**AECL-9986**

ATOMIC ENERGY
OF CANADA LIMITED

ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

# EQUILIBRIUM FUEL-MANAGEMENT SIMULATIONS FOR 1.2% SEU IN A CANDU 6

# SIMULATIONS DE GESTION DU COMBUSTIBLE A L'EQUILIBRE POUR SEU A 1,2% DANS UN REACTEUR CANDU 6

**M.H. YOUNIS and P.G. BOCZAR**

Presented at the 10th Annual Conference of the Canadian Nuclear Society,
Ottawa, Ontario, June 4-7, 1989

Chalk River Nuclear Laboratories
Laboratoires nucléaires de Chalk River

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ÉNERGIE ATOMIQUE DU CANADA, LIMITÉE

# SIMULATIONS DE GESTION DU COMBUSTIBLE À L'ÉQUILIBRE POUR SEU À 1,2% DANS UN RÉACTEUR CANDU 6

par

M.H. Younis et P.G. Boczar

## RÉSUMÉ

On a simulé la gestion du combustible à l'équilibre, pour l'uranium légèrement enrichi (SEU) à 1,2% dans un réacteur CANDU 6*. On a considéré trois possibilités de gestion du combustible, à savoir:

1) interversion (permutation) axiale,
2) déplacement normal de 2 grappes et
3) déplacement normal de 2 grappes, barres de compensation (réglage) étant retirées du coeur.

Les simulations se sont faites en temps moyen et en fonction du temps et on a calculé les caractéristiques de la physique des coeurs à l'équilibre à partir de celles-ci. On a tiré l'enveloppe de puissance et d'augmentation de puissance de la grappe de combustible à 37 éléments et de la grappe de combustible avancée CANFLEX.

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* CANada Deuterium Uranium. CANDU est une marque de commerce déposée auprès du U.S. Patent and Trademark Office.

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# EQUILIBRIUM FUEL-MANAGEMENT SIMULATIONS FOR 1.2% SEU IN A CANDU 6

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## ABSTRACT

Fuel-management simulations have been performed for 1.2% SEU in a CANDU 6* reactor at equilibrium, for three fuel-management options:

1) axial shuffling,
2) a regular 2-bundle shift with the adjuster rods removed from the core,
3) a regular 2-bundle shift with the adjuster rods present.

Both time-average and time-dependent simulations were performed, from which the physics characteristics of the cores at equilibrium were estimated. Power and power-boost envelopes were derived for both 37-element fuel, and the advanced CANFLEX bundle.

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# EQUILIBRIUM FUEL-MANAGEMENT SIMULATIONS FOR 1.2% SEU IN A CANDU 6

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## INTRODUCTION

### Background

The use of slightly enriched uranium (SEU) fuel in CANDU* offers many benefits(1,2). At the optimal enrichment of about 1.2%, fuel-cycle costs are reduced by about 25% compared to natural uranium fuel; the amount of energy derived from the mined uranium increases by 30%; burnup increases by a factor of three over natural uranium, resulting in a three-fold reduction in the amount of spent fuel produced per unit of energy; and in new reactors, enrichment offers greater flexibility in design.

The use of enrichment in CANDU does pose some challenges. The achievement of the same outstanding level of fuel performance at extended burnups as at natural uranium burnups is more demanding, especially if power maneuvering is required. Fuel-management strategies are key to ensuring acceptable fuel performance, as well as in maintaining bundle and channel powers within acceptable limits. Enrichment also affects reactor control and the response of the reactor and the fuel in postulated accident scenarios.

In order to meet these challenges with the highest degree of assurance, Atomic Energy of Canada Limited has developed an advanced fuel bundle, called CANFLEX (CANDU flexible fuelling) (3,4,5). This advanced bundle continues the trend of increased subdivision in successive CANDU bundles, featuring 43 elements arranged in four rings, with two pin-sizes (the pins in the inner two rings are larger than in the outer two rings). The increase in the number of pins and the grading of pin sizes results in ≈20% reduction in peak linear element ratings over the 37-element bundle (for a given bundle power). This reduction in ratings, along with changes to the pellet design, facilitate the achievement of higher burnups. The lower ratings are also in line with world-wide trends towards greater safety margins, and result in lower fuel temperatures during postulated large-break LOCAs. Additionally, boundary-layer flow-disturbers increase the critical channel power (CCP) by about 8%, providing increased operating and safety margins. The bundle will be compatible with fuel-handling equipment in existing and future reactors. Hence, the CANFLEX bundle is the optimal vehicle for introducing enrichment in CANDU.

### Fuel Management with Enriched Fuels

Enriched fuels necessitate different fuel-management strategies than for natural uranium fuel, because the initial reactivity is greater, and there is a greater variation of reactivity with burnup. The central location of the adjuster rods also complicates fuel-management with enriched fuels, because the flux and power tend to be depressed near the adjusters. Several fuel-management options have been identified for 1.2% SEU fuel, including the checkerboard fuel-management scheme(6), axial shuffling, a regular 2-bundle shift, and two-pass refuelling(7). In new reactors, reactivity devices, and in particular, adjuster rods, can be relocated to facilitate the use of a variety of fuel types( 8).

This paper looks in detail at three fuel-management options for 1.2% SEU in a CANDU 6 reactor:

1) axial shuffling,
2) a regular 2-bundle shift with the adjuster rods removed from the core,
3) a regular 2-bundle shift with the adjuster rods present.

Axial Shuffling. This fuel-management option provides the greatest flexibility in shaping the axial power distribution. Axial shuffling involves removing some or all of the bundles from the channel, rearranging the bundles in pairs, and reinserting some of the fuel-bundle pairs back into the channel in a different order, along with fresh fuel. Axial shuffling is the reference fuel-management strategy for the CANDU 3(9), since all fuelling is done from one end of the reactor. Preliminary studies indicate that axial shuffling is feasible in other CANDU reactors as well, although in some cases hardware changes may be needed.

The ease of application, and the number of bundles which can be removed from the channel, depend on several factors. For instance, the fuelling machine magazine capacity must be sufficient to hold all of the bundles discharged from the channel, the fresh bundles which are to be inserted into the channel, and other components, such as the channel closure and shield plug. The coolant flow must be sufficient to discharge all of the bundles.

The particular axial shuffling scheme chosen for this study was the best of several studied (10). The shuffling scheme is bi-directional, although in a reactor in which the fuelling is from one face of the reactor, such as in the CANDU 3, bi-directional fuelling can be "mimicked". If bundles are numbered from 1 to 12 starting at the "refuelling" end of the channel, then bundles are first loaded into positions 1 and 2. Upon subsequent fuelling operations, the bundles in positions 1 and 2 are shifted as follows:

1 → 5 → 3 → 9 → 7 → 11 → discharged

2 → 6 → 4 → 10 → 8 → 12 → discharged

The axial shuffling scheme was restricted to the central channels, in the vicinity of the adjuster rods. In the peripheral channels, a regular 2-bundle shift fuelling scheme was employed (Figure 1).

