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The Burnable Poisons Utilization for Fissile Enriched CANDU Fuel Bundle

Dumitru Serghiuta, Ovidiu Nainer

Team 3 Solutions
100 Graydon Hall Drive, Suite 205, Don Mills, CANADA, M3A 3A7

ABSTRACT

Utilization of burnable poison for the fissile enriched fueled CANDU 6 Mk1 core is investigated. The main incentives for this analysis are the reduction of void reactivity effects, the maximization of the fissile content of fresh fuel bundle and the achievement of better power shape control, in order to preserve the power envelope of the standard 37 rod fuel bundle.. The latter allows also the preservation of construction parameters of the standard core (for example: number and location of reactivity devices). It also permits the use of regular shift fueling schemes. The paper makes an analysis of MOX- weapons-grade plutonium- and 1.2% SEU fueled CANDU 6 Mk 1 core.

I. INTRODUCTION

Burnable poisons are often used in PWR fuel assemblies to compensate the initial reactivity excess, to flatten the radial power shape and to achieve higher discharge burnup.

Burnable poisons are not attractive for natural uranium fueled CANDU reactors, for neutron economy reasons. However, there are good reasons for using burnable poison in fissile enriched fueled CANDU reactors:

- to reduce void effects;
- to maximize the fissile content of fresh fuel bundle;
- to suppress the initial reactivity excess and to reduce the maximum rod power, in order to preserve the power envelope of the standard 37 rod fuel bundle;
- to control the power shape, which permits conservation of present construction parameters of the core as well as use of simple- regular shift- fuel-management schemes.

A first analysis of burnable poison utilization to control the power shape was presented in [1] for the case of 1.2% SEU fueled CANDU 6 MkI core. The objective of the analysis was the use of regular shift fueling schemes, as opposed to the more involved "advanced schemes", usually proposed for the SEU fueled core. The analysis of an equivalent 35 ppm B^{10} added to 1.2% SEU fuel revealed the following aspects:

- Adequate control of radial and axial power shape is obtained. Radial flattening and axial depression compensation are achieved.
- A four-bundle shift refueling scheme can be used. In spite of the higher CPPF, lower maximum bundle power is attained.
- Good fuel operating conditions are achieved. The lack of high burnup power boosts and the low linear power rating permit the use of standard 37 rod fuel bundle.
- The maximum discharge burnup penalty is of only 7.1%, compared to the no poison SEU fuel case.
- Significant reduction of the void effect is achieved (17.2 mk compared to 22.5 mk for no poison 1.2% SEU, and 20.8 mk for natural uranium- fresh fuel).

The purpose of this work was to investigate the ways to use the burnuble poisons for MOX- weapons-grade plutonium- CANDU 6MkI core, in order to obtain a zero void reactivity fuel bundle and to preserve the power envelope of the standard 37 rod fuel bundle for a large fissile content in fresh fuel.

In Section II we present the methodology, reactor model and computer programs used. The results are presented in Sections III. Finally, in Section IV, the conclusions and a discussion are provided.

II. METHODOLOGY

The enriched CANDU fresh fuel displays higher reactivity than the natural uranium one and, therefore, greater power ripples, due to refueling, tend to appear. These problems are amplified in the particular case of Pu^{239} enriched fresh fuel, due to the higher fission microscopic cross section and fission energy for Pu^{239} than the U^{235} one.

The aim to maximize the fissile content of fresh fuel bundle and to preserve the power envelope of the standard 37 rod fuel bundle can be reached by suppressing the excess reactivity and reducing the bundle radial form factor, or the maximum rod power.

For a CANDU cell, the loss of coolant leads to a reactivity increase, caused mainly by the significant decrease in the resonance integral - due to the increase in the mutual shielding between elements - that causes resonance absorbtions to decrease. Spectral changes, due to rethermalisation, influence the reactivity in a lesser extent.

A solution to suppress the reactivity excess and to reduce the void effects is to increase the fuel absorbtions by using burnable poison.

The analysis of the burnable poison utilization was performed in two steps:

1. Cell calculations - performed for cell parameter evolution with burnup analysis.
2. Core calculations - performed for equilibrium power shape analysis (time-average calculations) and for refueling overpower analysis (instantaneous calculations).

II. 1. Cell Calculations

Cell calculations were performed using the LATREP-T3S code, a modified version of LATREP-CYCLE 4[1]. The main modifications and improvements are:

- two new subroutines, MACON and COMIC, for data processing in order to obtain the two-group diffusion constants, the power distribution in fuel bundle for each burnup step, the integrated multiplication coefficient, the discharge burnup and the average residence time.

- the burnup routine was modified to account for the B^{10} isotope.
- an iterative procedure on flux level in fuel to assure an imposed fission power density.
- an option to perform fuel bundle irradiation in a definite flux distribution and for a given axial refueling scheme.
- a simplified procedure for reactivity effects calculations, similar to the procedure used in POWDERPUFS-V code.

