COMPARISON OF SLIGHTLY ENRICHED URANIUM FUEL AND MOX FUEL IN CANDU-6 REACTOR

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ABSTRACT

A comparison study has been performed between natural uranium (NU), 0.9% and 1.2% slightly enriched uranium (SEU), and mixed-oxide (MOX) fuels in a CANDU 6 reactor for various axial refueling schemes with and without the adjuster rods present in the core. The few group cross section databases including local parameter effects are generated by the multi-group transport code DRAGON using a Winfrith WIMS 69-group library. The 3D CANDU fuel management optimization code OPTEX-4 is then used to compare optimized time-average equilibrium core performance. Finally instantaneous calculations are performed by the 3D diffusion code DONJON, from which both the channel power peaking factor (CPPF) and local parameters effect were estimated.

I. INTRODUCTION

High neutron economy, on-line refueling, and a simple fuel bundle design allow CANDU reactors to operate with a wide variety of fuel cycles. Aside from the typical once-through natural uranium (NU) fuel cycle, various advanced fuel cycles are of interest for future use in CANDU reactors. These include slightly enriched uranium (SEU) fuel[1], mixed-oxide (MOX) fuel[2], thorium fuel[3] and direct use of spent PWR fuel in CANDU (DUPIC)[4].

The use of SEU fuel can offer many benefits such as lowering fueling costs, improving uranium utilization and reducing the quantity of spent fuel. In addition, weapons-grade plutonium could be safely and efficiently disposed of by using MOX fuel in existing CANDU-6 reactors. The use of SEU or MOX fuel leads to fuel-management strategies which differ from NU fuel because both the initial reactivity and reactivity decline curve with burnup are different. Appropriate fuel management strategies will be key to ensuring acceptable fuel performance, as well as to maintaining bundle and channel powers within acceptable limits in the reactor. Such fuel management strategies have been studied in past feasibility studies of the SEU fuel cycle[1] and more recently for the MOX fuel cycle[2] but their differences were not specifically addressed.

This paper looks at some details of the comparison of the 0.9%, 1.2% slightly enriched uranium (SEU) fuels and initially reactivity equivalent mixed-oxide (MOX) fuels in a CANDU 6 reactor for various axial refueling schemes with and without the adjuster rods present in the core. The calculations were carried out by the DRAGON/OPTEX-4/DONJON chain of codes[5-7] in three steps. First, the few group cross section databases are generated by the multi-group transport code DRAGON using the Winfrith WIMS 69-group microscopic cross section library. As an option, local parameter effects can be included. Then the 3D fuel management optimization code OPTEX-4 is used to obtain optimized discharge burnup distributions at equilibrium refueling. The optimization step is introduced to provide a coherent basis for comparison of the SEU and MOX fuel cycles. Finally, instantaneous calculations were performed by the 3D diffusion code DONJON, from which both the channel power peaking factors (CPPF) and local parameter effects were estimated.

Two reference SEU fuels were used in this study: SEU09, slightly enriched uranium fuel with a U235 content of 0.9%, and SEU12, fuel with a U235 content of 1.2%. In comparison, two reference MOX fuels were generated by mixing 0.2% depleted uranium with different amounts of weapons grade plutonium[2] to match the initial lattice reactivities of SEU09 and SEU12 fuels. Although the total amount of fissile material (uranium plus plutonium) in fresh SEU fuel and in corresponding MOX fuels are initially equivalent, different fuel and core operating characteristics are expected because the initial U/PU ratios are significantly different.

In this study, we have used the standard CANDU 37-element fuel bundle design without burnable poison blended. Although the 42-element CANLEX fuel-bundle design with burnable poison is expected to be used for these advanced cycles, the results reported here should be indicative of their relative merit.

II. DRAGON TRANSPORT CALCULATIONS

The study of the SEU and MOX fuel cycles requires the pre-calculation of the few-group homogenized cross sections of the CANDU lattice cell and of incremental cross sections of the in-core reactivity devices. Cell calculations also involve calculating the homogenized few-group cross sections which will be used in a 3D diffusion theory code for reactor analysis. In this study, the few group lattice properties for both the lattice (in 2D) and the in-core reactivity devices (in 3D) required for full core simulations are generated by the multi-group transport code DRAGON using Winfrith WIMS 69-group microscopic cross section library, with critical buckling search.

A. 2D CANDU Cell Calculation

The unit cell contains a single fuel bundle surrounded by moderator. Neutron flux distribution within the cell is obtained by the EXCEL module of DRAGON, which uses the collision probability method for both self-shielding and the 2D cluster geometry transport calculation. The depletion equations for the nuclide field are solved at constant power with a quasi-static approximation for the neutron field. This allows the burnup-dependent few group macroscopic cross sections for SEU and MOX fuels to be generated. If traditional uniform parameter procedure is applied, the effective (average) local parameters such as fuel temperature, coolant density and average neutron flux will be specified for the unit cell at full power, even though the appropriate local parameters do vary from one fuel bundle to next. To generate nuclear cross sections database with local parameters, we can use the feedback model[8] introduced in DRAGON lately.