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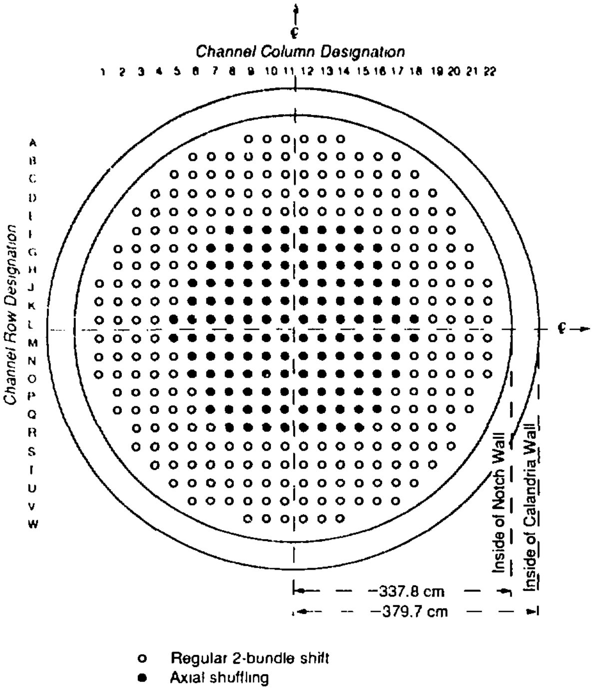


FIGURE 1: FACE VIEW OF REACTOR

Regular 2-bundle shift without adjusters. A regular 2-bundle shift fuelling scheme is near-optimal with 1.2% SEU, either in a core without adjuster rods, or in the peripheral channels of a core with adjuster rods. The axial power distribution peaks at the refuelling end of the channel, and decreases along the length of the channel. The axial form factor is good (i.e., the peak bundle power is relatively low for a given channel power). The margin to dryout for the equilibrium power distribution is increased if fuelling is in the direction of coolant flow, since the peak power then occurs at the inlet end of the channel, where the coolant enthalpy is lowest. Although these calculations are done for a CANDU 6 with the adjuster rods removed, it is expected that the general physics characteristics would apply also to Bruce A, in which there are no adjuster rods.

Regular 2-bundle shift with adjusters. When 1.2% SEU is employed with a regular 2-bundle shift fuel-management scheme in current reactors, the adjuster rods depress the power in the center of the channel. This results in a lower axial form factor ( i.e., a higher peak bundle power for a given channel power), and also in some power boosting at extended burnups.

## METHODOLOGY

### Outline of Method

For each of the three equilibrium fuel-management strategies, time-average calculations were performed to determine the average core properties such as burnup and refuelling rate, and the reference bundle and channel power distributions. The time-average calculation does not take into account refuelling ripples. To do this, an "instantaneous" calculation was first performed, which is meant to approximate a "snapshot" of the burnup and power distributions in the core at an arbitrary point in time. Then a time-dependent fuel-management simulation was carried out for each fuelling strategy, using the instantaneous calculation as the starting point. The refuelling simulations were carried out for 100 days, and from the simulations estimates of reactor core characteristics such as maximum powers were made, and the power and power-boost envelopes were derived.

### Reactor Model

The calculations were done for a CANDU 6 Mk I reactor, having 380 fuel channels, using the fuel-management code FMDP(11). To some extent, the results will be applicable to other reactor types. Figure 2 shows a top view of the reactor.

Cell-averaged cross sections for the FMDP model were calculated using the cell-code WIMS-AECL(12) for the CANFLEX bundle with 1.2% SEU. The transport calculation in WIMS was done in 20 energy groups, which were subsequently condensed to two energy groups using a critical spectrum. The burnup calculations were performed at the core-average fuel ratings, with critical bucklings.

Incremental cross sections for the reactivity devices were not specifically calculated for CANFLEX fuel: for the adjuster rods and zone controllers, values calculated in an earlier study for 1.2% MOX (mixed uranium/plutonium oxide) fuel were used; for the structural material, values appropriate for natural uranium were used. In general, the incremental cross sections have been found to be rather insensitive to fuel type.

### Time-average Calculations

In the time-average calculation, properties of the lattice cell were averaged over the dwell-time of the fuel, at each position in the core. The resultant flux and powers are indicative of what would be seen "on average". In reality there would be perturbations about the time-average distributions, due to refuelling, control rod action and so on. The time-average channel power distribution serves as the reference power distribution for actual refuelling.

In setting up the time-average model, the core is divided into irradiation zones, over which the average fuel discharge irradiation is constant. These irradiation zones are chosen to make the reactor critical (or to maintain some excess reactivity to account for parasitic absorption in the core which is not explicitly modelled). They also enhance the flattening of the radial channel power distribution provided by the adjuster rods (if they are present).

The water level in the zone control compartments was set to 45% full, representative of the normal operating conditions.

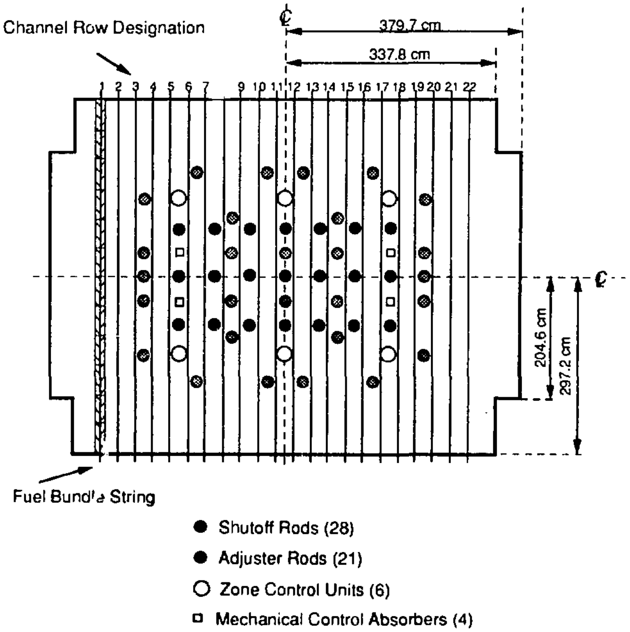


FIGURE 2: TOP VIEW OF REACTOR

## Instantaneous Calculations

The instantaneous calculation is meant to be a "snapshot" of the core power and burnup distributions at an arbitrary point in time. Every channel in the core is assigned an "age" -- a number between 0 and 1 which indicates the fraction of dwell-time between visits of the fuelling machine to the channel. A channel with an age of 0 has just been refuelled; a channel with an age of 1.0 has reached its target burnup and is about to be refuelled. The instantaneous irradiation of a bundle can be determined from its time-average irradiation, the fuelling scheme, and the channel age. In the instantaneous calculation, the channel ages range uniformly from 0 to 1, with an increment of 1/380 (380 channels in the core). In the past, a series of instantaneous calculations with a semi-random distribution of ages has sometimes been used to estimate core properties such as actual peak powers and refuelling ripples. However, any clustering of channel ages near 0 or 1 can result in large global tilts in flux and power, with large peak channel and bundle powers in one region of the core. With SEU fuel, the tilts in power resulting from a completely random age distribution are usually very large, and unrealistic. In this study, rather than "correct" for these global tilts in some rather arbitrary way, channel ages were assigned in such a way as to minimize global tilting, on the grounds that these tilts would be avoided in reality through careful selection of the channels for refuelling, and through the spatial control function of the zone controllers. The resultant instantaneous calculation was then used only as the starting point of the short time-dependent fuelling simulation.