The presence of the burnuble poison in a standard 37 rod fuel bundle was simulated by an equivalent quantity of B^{10}. A value of 25.84 w/gHE, for fission power density, and 45 mk, as excess reactivity for integrated multiplication coefficient, were considered.

II. 2. Core Calculation

The use of enriched fissile fuel requires fuel management schemes different from the case of natural uranium one. This is due mainly to the higher initial reactivity and reactivity decrease (with burnup) rate. The central location of the adjuster rods also complicates fuel-management enriched fuels, because the flux and power tend to be depressed near the adjusters.

On-power refueling is one of the main specific elements of the CANDU standard core used to compensate for the reactivity loss due to fuel burnup. It also provides a means for controlling the flux and power distributions in order to comply with the power restrictions, imposed by thermal-hydraulic conditions and fuel bundle behavior, as well as assuring satisfactory operational limits. It is for this reasons that choosing the refueling scheme is one of the major physics problems during the design phase as well as in the course of reactor operation.

Two types of calculations are mainly required in fuel-management analysis:

- those used to determine the nominal power and burnup distributions
- those used to determine instantaneous distributions ,which include the time varying fine structure of the power distributions, in order to evaluate the CPPF (Channel Power Peaking Factor) and BPPF (Bundle Power Peaking Factor).

The fueling scheme and core characteristics (number of burnup zones, discharge burnup for each zone) were chosen, based on the analysis, in such a manner that they comply with the maximum bundle and channel power limits.

Computations were made for a CANDU 6MK1 core using the fuel-management code SERA[2] . The code is based on the AECL method and includes some improvements and supplementary facilities[3] . The code can use cell parameters, data files generated with either LATREP or WIMS code. The results in this paper are obtained using the LATREP-T3S code.

Adjuster rods were modeled by their thermal absorption increments using the same values as for natural uranium fuel. The zone controller system was taken into account using the same increments as for the natural uranium fuel and a water level of 45% (a representative level for the usual operating conditions). The rest of reactivity devices was taken into account by means of a reactivity excess of 2 mk.

The equilibrium power and burnup distributions were computed using the time-average method. Reference burnup and power distributions as well as channel residence times and average refueling rates were obtained from the time-average calculations. The basic methodology for the time-average calculation is largely described in literature.

Instantaneous power distributions were computed using a modified random age method[2]. The objective of the analysis was to determine the refueling overpowers and the power envelopes.

Power envelopes were derived from the results of the time-dependent refueling simulation. Envelopes were calculated in the following manner: SERA stores the power and burnup of every bundle in the core for each instantaneous situation. From LATREP (or 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 are be determined for each ring of fuel, for every bundle in the core, for each instantaneous situation simulated. A separated module in SERA was used to do that. This module produces a "scatter plot" of element power and corresponding element burnup for every bundle in the core, for each ring of fuel. From this "scatter plot" the power envelope is drawn as a smooth curve through the power burnup prints, 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.

III. MOX - Weapons-grade Plutonium - Fueled CANDU 6 MK1 core

High operating neutron flux, high neutron economy and on-power refueling make CANDU particularly suitable for the annihilation of weapons -grade plutonium [5]. The option being considered in this paper for disposing of weapons-grade plutonium is burning the plutonium in the form of a mixed UO_2 - PuO_2 fuel using standard 37 rod fuel bundle.

The source for uranium can be: recycled uranium from LWR, low enriched uranium from enriching plant or CANDU spent fuel. For this analysis the fuel consists in a mixed CANDU spent fuel (0.23% U^{235}, 0.25% Pu^{239}) and Pu^{239}.

The objectives of the study were as follows:

- to preserve the power envelope of the standard 37 rod fuel bundle;
- to reduce to zero the void reactivity effect for equilibrium fuel.

To illustrate the problems associated with Pu^{239} utilization, the integrated multiplication properties for equilibrium fuel are presented in Figure 1. Figures 2 presents the evolution of bundle radial form factor (maximum rod power to average rod power) with burnup, respectively.

The problems associated with the use of burnable poison are:

- how to dispose the absorbent material in the ring rods
- what kind of absorbent material responds better to the proposed objectives.

The problems were resolved by analyzing the effects of different radial grading for the absorbent material.

The burnable poison added to the fuel increases the fuel absorbtions, thus decreasing the initial reactivity and compensating for the decreased resonance absorbtions caused by the loss of coolant. For the same concentration of poison, the effect in initial reactivity excess is large, if the poison is placed in the high level flux region of the bundle, as is illustrated in Figure 3. The effect on bundle radial form factor is illustrated in Figure 4.

The effect on void reactivity coefficient diminishes with burnup, due to poison burning[6] To expand the effect for equilibrium fuel is necessary to attenuate the poison burning. This goal can be reached by:

- choosing a material with a low absorption microscopic cross section than for B^{10} one. Potential candidates are Er and Dy, materials used in nuclear industries.
- choosing a material with nuclides in disintegration chain having alike absorption microscopic cross sections. A candidate is Eu, a material used also in nuclear industries.
- placing the burnable poison in the inner ring rods, corresponding to the low level flux region of the bundle.