A comparison of the lattice k-infinities of NU, SEU and MOX fuel bundles is shown in Figure 1. Although the reference MOX fuel initially has the same k-infinity as the corresponding SEU fuel, the k-infinity of the MOX fuel decreases much faster than that of the corresponding SEU fuel, which results in a significant lower average discharge burnup of MOX fuel. These differences may be explained in terms of different U/PU ratio in the initial CANDU fuel bundles. Different concentration ratios in the fuel will introduce variations in the neutron source spectrum and in neutron capture, resulting in large effects on the fuel and core operating characteristics.

B. 3D CANDU Supercell Calculation

3-D transport calculations are required to account for the reactivity devices present in a CANDU reactor such as adjuster rods and zone control units (ZCUs). The incremental cross sections are defined as the difference in macroscopic cross sections of a lattice cell introduced by the presence of the reactivity device. These were calculated in DRAGON with the same group structure as the 2D analysis and the multi-group incremental cross sections were then condensed to 2 groups. The flux is obtained by the EXCEL transport module in 3D general geometry. For calculation simplicity, the incremental cross sections were assumed independent of fuel burnup and were obtained using the time-average fuel composition.[9]

III OPTIMIZED EQUILIBRIUM CORE PERFORMANCE

Prediction of the time-average power distribution under equilibrium refueling is essential for the SEU-fueled and MOX-fueled CANDU core design because it ensures that limits on the fuel will not be exceeded during normal operation of the reactor. For the given reload fuel type and axial refueling scheme, the core-average discharge burnup at equilibrium is decided by the fuelling rate, i.e., radial burnup distribution over the reactor. In order to compare the equilibrium core performance for SEU fuel and MOX fuel, a typical design problem in CANDU reactors with various refueling schemes is performed in this study. The problem is to find the optimal time-average fueling rate distribution over the reactor that minimizes fueling costs and meets a number of operating constraints. Since adjuster rods were originally designed for CANDU reactors with NU fuel, their presence in the core will complicate fuel management strategy for SEU and MOX fuels, unless clear design objectives are indicated for adjusters in enriched cores. Therefore the optimization calculations with and without adjuster rods are carried out by 3D CANDU fuel management code OPTEX-4.

A. 6-Burnup-Zone Design

In previous studies,[1, 10] the traditional 2-burnup-zone approach was used for the time-average model. The core is divided into two radial zones and the discharge burnup of two zones are determined manually such that the reactor is critical and the peak channel power is minimized or at least is acceptable. As the division of burnup zone is arbitrary, minimizing peak power is not optimal for fuel consumption. With only 2 burnup zones, the problem is entirely determined by the constraints of criticality and peak power. With more than 2 zones, it becomes possible to optimize fuel costs, but it is impractical to tune the discharge burnup of each zone manually. Mathematical programming is required to make the reactor critical and fuel costs optimal within the peak power limits. OPTEX-4 automatically determines the optimized discharge burnup distribution of arbitrary zones which will provide an adequately flattened radial power shape.

Time-averaged equilibrium core performance was calculated by 6-burnup-zone design instead of the simple 2-burnup-zone approach, as shown in Figure 2. The optimized radial discharge burnup distributions of SEU-fueled and MOX-fueled cores were calculated by OPTEX-4 to achieve minimum fueling costs under the constraints of operating power peaking limit. During optimum search, all 14 ZCU water levels were assumed to remain at nominal 50% for calculation simplicity.

B. New Improvements in OPTEX-4

OPTEX-4 was originally developed for NU-fueled CANDU core design. To do optimization design of equilibrium core performance for advanced fuel cycles, modifications were made to OPTEX-4 code:

1) The source program is revised to read the latest few-group homogenized cross sections XSM files obtained from new version of DRAGAN directly. With this improvement, the time-average calculation between OPTEX-4 and DONJON agrees well.
2) Because the location of in-core reactivity devices is unsymmetrical, optimization model in the OPTEX-4 was applied to a 3D *full core* (380 radial channels with 12 axial bundles) instead of 3D 1/8 core used before[7].
3) In order to get an initial feasible guess of discharged burnup distribution for 6-burnup-zone SEU-fueled and MOX-fueled CNADU cores, minimizing peak channel power is designed in the source program as an *alternative* objective function.
4) To effectively control different flux shape of SEU-fueled and MOX-fueled core with various refueling schemes, the constraints on maximum channel powers are enforced by monitoring *all channels* in the high-power region of the core, i.e., burnup zones from 1 to 5.

C. Comparison of Optimized Equilibrium Core Performance for SEU and MOX fuels

OPTEX-4 was first run to minimize channel power peaking in CANDU reactor for different fuel types with various axial refueling schemes. The results are shown in Table 1. The power shapes can be flattened enough for all SEU-fueled and MOX-fueled cores with and without adjuster rods. The channel power and bundle power are controlled below 6300 Kw and 800 Kw separately for both 2BS and 4BS refueling schemes. Minimizing peak channel power tends to increase fueling rate in outer burnup regions and thus to increase the core leakage at the core periphery, resulting in an unexpected penalty on achievable discharge burnup. However, this solution is good enough as an initial feasible guess for the optimization runs in the next step.

To avoid the burnup penalty discussed above, we ran OPTEX-4 again this time to minimize fueling costs (i.e. maximize average discharge burnup) under different constraints imposed on channel power peaking limit, using the previous optimization results in the 6 radial zones of the core as the initial feasible guesses of the burnup distribution. Figures 3 and 4 present how the achievable discharge burnup varies in accordance with channel power peaking limit imposed for NU-fueled and SEU12-fueled reactors. The slope of these curve therefore measures the burnup penalty associated with radial flattening and with the nominal channel power limit. The increase in discharge burnup with channel power peaking is primarily due to the lower neutron leakage at the core periphery. As shown in Table 2 and Figure 4, the maximum discharge burnup increases almost linearly with the channel power peaking for SEU12 fuel at the given coverage of channel power peak limit.