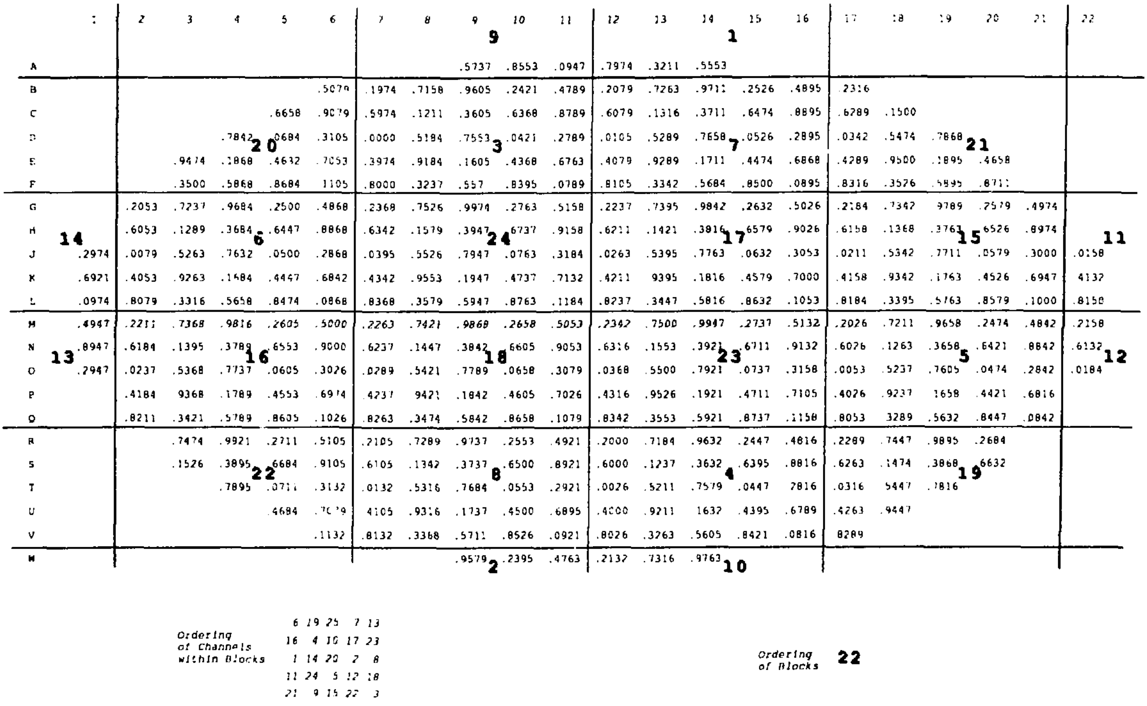
The following procedure was followed to arrive at a distribution of channel ages for the instantaneous calculation. The core was divided into 5x5 arrays of channels (Figure 3). In each 5x5 block, the channels were ordered, from 1 to 25 (shown in the lower left of Figure 3). This order was identical in each block. (Note that the peripheral channels did not occupy full blocks.) Next, each block was ordered (the large numbers shown in outline in Figure 3). Each channel was then assigned a number, starting from 0 and ending with 379, according to the order within the 5x5 blocks, and the order of the blocks. For instance, blocks 1 and 2 do not contain channel #1 (within the blocks). Hence, channel D-7 (channel #1 in block 3) was assigned the number 0; channel T-12 was assigned the number 1 (channel #1, block 4); channel O-17 was assigned the number 2 (channel #1, block 5); and so on until channel J-7, which was assigned the number 15 (channel #1, block 24); then the ordering continued, starting with channel #2 in block 1 (or the first block containing channel #2). Hence, channel D-10 was assigned the number 16 (channel #2 in block 3), and so on until all the channels in the core were assigned a number, ending with channel G-9 being assigned the number 379 (channel #25 in block 24). The channel age for each channel was then simply the number assigned to the channel, divided by the number of channels (380).

The resultant age map is shown in Figure 3. It is seen that the same location in each block has a similar age. From this age map, the irradiation and burnup of each bundle in the core was determined.

This method has several advantages. First, clustering of channels is avoided, at any age. The standard method of choosing a random distribution of channel ages, then removing clusters of channels with low age can still result in clusters of channels at higher ages. Although these channels may not produce a global tilt in power initially, if that distribution of channel ages is allowed to burn, and is refuelled, then at a later time, the cluster of channels having similar ages will need to be refuelled close together in time, and at that time a global tilt in power may result. Hence, if the instantaneous distribution is to be used as the starting point of a time-dependent fuel-management simulation, it is necessary to avoid clustering of channel ages about any age, not just low age. This method avoids this clustering. One can view this method as an attempt to define the order in which channels are to be refuelled. In practice, one attempts to spread out the refuelling of channels in a similar way, so as to avoid power peaking. Hence, this method aims for the smallest deviation from the time-average distribution, just as the refuelling engineer attempts.

The ripple, or deviation from time-average, resulting from this method is in fact smaller than what could be achieved in reality, and the time-dependent simulation is an effort at estimating more realistically the actual refuelling ripples and peak powers.

It has to be kept in mind that the results of the time-dependent refuelling simulation are influenced by the starting point, especially for a relatively short simulation such as this. In order to "forget" the starting point, the simulation would have to be continued for a longer period of time. Also, the burnup resulting from a short simulation starting from an instantaneous calculation will be somewhat low, since the exit burnups in the instantaneous calculation at the start of the simulation do not exceed the average exit burnup, while in reality there would be a distribution of burnups extending beyond the average exit burnup.



| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | | | | | | | | | .5737 | .8553 | .0947 | .7974 | .3211 | .5553 | | | | | | | | |
| B | | | | | | .5079 | .1974 | .7158 | .9605 | .2421 | .4789 | .2079 | .7263 | .9711 | .2526 | .4895 | .2316 | | | | | |
| C | | | | | .6658 | .9079 | .5974 | .1211 | .3605 | .6368 | .8789 | .6079 | .1316 | .3711 | .6474 | .8895 | .6789 | .1500 | | | | |
| D | | | | .7842 | .0684 | .3105 | .0000 | .5184 | .7553 | .0421 | .2789 | .0105 | .5289 | .7658 | .0526 | .2895 | .0342 | .5474 | .7868 | | | |
| E | | | .9474 | .1868 | .4632 | .7053 | .3974 | .9184 | .1605 | .4368 | .6763 | .4079 | .9289 | .1711 | .4474 | .6868 | .4289 | .9500 | .1895 | .4658 | | |
| F | | | .3500 | .5868 | .8684 | 1105 | .8000 | .3237 | .557 | .8395 | .0789 | .8105 | .3342 | .5684 | .8500 | .0895 | .8316 | .3576 | .5895 | .8711 | | |
| G | | .2053 | .7237 | .9684 | .2500 | .4868 | .2368 | .7526 | .9974 | .2763 | .5158 | .2237 | .7395 | .9842 | .2632 | .5026 | .2184 | .7342 | 9789 | .7579 | .4974 | |
| H | | .6053 | .1289 | .3684 | .6447 | .8868 | .6342 | .1579 | .3947 | .6737 | .9158 | .6211 | .1421 | .3816 | .6579 | .9026 | .6158 | .1368 | .3763 | .6526 | .8974 | |
| J | .2974 | .0079 | .5263 | .7632 | .0500 | .2868 | .0395 | .5526 | .7947 | .0763 | .3184 | .0263 | .5395 | .7763 | .0632 | .3053 | .0211 | .5342 | .7711 | .0579 | .3000 | .0158 |
| K | .6921 | .4053 | .9263 | .1684 | .4447 | .6842 | .4342 | .9553 | .1947 | .4737 | .7132 | .4211 | 9395 | .1816 | .4579 | .7000 | .4158 | .9342 | .1763 | .4526 | .6947 | 4137 |
| L | .0974 | .8079 | .3316 | .5658 | .8474 | .0868 | .8368 | .3579 | .5947 | .8763 | .1184 | .8237 | .3447 | .5816 | .8632 | .1053 | .8184 | .3395 | .5763 | .8579 | .1000 | .8158 |
| M | .4947 | .2211 | .7368 | .9816 | .2605 | .5000 | .2263 | .7421 | .9868 | .2658 | .5053 | .2342 | .7500 | .9947 | .2737 | .5132 | .2026 | .7211 | .9658 | .2474 | .4842 | .2158 |
| N | .8947 | .6184 | .1395 | .3789 | .6553 | .9000 | .6237 | .1447 | .3842 | .6605 | .9053 | .6316 | .1553 | .3921 | .6711 | .9132 | .6076 | .1263 | .3658 | .6421 | .8842 | .6132 |
| O | .2947 | .0237 | .5368 | .7737 | .0605 | .3026 | .0289 | .5421 | .7789 | .0658 | .3079 | .0368 | .5500 | .7921 | .0737 | .3158 | .0053 | .5237 | .7605 | .0474 | .2842 | .0184 |
| P | | .4184 | 9368 | .1789 | .4553 | .6974 | .4237 | 9421 | .1842 | .4605 | .7026 | .4316 | .9526 | .1921 | .4711 | .7105 | .4026 | .9237 | 1658 | .4421 | .6816 | |
| Q | | .8211 | .3421 | .5789 | .8605 | .1026 | .8263 | .3474 | .5842 | .8658 | .1079 | .8342 | .3553 | .5921 | .8737 | .1158 | .8053 | 3289 | .5632 | .8447 | .0842 | |
| R | | | .7474 | .9921 | .2711 | .5105 | .2105 | .7289 | .9737 | .2553 | .4921 | .2000 | .7184 | .9632 | .2447 | .4816 | .2289 | .7447 | .9895 | .2684 | | |
| S | | | .1526 | .3895 | .6684 | .9105 | .6105 | .1342 | .3737 | .6500 | .8921 | .6000 | .1237 | .3632 | .6395 | .8816 | .6263 | .1474 | .3868 | .6632 | | |
| T | | | | .7895 | .0711 | .3132 | .0132 | .5316 | .7684 | .0553 | .2921 | .0026 | .5211 | .7579 | .0447 | 7816 | .0316 | 5447 | .7816 | | | |
| U | | | | | .4684 | .7079 | 4105 | .9316 | .1737 | .4500 | .6895 | .4000 | .9211 | 1632 | .4395 | .6789 | .4263 | .9447 | | | | |
| V | | | | | | .1132 | .8132 | .3368 | .5711 | .8526 | .0921 | .8026 | .3263 | .5605 | .8421 | .0816 | 8289 | | | | | |
| W | | | | | | | | | .9579 | .2395 | .4763 | .2132 | .7316 | .9763 | | | | | | | | |