We simulated such a kind of burnable poison by an equivalent concentration of B^{10} placed in inner ring rods. The B^{10} concentration was kept constant for each irradiation step and was evaluated from the condition to obtain a zero void reactivity effect for equilibrium fuel.

Zero void reactivity effect for equilibrium fuel was reached for 2% B^{10} in inner ring rods, for 1.5% Pu^{239} enriched fuel bundle, and 1.35% B^{10} in inner ring rods, for 1.2% Pu^{239} enriched fuel bundle, respectively.

This objective is reached accepting a large penalty in discharge burnup (~70%). This penalty is attenuate by the low increase in spent fuel radiotoxicity, due to the accumulation of Pu^{241}, without implications in further waste disposal. The quantity of accumulated Pu^{241} is 3-4 time large than for natural uranium CANDU spent fuel bundle.

An acceptable power envelope, from fuel-management analysis, was obtained for 1-bundle shift refueling scheme, for the case of 1.5% Pu^{239} enriched fuel bundle. A 2-bundle shift refueling scheme is not acceptable , because the power envelope overpass 60 kW/m, the maximum linear power rating, as is illustrated in Figure 5. The main reasons are the large value, at low burnup, for the bundle radial form factor.

A significant attenuation of the initial reactivity excess and reactivity depletion rate, associated with a reduction of the bundle radial form factor, can be achieved using different enrichments for bundle rings. The results are illustrated in Figures 6, 7 for the configurations presented in Table 1.

For the fuel bundle with radial grading for the absorbent and fissile materials corresponding to Bundle D15 in Table 1, an acceptable power envelope was derived from fuel-management analysis. The main results are presented in Table 4 and Figures 8..

For 1.2% Pu^{239} enriched fuel bundle the optimal result is a fuel bundle with a composition presented in Table 2 (Bundle B12) and a 4-bundle shift refueling scheme. The main results from fuel-management analysis are illustrated in Table 4 and Figures 9.

A high priority level for refueling ratio (channels/day) than for discharge burnup was considered in the process of optimal solution search.

Opposite to the radial grading for the absorbent and fissile materials in fuel bundle presented are the solutions in Table 1 and Table 2 as Bundle CF15 and Bundle CF12, respectively. The fissile material is shared between the external rings, in a ratio corresponding to the rods ratio and flux depression. Such a solution leads to:

- an attenuation of bundle radial form factor
- an increase in initial reactivity excess

- an increase in reactivity depletion rate with burnup
- an increase in discharge burnup
- an increase in void reactivity effect, for the same amount of poison

compared to the case without radial grading of fissile material.

Acceptable power envelopes can be reached with 1-bundle refueling scheme, for 1.5% Pu^{239} enriched fuel bundle, and 2-bundle shift refueling scheme, for 1.2% Pu^{239} enriched fuel bundle, respectively.

A comparative presentation is illustrated in Table 4 and Figures 10. The main advantage of this solution is the gain in discharge burnup.

IV. CONCLUSIONS

The analysis of the burnable poison utilization for fissile enriched CANDU fuel bundle revealed the following aspects:

- the feasibility of weapons-grade plutonium burning in CANDU 6MkI core, in a form of mixed CANDU spent fuel and Pu^{239} , using the standard 37 rod fuel bundle.
- the optimal result is a fuel bundle with a combined different radial grading for the absorbent and fissile materials.
- a zero void reactivity effect can be reached accepting a large penalty in discharge burnup. This penalty is attenuate by the low increase in spent fuel radiotoxicity, due to the accumulation of Pu^{241}, without implications in further waste disposal.
- as burnable poison is proposed the use of Dy or Eu, materials used in nuclear industry.

In conclusion, the analysis undertaken proved the advantages of burnuble poison for enriched fissile CANDU fuel bundle and, with the results presented in [1], covers the main aspects regarding the burnuble poison utilization for enriched fissile CANDU fuel bundle.

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Table 1. Standard 37 rod fuel bundle configuration: Equivalent 1.5% Pu^{239} Enrichement

Bundle Type	***O15***	***B15***	***D15***	***F15***	***CF15***
Central Rod	1.5% Pu-239 2.0% B-10	1.7% Pu-239 2.0% B-10	1.9% Pu-239 2.0% B-10	2.1% Pu-239 2.0% B-10	0.25% Pu-239 2.0% B-10
1-st Inner Ring	1.5% Pu-239 2.0% B-10	1.7% Pu-239 2.0% B-10	1.9% Pu-239 2.0% B-10	2.1% Pu-239 2.0% B-10	0.25% Pu-239 2.0% B-10
2-nd Inner Ring	1.5% Pu-239	2.08% Pu-239	2.01% Pu-239	1.94% Pu-239	2.56% Pu-239
External Ring	1.5% Pu-239	1.04% Pu-239	1.00% Pu-239	0.97% Pu-239	1.28% Pu-239

Table 2. Standard 37 rod fuel bundle configuration: Equivalent 1.2% Pu^{239} Enrichement