A value of 6.5 MW was selected as the reference channel power limit in the comparison of optimized equilibrium core performance for SEU and MOX fuels. Figure 5 illustrates the radial channel power distribution for a row of channels along the horizontal mid-plane of the NU-, SEU12-, and MOX12-fueled cores with adjuster rods inserted. The adjuster rods were unmodified, using incremental cross sections generated with the appropriate fuel compositions. As we can see, the flattening effect of the adjusters differs with enriched fuels.

The axial fuelling scheme has a great influence on the bundle power distribution. This is illustrated in Figure 6, where the axial flux shape is shown for an infinite lattice of channel with bi-directional fuelling. A simple 2BS refueling scheme of SEU12 and MOX12 fuels results in an over-flattened bundle power distribution compared with 8BS scheme of NU fuel resulting in a symmetric double hump as shown in Figure 6.

Clearly adjuster rods provide flux and power flattening with 8BS NU fuel but are not needed for this purpose with SEU and MOX fuels. The radial channel power can be designed well enough without adjuster rods for SEU and MOX fuels, as shown in Figure 7. In fact, the presence of adjuster rods not only overflattens the channel power in the center of SEU12-fueled core, but also introduces a 5% burnup penalty, with a corresponding increase in fueling costs. As shown in Table 5, the adjuster worth in 2BS SEU12-fueled core is about 60% less than in 8BS NU-fueled core because of the depression of flux shape in the adjuster region. Therefore the adjuster grading (location and strength of the adjusters) should be redesigned for advanced fuel cycles in the future.

More detailed calculation results such as time-average bundle and channel powers, average discharge burnup and adjuster worth of NU-fueled, SEU-fueled and MOX-fueled cores on various axial refueling schemes are illustrated and compared in Table 3. We observed that the MOX-fueled CANDU core has about 40-50% lower discharge burnup than that of the corresponding SEU-fueled CANDU core, which is consistent with the above lattice calculation results. To extend the discharge burnup of MOX fuel bundle and to dispose more weapons-grade plutonium, it is recommended to increase initial contents of plutonium and use burnable poison simultaneously to match the K-infinity decline of SEU fuel.

IV. INSTANTANEOUS CORE CALCULATION

The time-average equilibrium core is not the actual core condition during the continuous refueling operation. Thus, the time-average distribution does not yield the actual peaking power resulting from the application of a particular fuel management scheme. For this, instantaneous reactor calculations are required. An instantaneous power distribution at equilibrium refueling can be obtained if the current value of burnup is known for each fuel bundle in the core. A simple approach based on the patterned channel age model was implemented in DONJON to allocate individual bundle burnup reflecting a particular channel refueling sequence.

The time-average calculation is first carried out. This provides the fuel burnup for each bundle at the beginning (BOC) and the end (EOC) of the fuelling cycle, ω_{jk}^{BOC} and ω_{jk}^{EOC}. The age model assumes that burnup varies linearly with time during the cycle, so that current values of burnup are simply a function of the age of the channel. Channel age at time t is defined simply as the fraction of the refueling interval elapsed since the last refueling in that specific channel. The instantaneous procedure is thus reduced to specifying an age for each channel in the core such that it reflects a particular refueling sequence.

In order to achieve this, the core was divided into 4x4 blocks and blocks were ordered from 1 to 16 as shown in Figure 8. In each odd and even block, the 36 channels were numbered in the order shown. This sequence was chosen to disperse successive refueling in the same block and avoid clustering of fresh fuel. The final refueling sequence for the whole core l_j (j=1, 380) shown in Figure 8 was obtained by following the order within the 4x4 blocks, and the order of the blocks. The channel age for each channel f_j was then calculated by:

$$f_j = \frac{(\ell_j - 0.5)}{380}, \; j = 1, 380 \tag{1}$$

Based on the resultant age map, the burnup of each bundle in the core was determined to be:

$$\omega_{jk}(t) = \omega_{jk}^{BOC} + f_j(t) \cdot \left[\omega_{jk}^{EOC} - \omega_{jk}^{BOC}\right] \tag{2}$$

Using this burnup distribution, an instantaneous power distribution can thus be obtained with a single diffusion calculation from which peak power can be determined. The instantaneous power distribution can then compared to the previous time-average power distribution, yielding the channel power peaking factor (CPPF) expected to occur during actual refueling operation. CPPF is defined as the largest channel over-power (ratio of instantaneous to time-average channel power). The CPPF is an important parameter in the CANDU design to ensure sufficient operating margin.

CPPF, instantaneous channel and power peaking for different SEU-fueled and MOX-fueled CANDU cores with various axial refueling schemes are summarized in Table 4 and compared to those of the NU-fueled core. Table 4 indicates that all instantaneous power peaking factors are within operating limits except SEU12 and MOX12 fuels with 4BS scheme. CPPF is strongly affected by fuel type and refueling scheme. To limit the CPPF of the SEU-fueled and MOX-fueled cores, the number of bundles introduced at each refueling must be reduced (thus increasing the refueling frequency). Compared to the 8BS NU-fueled core, 4BS refueling scheme is recommended for SEU09-fueled and MOX09-fueled cores, while only 2BS refueling scheme can be used in SEU12-fueled and MOX12-fueled cores. This conclusion is similar to previous studies.