Ordering of Channels within Blocks

| | | | | |
|---|---|---|---|---|
| 6 | 19 | 25 | 7 | 13 |
| 16 | 4 | 10 | 17 | 23 |
| 1 | 14 | 20 | 2 | 8 |
| 11 | 24 | 5 | 12 | 18 |
| 21 | 9 | 15 | 22 | 3 |

Ordering of Blocks **22**

FIGURE 3: AGE MAP

### Time-dependent Fuelling Simulation

In order to estimate core characteristics such as peak powers and refuelling ripple, a time-dependent refuelling simulation was performed for 100 full-power days for each of the fuelling schemes, using the SIMULATE module in FMDP. Individual channels were selected for refuelling, and the flux and powers were calculated at 10-day intervals. The same instantaneous calculation was used as the starting-point in each of the simulations. By the end of the 100 day period, a total of 582 fuel bundles had been discharged from the core, corresponding to the refuelling of 291 channels. In selecting channels for refuelling, the following guidelines were followed:

1) The channel should have reached or exceeded its target burnup (more precisely, those bundles which would be discharged during refuelling should have reached their target burnup). Note that the channels with the highest age also tend to provide the highest reactivity increase on refuelling.

2) Candidate channels and their neighbours should not have high power or overpower before refuelling. This criterion minimizes power peaking resulting from refuelling, and generally complements the first one, since channel powers generally decrease with age.

3) Clustering of highly reactive channels or high power channels must be avoided. This guideline reduces global and local power peaking.

4) Fuelling should occur in symmetric parts of the core (both radially and axially). This criterion again aims at avoiding global tilts in the power distribution. Because of the asymmetric axial power profile with SEU fuel, it is much more important to maintain a balance in the number of channels refuelled in each direction than it is with natural uranium fuel.

5) The number of channels refuelled is determined by the need to maintain criticality.

The refuelling simulation was performed first for the axial shuffling scheme. Exactly the same channels were then refuelled for the other two cases (regular 2-bundle shift with and without adjuster rods). There are several reasons why the same channels could be refuelled in all three cases. Each case started from exactly the same age distribution (i.e., the fractional burnup of a particular channel at the starting point of the simulation was the same in each case). Hence, the choice of channels for refuelling at the start of the simulation would be the same (or very similar). The cases had similar power and flux distributions (in particular, the cases with adjuster rods present had nearly the same channel power distributions), and so would tend to "age" at the same rate. With a 2-bundle shift fuelling scheme, bundles have accumulated about 90% of their burnup by the time they reach the final position in the channel. Hence, refuelling a channel before it has reached its target burnup has a relatively minor effect on the average discharge burnup and peak powers.

The action of the zone controllers was not modelled during the simulation: the zone control fill was kept at 45% during the entire simulation. This approximation is conservative, since in practice the zone control fill changes in order to minimize the deviations in zonal power from the reference values.

Power and power-boost envelopes were derived from the results of the time-dependent refuelling simulation. Envelopes were calculated for both 37-element and CANFLEX fuel, in the following manner. FMDP stores the power and burnup of every bundle in the core (in the 'STORE' file), at each time-step in the simulation at which the flux is calculated. From the WIMS cell code, the relative element power and burnup distributions within the bundle are known as a function of average bundle burnup. Hence, the element power and burnup can be determined for each ring of fuel, for every bundle in the core, at each time-step in the simulation. The program PHISTRY(13) was used to do this, along with the FMDP 'STORE' file (containing the bundle power and burnup information) and the WIMS 'TAPE 16' (which contains the relative element power and burnup distribution as a function of average bundle burnup). PHISTRY produces a "scatter plot" of element power and corresponding element burnup for every bundle in the core, for each ring of fuel, for selected times in the simulation. From this "scatter plot" the power envelope is drawn as a smooth curve through the power/burnup points, such that no points lie above this envelope. Thus, the power envelope shows the maximum element power (or linear element rating) in the core, as a function of element burnup, for each ring of fuel.

Although the simulation was done using the CANFLEX bundle, power envelopes were deduced for the 37-element bundle by simply substituting the WIMS 'TAPE 16' corresponding to the 37-element bundle. PHISTRY then used the bundle powers and burnups in FMDP which were calculated using CANFLEX fuel, with the intra-bundle element power and burnup distributions appropriate for the 37-element bundle. This method assumes that the axial bundle power and burnup distributions would be similar for the two bundle types, which is a good approximation.

For the 37-element bundle, scatter plots of linear element rating (element power divided by element length) vs element burnup were calculated only for the outer ring of fuel, since the maximum power always occurs in this ring. The CANFLEX bundle has two pin sizes, and the location of the peak linear element rating shifts from the outer ring (ring 4) at low burnup, to ring 2 at bundle average burnups greater than about 7 MWd/kg (burnups are given in terms of heavy element mass). Hence, for the CANFLEX bundle, linear element ratings were calculated for both rings 2 and 4.

Power boost envelopes were derived in a similar manner to the power envelopes, using PHISTRY with input from FMDP and WIMS. PHISTRY computes the change in power for each bundle in the core between successive flux calculations. If a channel was refuelled during the time-step, the program uses the bundle powers at the new bundle position after refuelling, and at its old location before refuelling, to determine the change in power. WIMS is used to convert the average bundle power and average bundle burnup into element powers and burnups. PHISTRY produces a scatter plot of power boosts over the specified time interval.

## RESULTS

### Time-average Calculations

The time-average radial channel power distributions are illustrated in Figure 4 for a row of channels along the horizontal mid-plane of the core. With SEU fuel, there is greater opportunity for flattening the radial channel power distribution through "burnup flattening" (i.e., through the use of different irradiations, or refuelling rates, in different parts of the core) than with natural uranium fuel, because the resultant fractional burnup penalty is smaller. As a result, the peak channel powers in Figure 4 are lower than with natural uranium fuel. The channel power distributions for the cases with adjuster rods present are nearly identical. The flattening effect of the adjuster rods on the radial power distribution is clear. The radial form factor (ratio of average to peak channel power) is 0.88 with the adjusters present, and 0.86 with the adjuster rods removed from the core.