Bundle Type	***B12***	***CF12***
Central Rod	1.75% Pu-239 1.23% B-10	0.25% Pu-239 1.35% B-10
1-st Inner Ring	1.75% Pu-239 1.23% B-10	0.25% Pu-239 1.35% B-10
2-nd Inner Ring	1.48% Pu-239	2.03% Pu-239
External Ring	0.80% Pu-239	1.01% Pu-239

Table 3. Cell Parameters for Different Fissile Grading
(Standard 37 rod fuel bundle configuration on Table 1)

Bundle Type	***O15***	***B15***	***D15***	***F15***	***CF15***
Discharge Burnup (MWd/kgHE)	8.820	7.494	7.130	6.752	9.743
$\Delta\rho_{void}$ - fresh fuel (mk)	+1.64	+2.95	+2.74	+2.53	+4.55
$\Delta\rho_{void}$ - equilibrium fuel (mk)	-0.79	+0.61	+0.41	+0.22	+2.11

Table 4. The main parameters for MOX- weapons-grade plutonium-fueled CANDU 6MK1 core

Parameter	**Bundle O15** *1-bundle shift*	**Bundle CF15** *1-bundle shift*	**Bundle D15** *2-bundle shift*	**Bundle B12** *4-bundle shift*	**Bundle CF12** *2-bundle shift*
Equilibrium Maximum Channel Power (kW)	6402	6398	6406	6471	6404
Equilibrium Maximum Bundle Power (kW)	749	747	725	745	731
Maximum Average Channel Power (kW)	6688	6996	6817	7035	6840
Maximum Average Bundle Power (kW)	782	813	793	871	803
Average CPPF	1.07	1.12	1.09	1.18	1.11
Average BPPF	1.07	1.14	1.11	1.27	1.12