V. LOCAL PARAMETER EFFECTS

The local parameter effects on NU-fueled CANDU core has been studied before[11,12] but their effects on SEU-fueled and/or MOX-fueled CANDU cores are not documented. The effect of the local parameter correction (fuel temperature, coolant density, flux level, etc.) on the instantaneous core performance with SEU and MOX fuels have been estimated. As shown in Table 4, the application of local parameters has a flattening effect on the power distribution for all fuel types with various refueling schemes. For the 2BS SEU12-fueled instantaneous CANDU core, the channel power peaking dropped by 5% from 6817KW to 6733 KW, while the bundle power peaking decreased by 1.2% from 898 Kw to 860 Kw. Figure 9 illustrates the instantaneous axial power distribution along a particular channel (Channel L11), showing how the power is flattened at the channel when local parameters are introduced during calculation. We see that the influence of local parameters on SEU and MOX fuels is not so significant, of the same order as that of NU fuel.

With local parameter feedback model, it is possible to estimate void coefficients of CANDU reactor with various fuel types by DONJON code. Table 5 summarized the various void coefficients of CANDU 6 calculated by the 2D lattice code and by the 3D full core code separately. It was concluded from Table 5 that: 1) Void coefficient is sensitive to burnup of the unit cell used in calculation, but it is not sensitive to axial refueling scheme. 2) Prediction of void coefficient by the lattice code with middle burnup will agree with 3D full core calculation within 7%. 3) Void coefficients of SEU and MOX fuels are smaller than that of NU fuel.

VI. CONCLUSION

A comparison study has been performed in this paper for 0.9%, 1.2% slightly enriched uranium (SEU) fuels and initially reactivity equivalent mixed-oxide (MOX) fuels in a CANDU 6 reactor for various axial refueling scheme with and without the adjuster rods present in the core, using the DRAGON/OPTEX-4/DONJON chain of codes.

Although the reference MOX fuel initially has a same k-infinity as the corresponding SEU fuel, the fuel and core performance is expected to be different because of different U/PU ratio in the initial fuel bundles. As the reactivity of the MOX fuel decreases much faster, the MOX-fueled CANDU core has about 40-50% lower discharge burnup than that of the corresponding SEU-fueled CANDU core.

In this paper, time-averaged equilibrium core performance was calculated with a 6-burnup-zone design instead of the simple 2-burnup-zone approach. In order to compare the equilibrium core performance for SEU fuel and MOX fuel, a typical design problem in CANDU reactors with and without adjuster rods is performed to find the optimal time-average fueling rate distribution over the reactor that minimizes fueling costs and meets a number of operating constraints. The calculations show that the power distribution and discharge burnup in equilibrium SEU-fueled and MOX-fueled core vary with various axial refueling schemes and channel power peaking limit imposed. The radial channel power can be designed well enough without adjuster rods for SEU and MOX fuels. Compared to the natural uranium core that uses an 8-bundle shift (8BS) axial refueling scheme, 4BS refueling scheme is recommended for SEU09-fueled and MOX09-fueled cores, while only 2BS refueling scheme is recommended for SEU12 core and MOX12 core because of more axial power flattening and acceptable CPPF.

The effect of the local parameter correction (fuel temperature, coolant density, flux level, etc.) on the instantaneous core performance with SEU and MOX fuels are also estimated in this paper. The calculations show that the local parameters effect on SEU and MOX fuels is not so significant, it is in the same order as that of NU fuel.

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Table 1: OPTEX-4 6-Burnup-Zone Time-Averaged Results of CANDU-6 Core with Different Fuel Types (Objective: Minimization of Channel Power Peaking)

Fuel Type	BS	Without Adjusters Avg. Exit Burnup (MWD/T)	Without Adjusters Bundle Power Kw	Without Adjusters Channel Power Kw	With Adjusters Avg. Exit Burnup (MWD/T)	With Adjusters Bundle Power Kw	With Adjusters Channel Power Kw	With Adjusters ADJ Worth mk
Nat. U	2	7825	915	6287	7101	860	6263	15.50
	4	7905	890	6294	7014	835	6265	15.24
	8	7761	831	6317	6884	808	6297	16.70
SEU09	2	14766	794	6225	13755	742	6133	11.83
	4	14900	796	6210	13789	755	6121	12.54
SEU12	2	21833	738	6032	21195	790	6162	6.82
	4	22327	758	6023	21528	788	6012	8.90
Mox09	2	6032	717	6158	5538	697	6181	10.23
	4	6210	740	6068	5785	729	6209	11.48
Mox12	2	12748	734	6168	11953	754	6307	5.71
	4	13170	756	6176	12440	770	6157	7.87

Table 2: OPTEX-4 6-Burnup-Zone Time-Averaged Results of CANDU-6 Core with Different Fuel Types (Objective: Minimization of Fuel Cost)