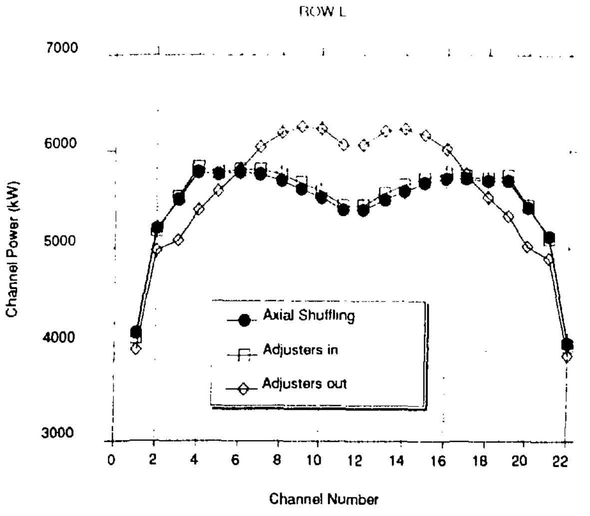


FIGURE 4: RADIAL CHANNEL POWER PROFILES

In operating reactors, channel flows and/or coolant inlet temperatures are chosen to match the channel power distribution with natural uranium fuel. Hence, in practice it may not be possible to use SEU in operating reactors to realize the degree of flattening achieved here. SEU provides great flexibility in shaping the channel power distribution, and a channel power distribution corresponding to natural uranium fuel could as easily be achieved, if so desired. The powers and power envelopes calculated in this study can be renormalized to another value of peak time-average channel power, by multiplying by the ratio of the desired peak time-average channel power to the peak time-average channel power in this study.

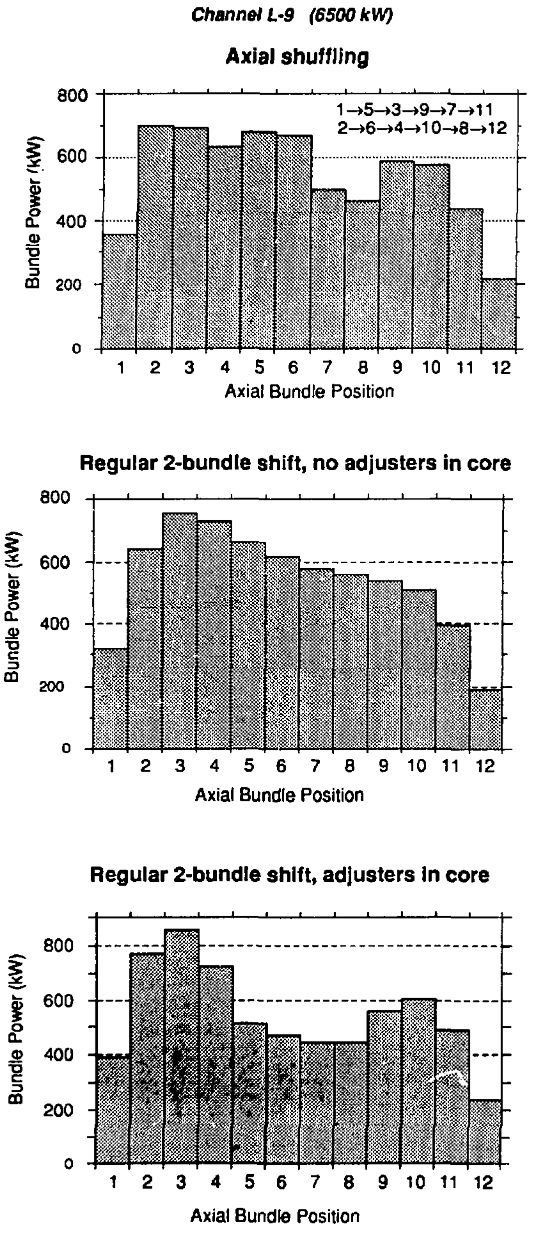


**FIGURE 5: TYPICAL TIME-AVERAGE AXIAL POWER PROFILES**

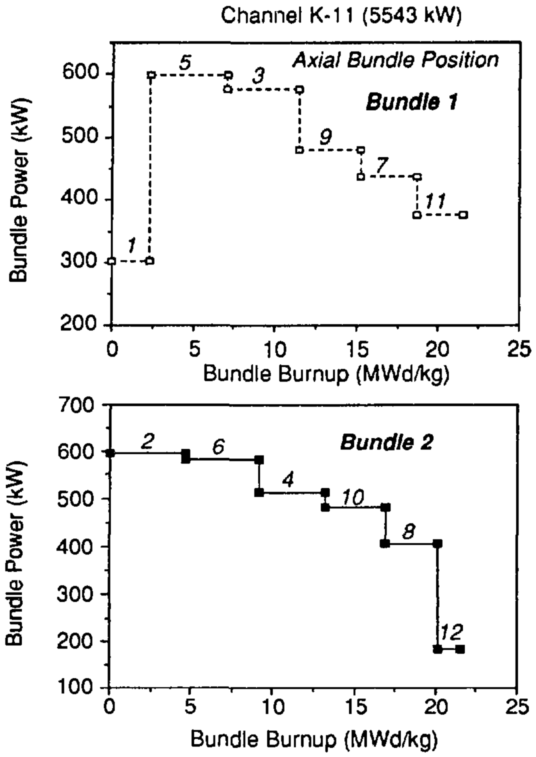


**FIGURE 6: TIME-AVERAGE BUNDLE POWER HISTORY, AXIAL SHUFFLING**

Figure 5 illustrates the axial time-average bundle power profiles for a central channel for all three cases, normalized to the same channel power (6500 kW). The greatest degree of axial flattening is achieved with the axial shuffling fuel-management scheme. In other words, this fuel-management option yields the lowest bundle power for a given channel power. The regular 2-bundle shift scheme with no adjusters in the core also results in a good axial form factor. In this case, the power distribution peaks at the third bundle from the refuelling end of the channel, and decreases monotonically along the length of the channel. With a regular 2-bundle shift scheme, the adjuster rods depress the power in the center of the channel, resulting in a larger peak bundle power for a given channel power, and an asymmetrical double hump in the axial power distribution.

The effect of the axial power distribution on the critical channel power (CCP) has been studied for the time-average equilibrium axial power distribution corresponding to a regular 2-bundle shift fuelling scheme with no adjuster rods(14). In this case, the CCP is about 4% greater if the direction of fuelling and the direction of coolant flow are the same, than if they are in opposite directions.

From the time-average power and burnup distributions, power histories can be constructed, which show the variation of bundle power and bundle burnup as a bundle gets shifted along the channel. These are illustrated in Figures 6 through 8 for a typical central channel for the three fuel-management options. These are particularly enlightening in this study, since the time-dependent fuel-management simulations were not carried out for a long enough period of time to follow any bundles completely through the channel. While the time-average histories do not show the variations in power due to refuelling, they do indicate the general features that can be expected in typical power histories. The power histories for axial shuffling and a regular 2-bundle shift without adjusters are remarkably similar (Figures 6 and 7), and are excellent from the point of view of fuel performance. Power boosting is either not present (bundle 2 for axial shuffling), or occurs only for relatively fresh fuel, which is resilient to power boosts. For the case of a regular 2-bundle shift with the adjuster rods present, power boosts of at least 100 kW will occur at higher burnups in shifting from positions 7 to 9, and 8 to 10 (Figure 8).