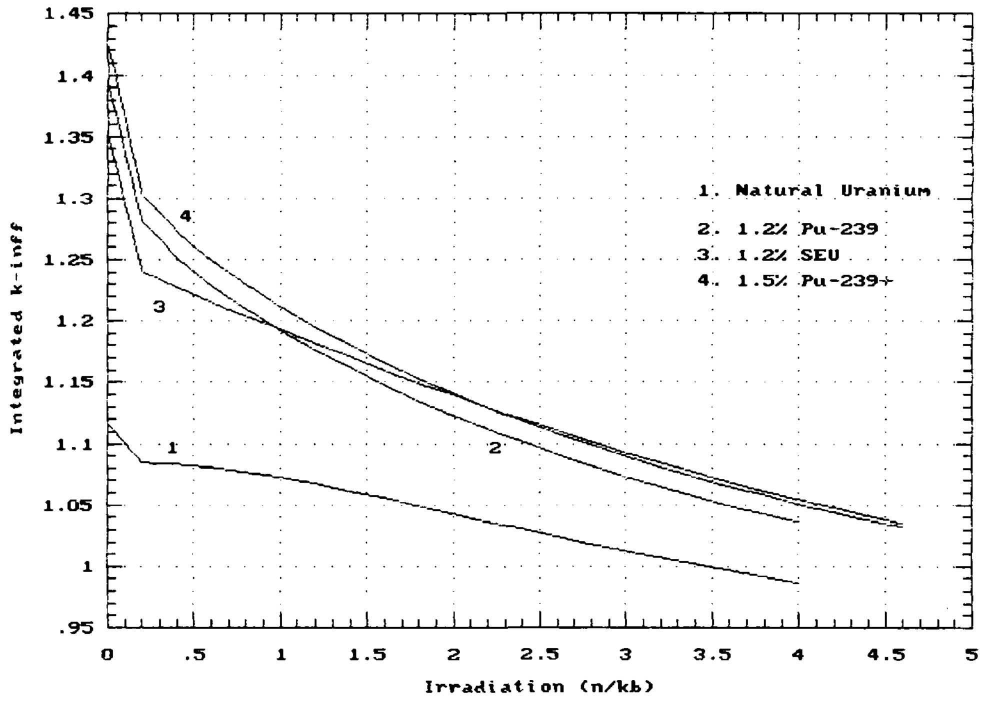

Figure 1.Lattice reactivity depletion- CANDU Cell, LATREP-T3S Calculations

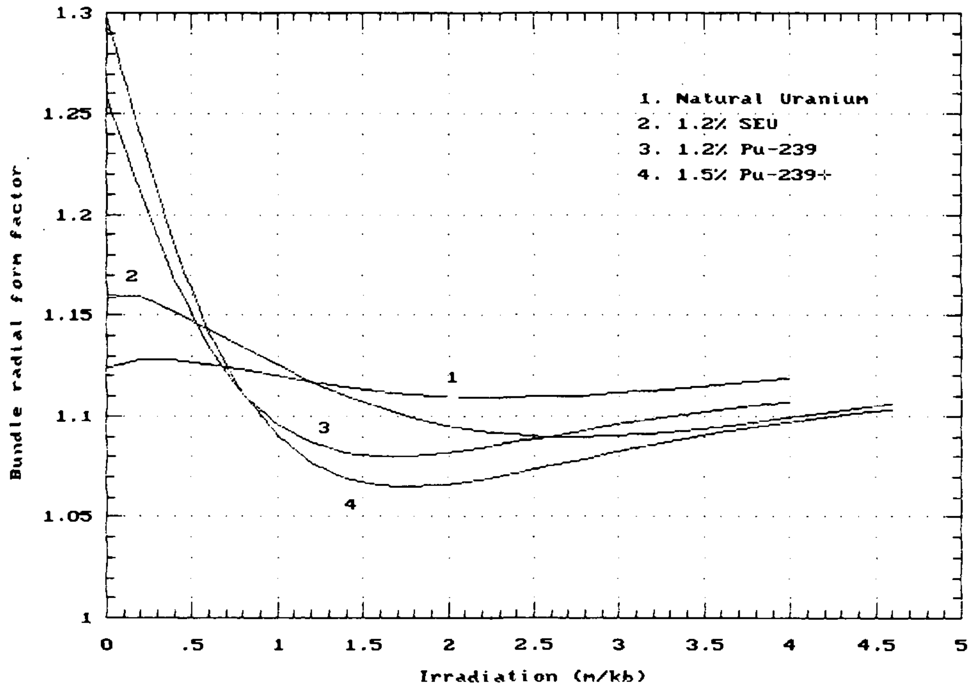

Figure 2. Bundle Radial Form Factor Evolution with Burnup
CANDU Cell, LATREP-T3S Calculations

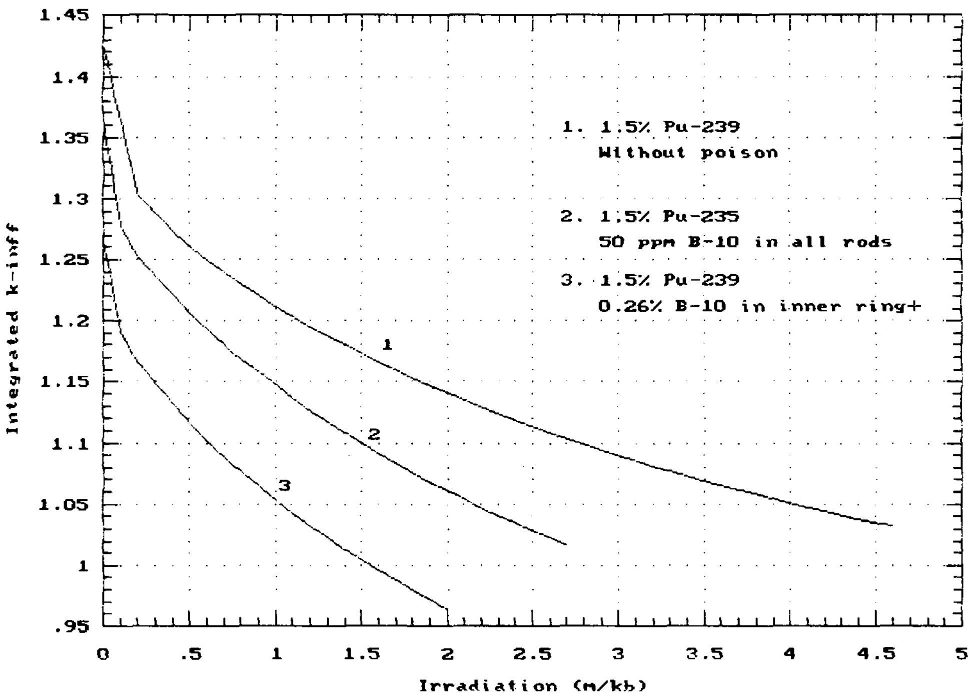

Figure 3. Poison Effect on Lattice Reactivity Depletion
CANDU Cell, LATREP-T3S Calculations