Fuel Type (BS)	Peak Channel Power Limit (Kw)	Without Adjusters Avg. Exit Burnup (MWD/T)	Without Adjusters Bundle Power Kw	Without Adjusters Channel Power Kw	With Adjusters Avg. Exit Burnup (MWD/T)	With Adjusters Bundle Power Kw	With Adjusters Channel Power Kw	With Adjusters ADJ Worth mk
Nat. U (8BS)	6300	7773	831	6298	7096	818	6299	16.84
	6500	8526	852	6506	7459	823	6499	17.40
	6700	8872	880	6709	7580	842	6700	17.86
SEU12 (2BS)	6300	22381	775	6293	21482	814	6302	7.12
	6500	22622	800	6499	21597	814	6501	7.11
	6700	22862	826	6704	21635	814	6692	7.08

Table 3: OPTEX-4 6-Burnup-Zone Time-Averaged Results of CANDU-6 Core with Different Fuel Types (Objective: Minimization of Fuel Cost, Channel Power peak limit is 6.5 Mw)

Fuel Type	BS	Without Adjusters Avg. Exit Burnup (MWD/T)	Without Adjusters Bundle Power Kw	Without Adjusters Channel Power Kw	With Adjusters Avg. Exit Burnup (MWD/T)	With Adjusters Bundle Power Kw	With Adjusters Channel Power Kw	With Adjusters ADJ Worth mk
Nat. U	2	8732	953	6507	7579	868	6498	16.15
	4	8729	925	6507	7533	838	6499	16.02
	8	8526	852	6506	7459	823	6499	17.40
SEU09	2	15193	821	6502	14196	781	6501	12.75
	4	15331	825	6504	14259	797	6500	13.49
SEU12	2	22622	800	6499	21597	814	6501	7.11
	4	23194	824	6502	22022	815	6500	9.25
Mox09	2	6568	758	6498	5946	776	6499	11.49
	4	6658	770	6497	6040	774	6499	12.29
Mox12	2	13035	773	6497	12379	814	6500	6.55
	4	13527	800	6500	12798	824	6499	8.55

Table 4: Instantaneous Calculation of CANDU-6 Core for Different Fuel Types (With Adjusters)

Fuel Type	BS	Without Local Parameter CPPF	Without Local Parameter Bundle Power, Kw	Without Local Parameter Channel Power, Kw	With Local Parameters Bundle Power, Kw	With Local Parameters Channel Power, Kw
Nat. U	2	1.074	866	6799	823	6698
SEU09	2	1.052	810	6726	790	6670
	4	1.107	854	7002	830	6951
SEU12	2	1.086	898	6817	860	6733
	4	1.188	1005	7262	950	7096
Mox09	2	1.042	788	6708	767	6624
	4	1.089	836	6943	820	6855
Mox12	2	1.082	945	6908	888	6808
	4	1.184	1084	7440	1022	7308

Table 5: Void Reactivity (mk) of CANDU6 with Different Fuel Types

Fuel Type	2D Lattice Calculation Fresh Fuel	2D Lattice Calculation Middle Burnup	2D Lattice Calculation Discharge Burnup	3D Full Core Calculation 2BS	3D Full Core Calculation 4BS	3D Full Core Calculation 8BS
Nat. U	16.3	12.8	11.7	----	----	13.8
SEU 0.9 w/o	15.1	13.1	10.9	13.2	13.3	----
SEU 1.2 w/o	13.9	13.8	10.0	12.9	13.0	----
MOX 0.9 w/o	11.5	11.3	10.6	10.9	10.9	----
MOX 1.2 w/o	12.3	12.0	10.2	11.3	11.4	----