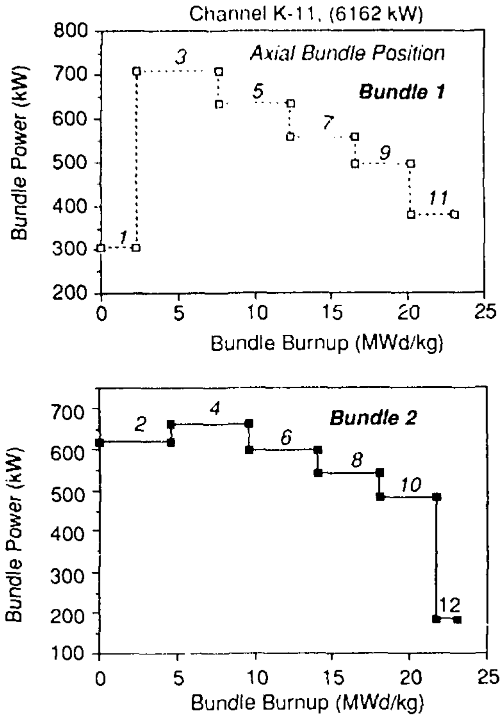


FIGURE 7: TIME-AVERAGE BUNDLE POWER HISTORY, ADJUSTERS OUT

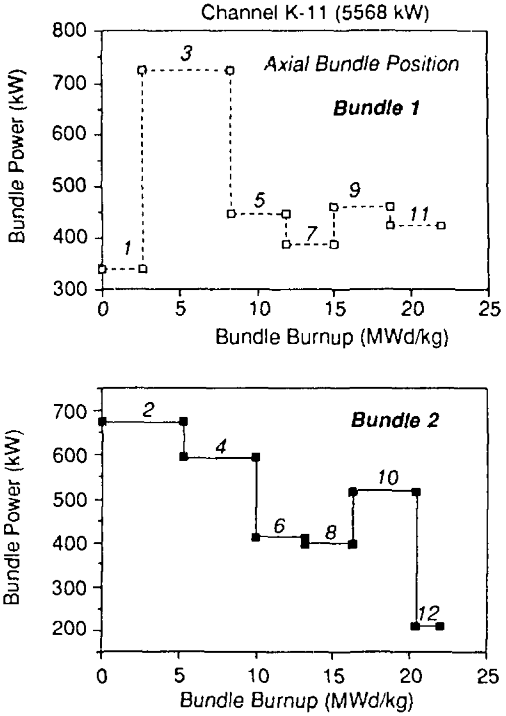


FIGURE 8: TIME-AVERAGE BUNDLE POWER HISTORY, ADJUSTERS IN

Further time-average results are given in Table 1. In each case, $k_{eff}$ is close to 1.000. The axial shuffling fuel-management scheme results in the lowest peak bundle and channel powers. For a regular 2-bundle shift fuelling scheme, while the radial channel power flattening is greater with adjuster rods present, the axial flattening is better when the adjuster rods are removed. In fact, the greater axial flattening for the case without adjusters more than compensates for the lack of radial flattening, and the peak bundle power is lower with adjuster rods removed. Note too that greater radial channel power flattening could be achieved without adjuster rods, through adjusting the burnup distributions of the core. It is also interesting to note that the burnup for the case without adjuster rods is not much higher than for the other cases.

The reactivity worths of some of the control devices are also given in Table 1. The worth of the adjuster rods is 11.1 mk with axial shuffling, and 8.2 mk for a regular 2-bundle shift. The reactivity required to compensate the increase in xenon during 30 minutes following shut-down from full power (i.e., 30 minutes xenon over-ride time) has not been calculated in this study, but has been calculated in earlier studies(8). In particular, it has been found that WIMS provides a good estimate of the xenon reactivity transient, as long as normalization is to the flux-squared average thermal flux, obtained from a reactor calculation. The reactivity required for 30-minutes xenon over-ride time has been calculated for a core with repositioned reactivity devices, using both WIMS, and a 3-dimensional spatially-dependent model. With 1.2% SEU, the reactivity required for 30 minutes xenon over-ride time is about 9 mk. Assuming the xenon reactivity transient during a shutdown is linear over the first half an hour or so, then in the case of axial shuffling, the adjuster rods provide about 37 minutes xenon over-ride time, while in the case of a regular 2-bundle shift, the adjuster rods provide about 27 minutes xenon over-ride time. These estimates would have to be verified for the current core configurations by more detailed calculations, and with incremental cross sections for the adjuster rods calculated explicitly for 1.2% SEU.

The worth of the shut-off rods is about 80 mk for all three cases, which is judged to be ample static reactivity for shutdown purposes. The zone controller worth is also judged to be sufficient for both bulk and spatial control, in all three cases.

TABLE 1: TIME-AVERAGE RESULTS

| | Axial Shuffling | Adjusters in | Adjusters out |
|---|---|---|---|
| keff | 0.99968 | 0.99775 | 0.99942 |
| Maximum Bundle Power (kW) | 732 | 772 | 735 |
| Maximum Channel Power (kW) | 6144 | 6187 | 6323 |
| Average Burnup (MWd/kg) | 20.1 | 20.4 | 20.8 |
| Feed Rate (Bundles/day) | 5.7 | 5.62 | 5.52 |
| (Channels/day) | 2.85 | 2.81 | 2.76 |
| Adjuster rod worth (mk) | 11.1 | 8.2 | |
| Xenon over-ride time (minutes) | 37 | 27 | |
| Zone-control worth (mk) | 7.5 | 7.9 | 7.7 |
| Shut-off rod worth (mk) | 79 | 78 | 82 |

|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A |  |  |  |  |  |  |  |  | 948 | [illegible] | 1064 | [illegible] | [illegible] | [illegible] |  |  |
| B |  |  |  |  |  | 1019 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| C |  |  |  |  | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| D |  |  |  | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| E |  |  | 951 | 1032 | 1019 | 993 | 1029 | 964 | 1056 | [illegible] | 1004 | 1025 | 968 | 1048 | [illegible] | [illegible] |
| F |  |  | 1010 | 991 | 966 | 1056 | [illegible] | 1022 | 991 | [illegible] | 1053 | [illegible] | [illegible] | 992 | [illegible] | [illegible] |
| G |  | 1046 | 985 | 949 | [illegible] | 1003 | 1034 | 966 | 941 | 1016 | 1000 | 1029 | 972 | 942 | [illegible] | 994 |
| H |  | 1018 | 1048 | [illegible] | 983 | 964 | 986 | 1036 | 1002 | 974 | 952 | 986 | [illegible] | 1011 | 978 | [illegible] |
| J | 1056 | 1073 | 1011 | 974 | 1065 | 1032 | 1056 | 989 | 964 | 1040 | 1022 | 1050 | [illegible] | 969 | [illegible] | [illegible] |
| K | 992 | 1020 | 947 | 1040 | 1004 | 981 | 996 | 939 | [illegible] | 942 | 967 | 998 | 942 | 1026 | [illegible] | [illegible] |
| L | 1055 | 966 | 1010 | 975 | 954 | 1032 | 952 | 989 | 964 | [illegible] | [illegible] | 949 | 996 | [illegible] | [illegible] | [illegible] |
| M | 999 | 1025 | [illegible] | 928 | 1006 | 987 | 1012 | 952 | [illegible] | [illegible] | 979 | 1012 | 952 | [illegible] | 1008 | [illegible] |
| N | 955 | 983 | 1034 | 996 | 968 | 944 | 975 | 1021 | 994 | [illegible] | 944 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| O | 1016 | 1044 | 981 | 957 | 1039 | [illegible] | 1042 | 984 | 956 | [illegible] | 1014 | 1044 | 985 | 964 | [illegible] | [illegible] |
| P |  | 986 | 934 | 1013 | 990 | 964 | 992 | 934 | 1015 | 990 | 969 | [illegible] | [illegible] | 1019 | [illegible] | [illegible] |
| Q |  | [illegible] | 975 | 958 | 934 | 1024 | 945 | 992 | 965 | 946 | [illegible] | 955 | [illegible] | [illegible] | [illegible] | 1042 |

FIGURE 9: CHANNEL OVERPOWER MAP, AXIAL SHUFFLING

### Instantaneous Calculations

Figure 9 illustrates the channel over-power map for part of the core in the instantaneous calculation for the case with axial shuffling. The over-power (or ripple) of a channel is simply the ratio of the channel power to the time-average power of that channel (multiplied by 1000 in Figure 9). If a channel has an over-power equal to 1.0, then its instantaneous power is equal to its time-average power. By relating the over-power map in Figure 9 to the age map in Figure 3, it is seen that high over-powers correspond to low ages (i.e., to channels which have been recently refuelled), while low over-powers correspond to ages approaching 1 ("old" channels which are about to be refuelled). The peak over-power for channels not on the core boundary is 1.090, occurring at channel O-20. The peak channel power is 6412 kW, (channel O-17).

### Time-dependent Fuelling Simulations

The key results of the simulation are presented in Figure 10. For the cases with the adjuster rods present in the core (axial shuffling and regular 2-bundle shift), $k_{eff}$ shows a variation of about 0.5 mk about its average value, with a slight tendency to increase over the last half of the simulation. With adjusters out, $k_{eff}$ increases more, by about 2 mk over the last half of the simulation. The reason for this is that the equilibrium refuelling rate for the case without adjusters is about 3% lower than for the other cases (Table 1). However, the same refuelling rate was used in the simulation for each case, since exactly the same channels were refuelled during each time-step between flux calculations. The refuelling rate could have been lowered by 3% in the case without adjusters, while refuelling the same channels as in the other cases, by increasing the length of the time-steps by 3%.