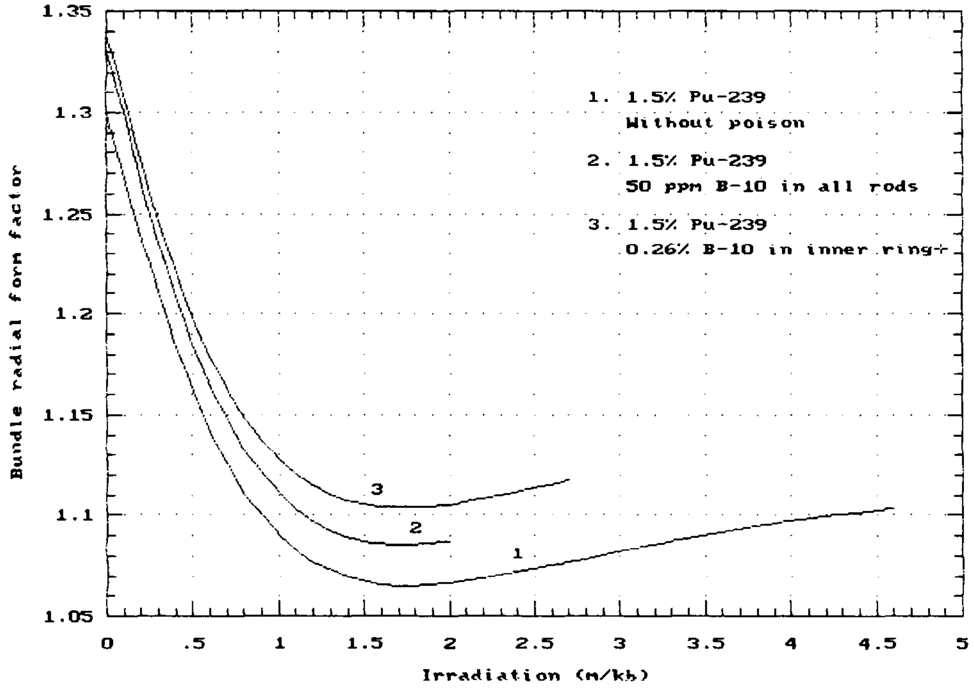

Figure 4. Poison Effect on Bundle Radial Form Factor
CANDU Cell, LATREP-T3S Calculations

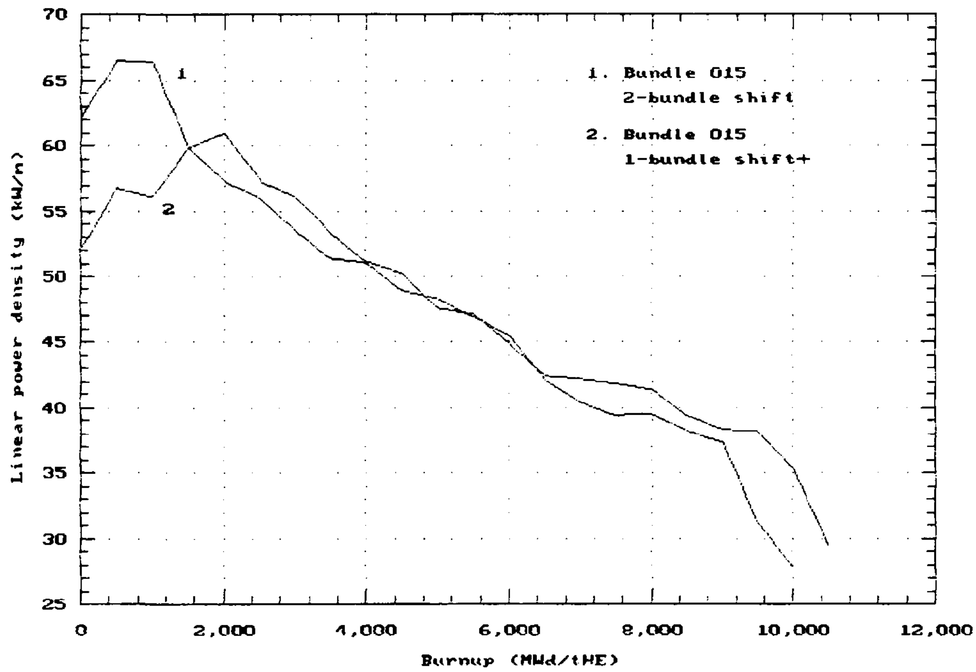

Figure 5. Maximum Linear Power Density for Bundle O15 (Table 3)
CANDU 6Mk1 Core, SERA Calculations

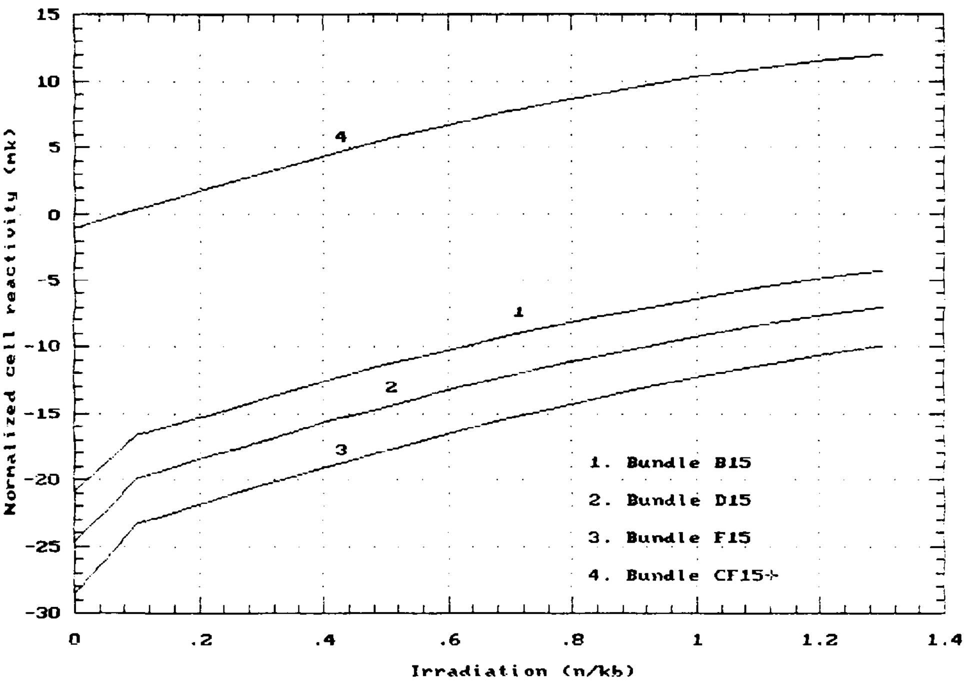

Figure 6. Fissile Grading Effect on Lattice Reactivity Depletion
CANDU Cell, LATREP-T3S Calculations

