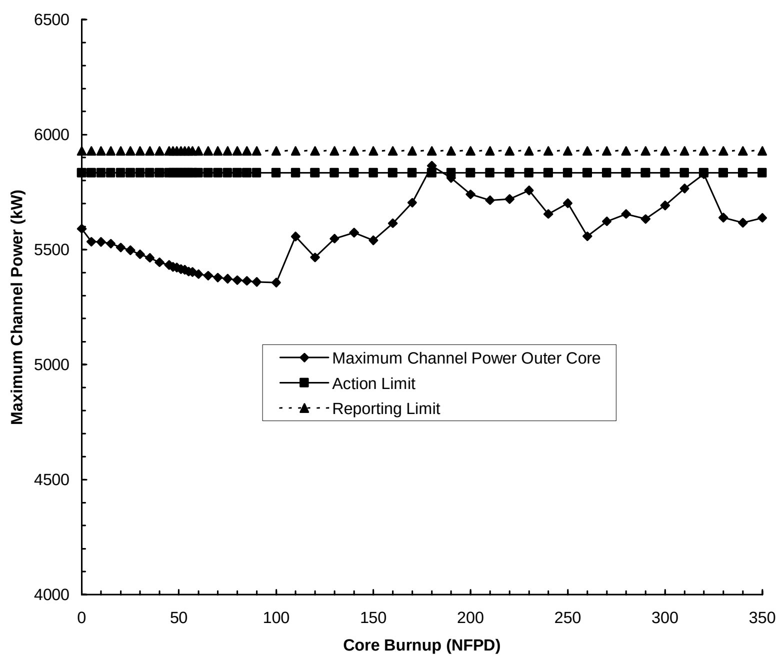

Figure 20: Option M maximum channel power in the outer core region versus core burnup—RFSP/SCM simulations.

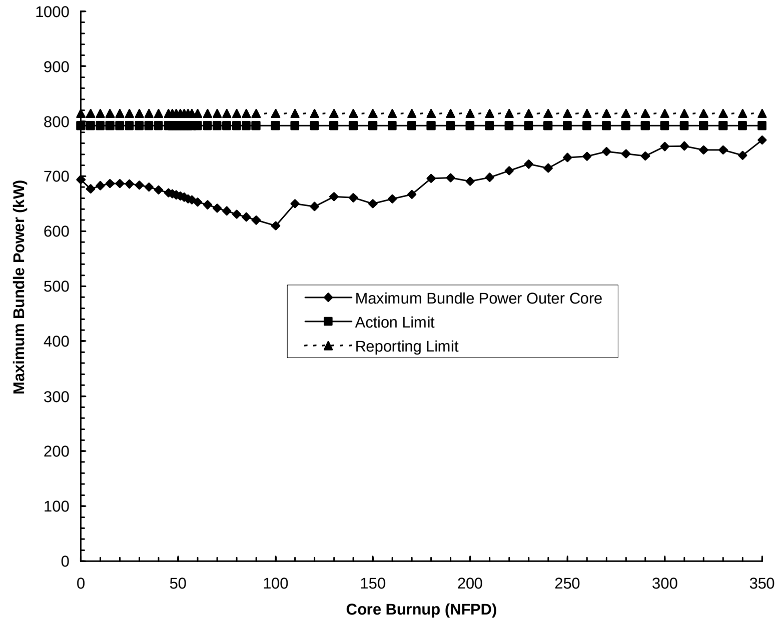

Figure 21: Option M maximum bundle power in the outer core region versus core purnup—RFSP/SCM simulations.

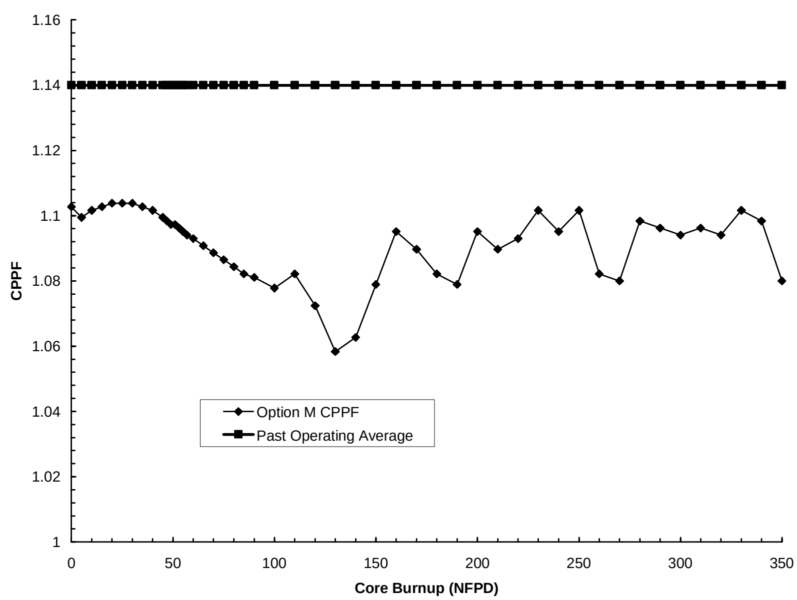

Figure 22: Option M CPPF versus core burnup—RFSP/SCM simulations.