The channel power peaking factor (CPPF) is a measure of the refuelling ripple, and is defined here as the largest channel over-power (ratio of channel power at a point in time to the time-average power of that channel), taken over channels having an instantaneous power of at least 90% of the peak channel power at that point in time. The CPPF is an important parameter in the method currently used in calibrating the neutron over-power (NOP) detectors to determine the operating margin. The method involves the periodic calculation of the channel power distribution to determine the current value of CPPF. It is conservatively assumed that the actual power distribution equals the time-average or reference distribution, scaled up by the calculated CPPF. Hence, the maximum over-power is applied to all channels, rather than to the single channel to which it actually applies.

It is usual to restrict the calculation of the CPPF to either the channels having an instantaneous power greater than 0.9 of the maximum channel power at that time, or to the high-power region of the core. The peak over-power for the whole core often occurs in a peripheral channel, which may have a larger margin to dryout than the other channels. For instance, at 40 days in this simulation, with the axial shuffling fuel-management scheme, the largest over-power for the whole core was 1.244, and occurred in the peripheral channel E-3. The location of the largest over-power remained at this channel for the rest of the simulation.

The average CPPF over the simulation is 1.11 for all three cases (calculated for channels having an instantaneous power greater than 0.9 of the instantaneous maximum channel power). The CPPF is determined mainly by the enrichment and the number of bundles shifted, and the core configuration should have but a small effect on the CPPF. The value of CPPF for natural uranium using an 8-bundle shift fuelling scheme is about 1.10.

The variation of maximum channel power is almost identical for the two cases with adjuster rods present, yielding an average maximum of 6479 kW for the axial shuffling scheme, and 6503 kW for the regular 2-bundle shift. For the case without adjuster rods, the average maximum channel power is 6816 kW, 5% greater than the other two cases. The average peak bundle powers over the simulation are 777 kW for the axial shuffling scheme, 868 kW with adjusters present, and 829 kW with adjusters absent. The peak powers are well within limits, even allowing for uncertainty in the modelling. The axial shuffling scheme has very low peak channel and bundle powers.

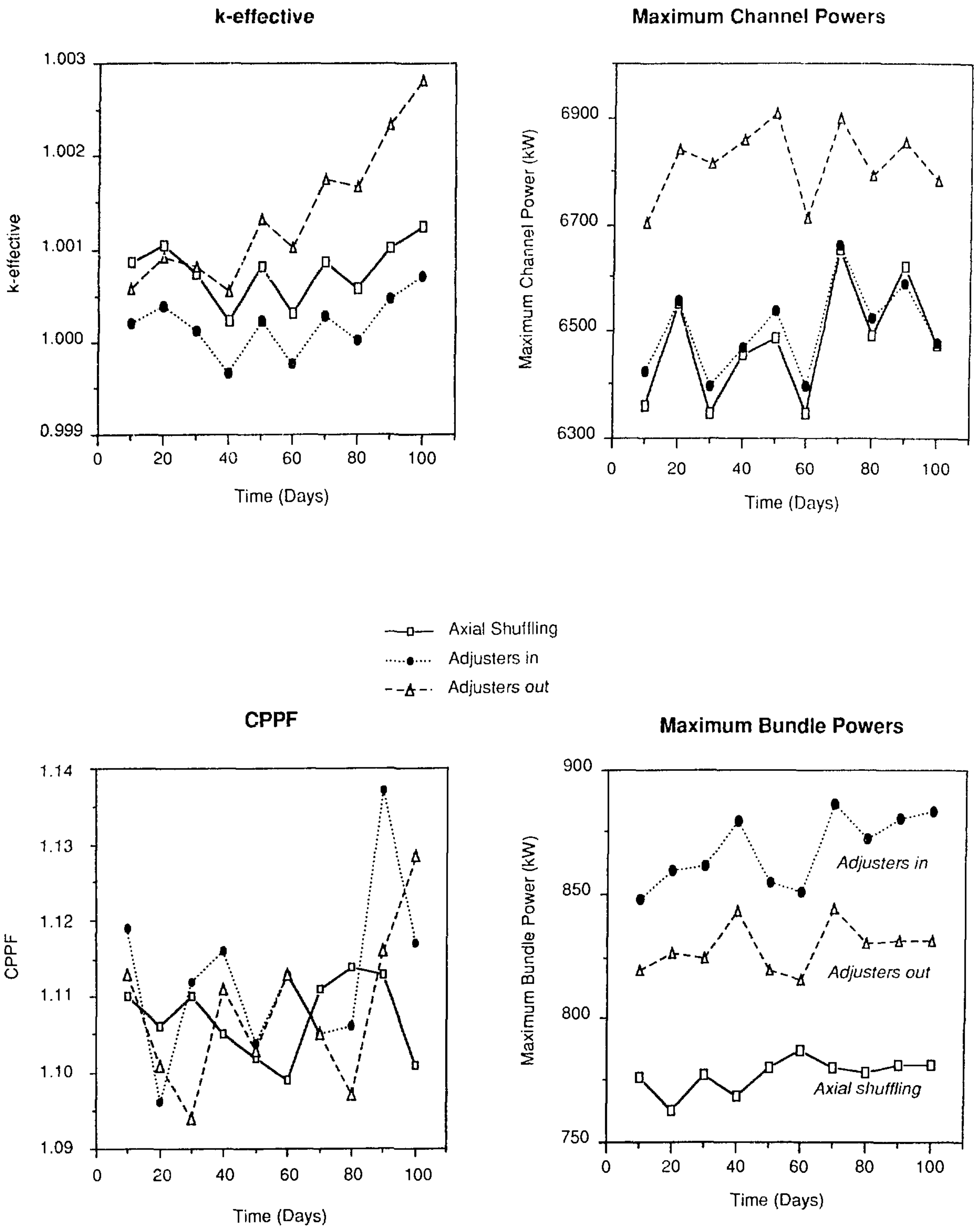


**FIGURE 10: RESULTS OF REFUELLING SIMULATION**

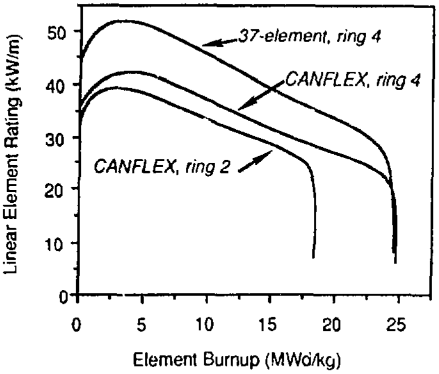


FIGURE 11: PIN POWER ENVELOPES, AXIAL SHUFFLING

The pin power envelopes are shown in Figure 11 for the case with axial shuffling at 70 full-power-days in the simulation, a time at which the peak powers were near their maximum values. Envelopes are shown for ring 4 of the 37-element bundle, and for rings 2 and 4 of the CANFLEX bundle. With axial shuffling, the power envelope for ring 4 of the CANFLEX bundle is always greater than for ring 2, regardless of burnup. The power envelopes peak at about 3 MWd/kg, and thereafter decline monotonically with increasing burnup. The power envelope for the outer ring of the CANFLEX bundle is about 20% lower than for the 37-element bundle. The peak linear element rating is 41 kW/m in the CANFLEX bundle, and 52 kW/m in the 37-element bundle. One would expect very little fission gas release at these low CANFLEX ratings. Recent calculations of CANFLEX fuel performance during a postulated LOCA have verified the expected very low strains at these low power levels, and the consequent benefits in terms of safety (15).