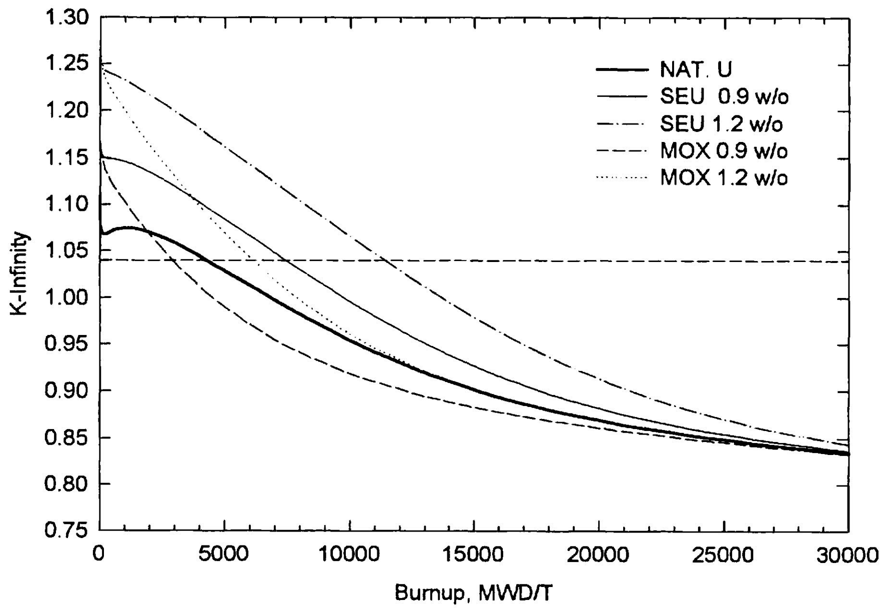

Figure 1: Lattice K-infinity vs. Burnup for Different Fuel Types

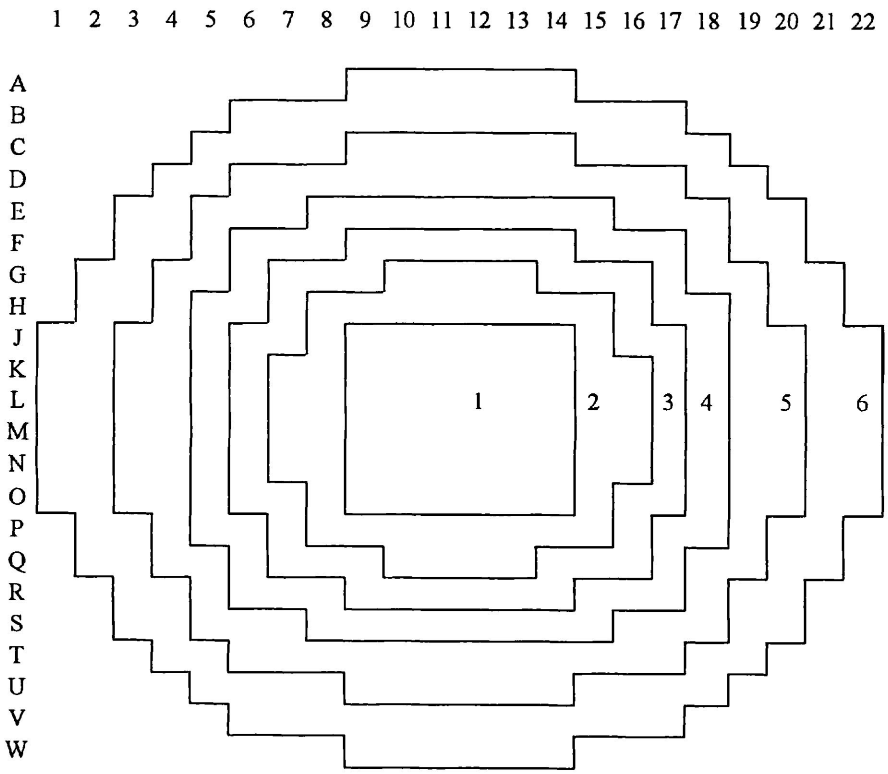

Figure 2: Boundary of 6 Radial burnup zones in CANDU-6 core

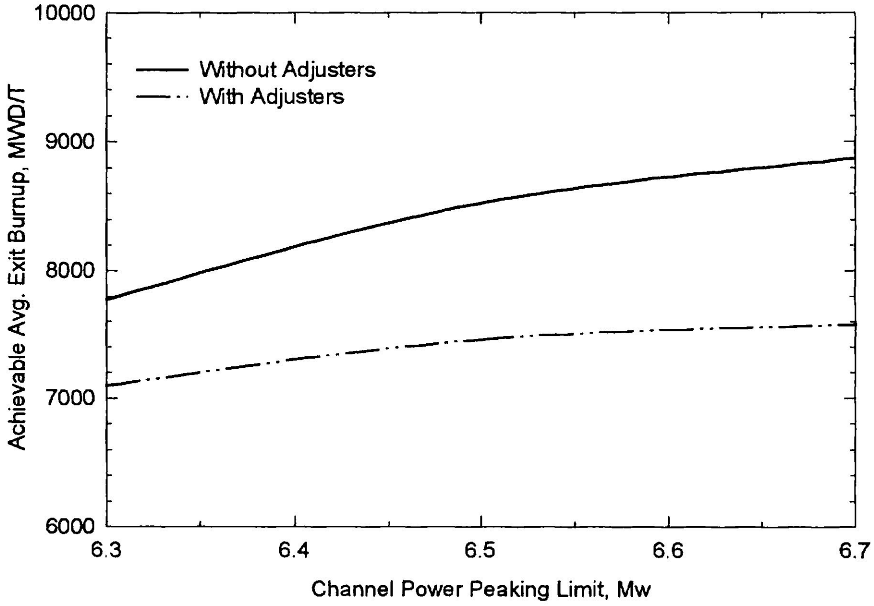

Figure 3: Achievable Averaged Exit Burnup vs. Channel Power Peaking Limit for Nat. U CANDU Core with 8BS

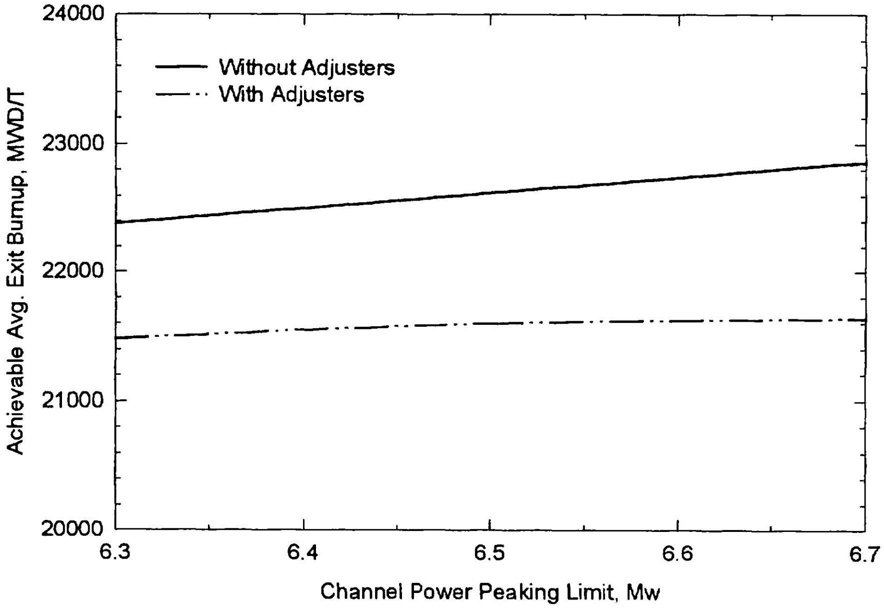

Figure 4: Achievable Averaged Exit Burnup vs. Channel Power Peaking Limit for SEU12 CANDU Core with 2BS