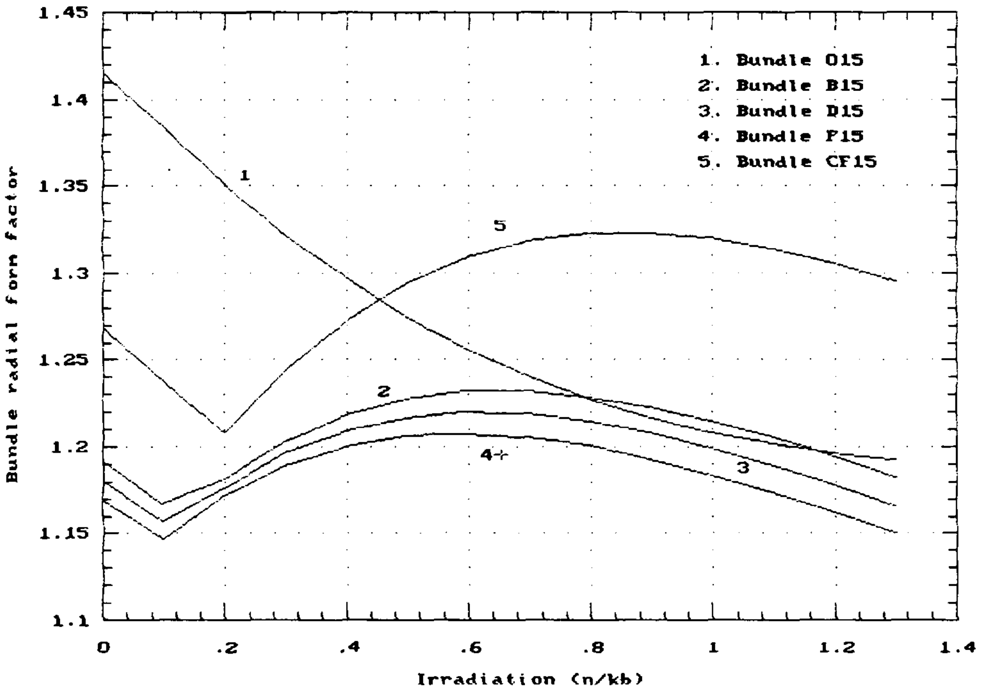

Figure 7. Fissile Grading Effect on Bundle Radial Form Factor
CANDU Cell, LATREP-T3S Calculations

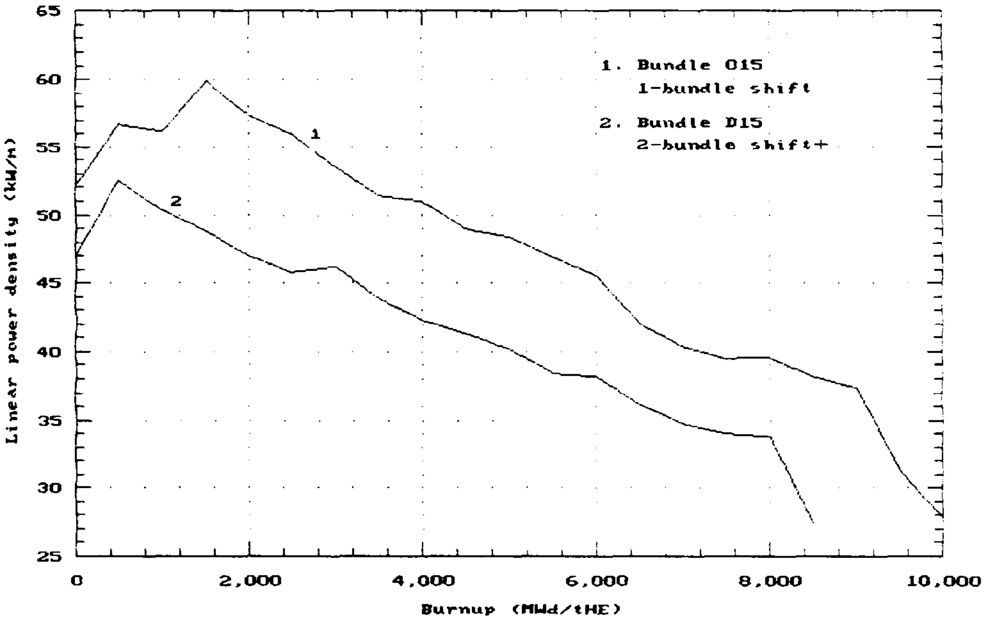

Figure 8. Maximum Linear Power Density: Bundle D15 versus Bundle O15
CANDU 6Mk1 Core, SERA Calculations