The power envelopes for a regular 2-bundle shift fuelling scheme in a core without adjuster rods are similar to those for axial shuffling, and are not shown here. The peak ratings are slightly greater than for axial shuffling -- 45 kW/m for the CANFLEX bundle, and 56 kW/m for the 37-element bundle. With the CANFLEX bundle, most of the fuel in the core is below 40 kW/m.

With a regular 2-bundle shift fuelling scheme with adjusters in the core, the power envelopes show a slight increase at high burnup, due to the asymmetric double hump in the axial power distribution caused by the adjuster rods (Figure 12). The peak fuel ratings are 47 kW/m for the CANFLEX bundle, and 58 kW/m for the 37-element bundle. The power envelope for ring 2 of the CANFLEX bundle is greater than for ring 4 at burnups between 12 and 17 MWd/kg.

The power-boost envelopes are very similar for the case of axial shuffling, and a regular 2-bundle shift fuelling scheme in a core without adjuster rods (Figure 13 shows the power-boost envelope for the 2-bundle shift without adjusters). Sizable power boosts occur only at small burnups, when the fuel is resilient to power boosting. With the 37-element bundle, the largest power boosts are 36 kW/m at an element burnup of 3 MWd/kg. The power boosts decline monotonically with increasing burnup, having values of 9 kW/m at a burnup of 11 MWd/kg, and 3 kW/m at 20 MWd/kg. With CANFLEX fuel, the power boosts decline from a peak of 29 kW/m at an element burnup of 3 MWd/kg, to 7 kW/m at 11 MWd/kg, and 2 kW/m at 20 MWd/kg.

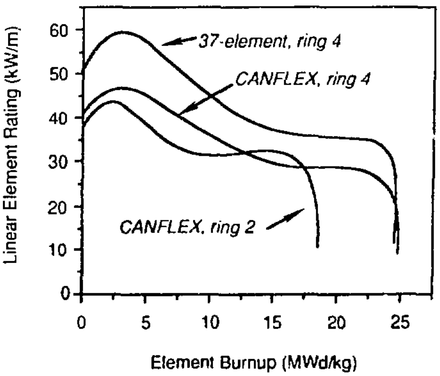


FIGURE 12: PIN POWER ENVELOPES, ADJUSTERS IN

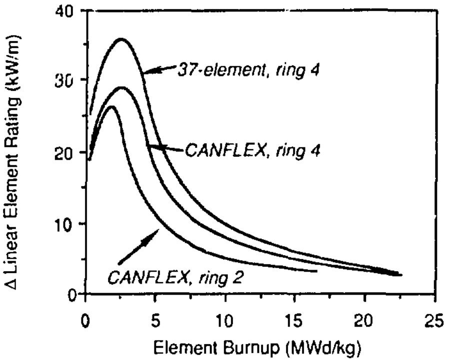


FIGURE 13: POWER BOOST ENVELOPES, ADJUSTERS OUT

The power-boost envelopes with the adjusters in the core show power-boosting at higher burnups (Figure 14). With the 37-element bundle, power-boosts of 12 kW/m occur at an element burnup of 18 MWd/kg, while with CANFLEX fuel, these boosts are reduced to 10 kW/m. While this is not optimal from the fuel performance point of view, it is judged that the CANFLEX bundle will be able to withstand these power-boosts, due to optimization of the pellet design.

There are other sources of power boosting. One arises from the transient changes in power during the actual refuelling operation, as the bundles move along the channel. These transients could be particularly important with axial shuffling, since the entire channel is emptied during refuelling. Power-boosting would also occur with load-following. The power-boost envelope arising from load-following would simply be the steady-state power envelope, scaled down by some fraction depending on the extent of loading-following. Each of these situations differ in the time over which the power ramp occurs, and the time at the ramped power.

In assessing fuel performance at extended burnup under these operating conditions, we are faced with the fact that our current data-base is insufficient to predict with certainty the performance of either the 37-element or CANFLEX bundles. However, our experimental data-base and our fuel models give us confidence that the lower ratings, and internal design modifications in the CANFLEX bundle, will lead to a defect rate which is equal to or lower than that currently achieved with natural uranium fuel. This will be confirmed through in-reactor testing under the CANFLEX program(3,4,5).

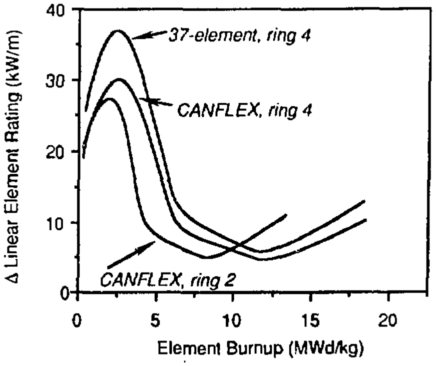


FIGURE 14: POWER BOOST ENVELOPES, ADJUSTERS IN

## SUMMARY

### Axial Shuffling

In the central channels near the adjuster rods, axial shuffling is an excellent fuel-management option with 1.2% SEU, from the reactor physics and fuel performance perspectives. Axial shuffling provides good flattening of the axial power distribution, with low peak powers. With the CANFLEX bundle, the ratings of almost all of the fuel elements in the core can be reduced to below 40 kW/m, with significant operational and safety benefits. The average peak bundle and channel powers during the time-dependent fuel-management simulation were very low: 777 kW and 6479 kW respectively, while the average CPPF was 1.11. Axial shuffling results in a declining power history, with very little power boosting at extended burnup as a result of refuelling. The reactivity worths of control devices with axial shuffling is ample. Preliminary assessments indicate that axial shuffling is feasible in all CANDU reactors. Further studies are needed to address the details of fuel handling in CANDU 6 and Bruce-type reactors, and to determine the transient powers during refuelling, and their impact on fuel performance and flux detector readings.

### Regular 2-Bundle Shift with Adjuster Rods Absent

This option provides an indication of what might be expected in using a regular 2-bundle shift fuelling scheme with 1.2% SEU in the Bruce A reactors, in which there are no adjuster rods. This is a very attractive fuel-management option, especially if the direction of fuelling and coolant flow are the same, which would increase the margin to dryout. While the axial flattening is not as great as with axial shuffling, it is about the same as that provided by the adjuster rods with natural uranium fuel. The axial power distribution is excellent from the viewpoint of fuel performance, with the power peaking at the refuelling end of the channel and decreasing along the length of the channel. Hence, significant power boosting during refuelling occurs only for relatively fresh fuel. In the refuelling simulation with the CANFLEX bundle most of the fuel in the core was at ratings below 40 kW/m. Average peak bundle and channel powers during the simulation were low, 829 kW and 6816 kW, respectively. The average peak channel power was greater than in the other two cases, due to less radial flattening of the channel power distribution with no adjuster rods. The CPPF was 1.11.

### Regular 2-Bundle Shift with Adjuster Rods Present

This fuel-management option results in an asymmetric axial power distribution, with the adjuster rods pulling down the power in the center of the channel. As a result, there is some power boosting at extended burnup: at a burnup of 20 MWd/kg, there are increases in linear element ratings of about 11 kW/m. However, it is judged that the CANFLEX bundle will be able to handle this power history without excessive fuel failures, due to the optimization of the pellet design. The worths of the reactivity devices are adequate, although the xenon override time is slightly reduced. The average peak bundle and channel powers during the refuelling simulation were acceptable: 868 kW and 6503 kW respectively, while the CPPF was 1.11. While this is not the optimal fuel-management strategy with 1.2% SEU from the physics and fuel performance perspectives, it is the simplest option, and hence one which should be given due consideration, especially since the CANFLEX bundle should be able to provide acceptable fuel performance.

### CANFLEX vs 37-element

With any of these fuel-management options, the fuel performance data-base at extended burnups is not sufficient to predict with certainty the performance of either the 37-element or CANFLEX bundle, especially if load-following capability is required. The CANFLEX bundle features a 20% reduction in peak element ratings, and optimization of the pellet design for extended burnup. These features provide confidence that the CANFLEX bundle will be able to meet the duty-cycle required for 1.2% SEU with low probability of fuel defect. The CANFLEX program now in progress will help to confirm this.

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