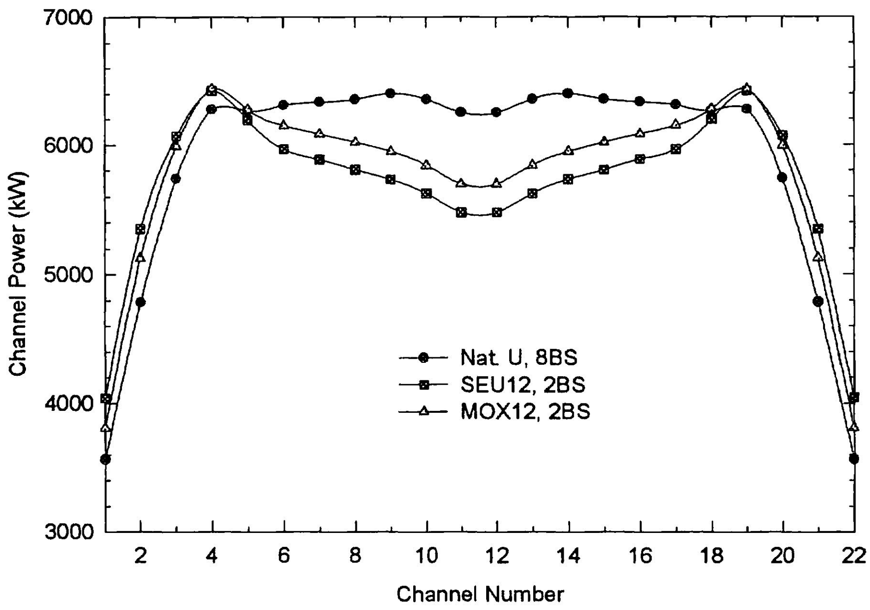

Figure 5: Time-Averaged Radial Channel Power Profiles (Row L, With Adjusters)

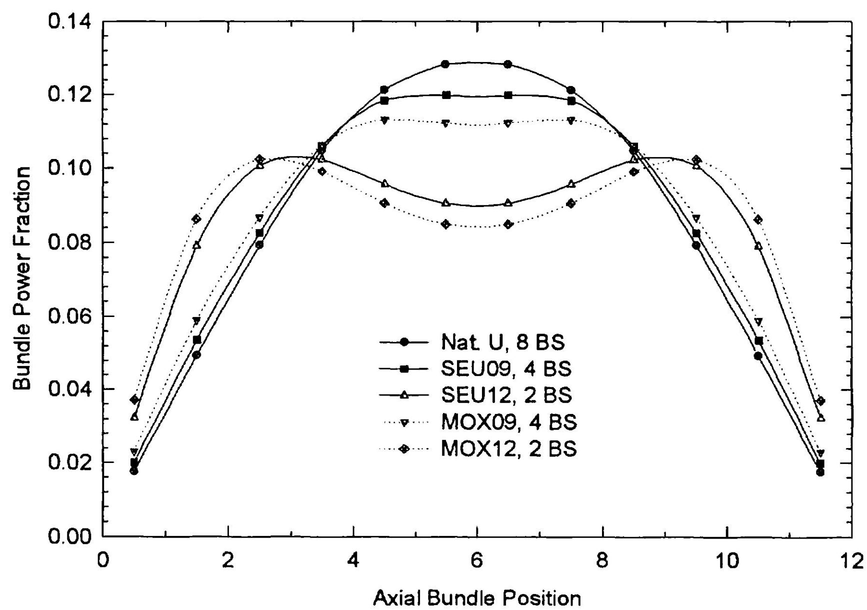

Figure 6: Bundle Powers in an Average Channel for Different Fuel Types with Various Bundle Shift Strategies