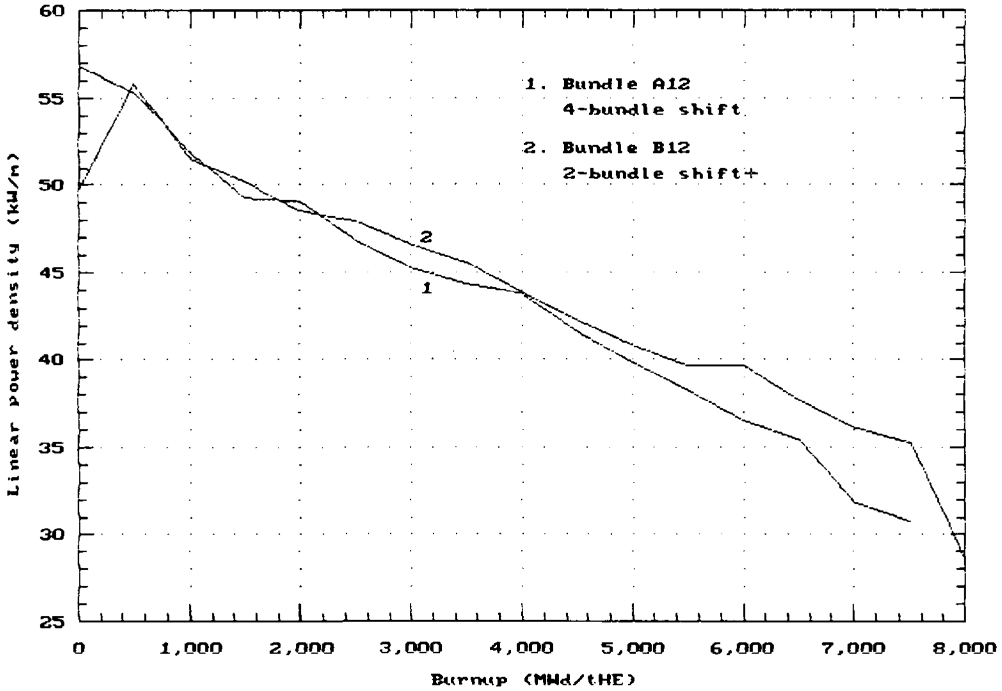

Figure 9. Maximum Linear Power Density: Bundle B12 versus Bundle O12 CANDU 6Mk1 Core, SERA Calculations

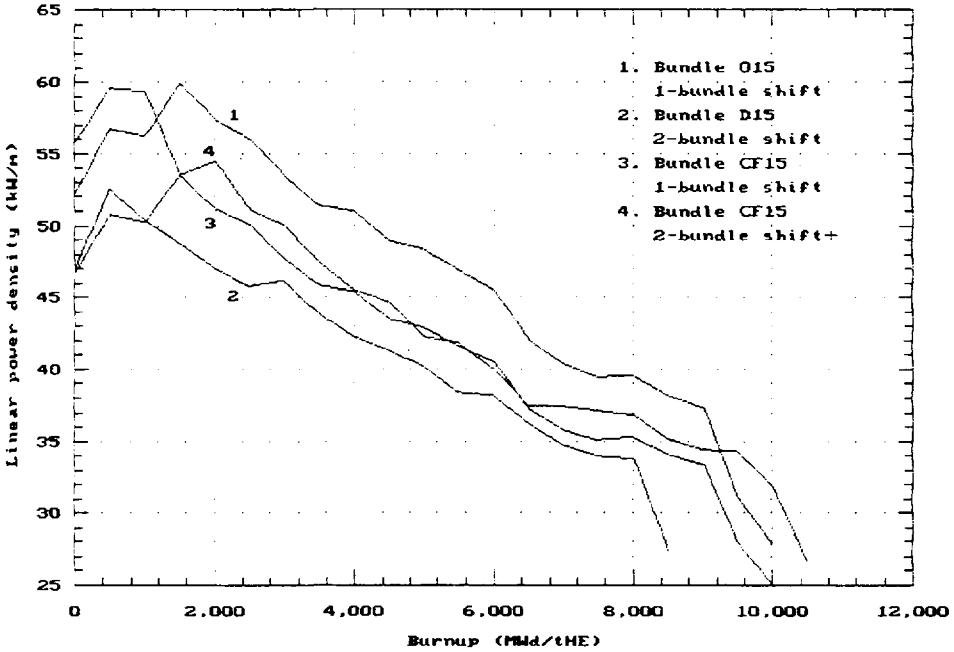

Figure 10. Maximum Linear Power Density: A Comparison of Fuel Bundle Characteristics and Axial Refueling Scheme CANDU 6Mk1 Core, SERA Calculations