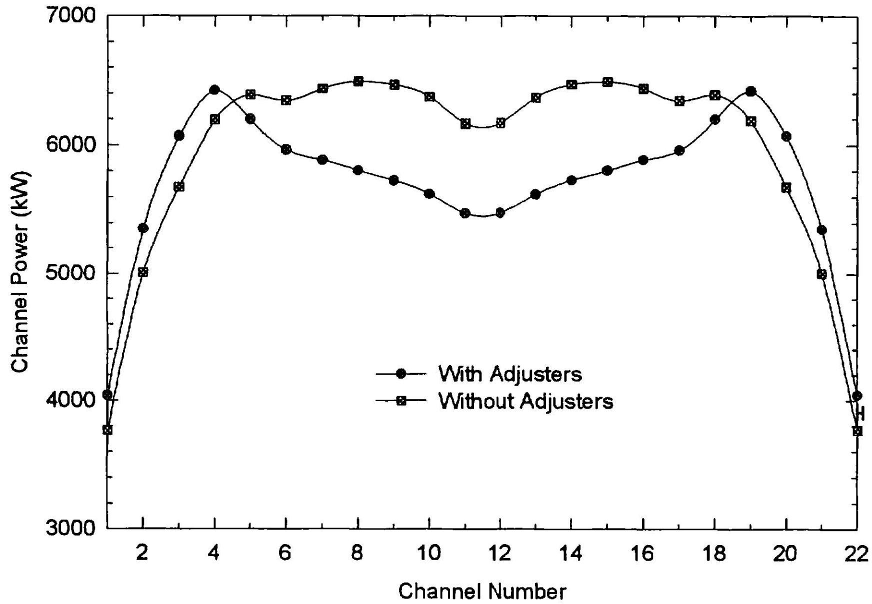

Figure 7: Time-Averaged Radial Channel Power Profiles (SEU12, 2BS,Row L)

								358	91	39	67	162	234								
					315	113	294	196	248	366	309	109	287	191	245	363					
				59	33	208	346	19	219	61	25	202	340	14	213	55	31				
			271	322	123	261	103	156	273	323	118	254	97	149	265	318	122	260			
		333	7	184	51	377	135	334	8	185	44	371	127	327	1	179	50	376	133		
		176	145	283	226	301	79	173	142	279	232	307	86	177	147	285	228	303	81		
	241	360	93	40	69	164	236	353	88	37	76	171	243	361	95	42	71	166	238	355	
	296	198	250	367	311	110	289	193	246	364	316	116	298	200	252	369	313	112	291	195	
210	348	21	221	63	27	204	342	16	215	57	35	211	350	23	223	65	29	206	344	18	217
262	105	158	275	324	119	256	99	151	267	319	125	263	107	160	276	325	121	258	101	153	269
378	137	336	10	187	46	372	129	329	3	181	53	379	139	338	12	189	48	374	131	331	5
292	72	167	132	270	224	299	77	172	140	277	216	290	70	165	130	268	222	297	75	170	138
154	229	345	82	30	66	161	233	351	87	36	58	152	227	343	80	28	64	159	231	349	85
102	281	183	239	356	308	108	286	190	244	362	302	100	280	182	237	354	306	106	284	188	242
	332	6	207	49	24	201	339	13	212	54	17	194	330	4	205	47	22	199	337	11	
	90	144	259	314	117	253	96	148	264	317	111	247	89	143	257	312	115	251	94	146	
		321	375	175	43	370	126	326	380	178	38	365	120	320	373	174	41	368	124		
		168	134	272	214	288	68	163	128	266	220	295	74	169	136	274	218	293	73		
			83	32	56	150	225	341	78	26	62	157	230	347	84	34	60	155			
				357	300	98	278	180	235	352	305	104	282	186	240	359	304				
					15	192	328	2	203	45	20	197	335	9	209	52					
								141	255	310	114	249	92								

Refueling Sequence in odd block

22	29	8	17	14	27
7	16	23	34	9	4
30	11	28	19	24	35
3	20	33	2	21	6
12	25	10	15	26	31
5	36	13	32	1	18

Refueling Sequence in even block

21	28	7	16	13	26
6	15	22	33	8	3
29	10	27	18	23	34
2	19	32	1	20	5
11	24	9	14	25	30
4	35	12	31	36	17

Block Order

7	11	1	9
13	3	15	5
6	16	4	14
10	2	12	8

Figure 8: Refueling Sequence in the hole Core

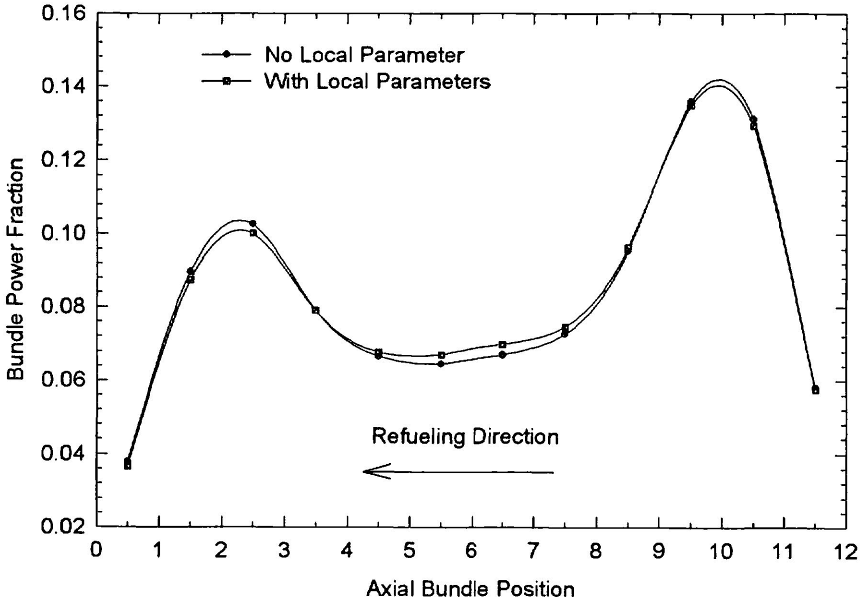

Figure 9: Local Parameters Effect on Instantaneous Bundle Powers for 2BS SEU12 Fuel (Channel L11)