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FUEL-MANAGEMENT SIMULATIONS FOR ONCE-THROUGH THORIUM FUEL CYCLE IN CANDU REACTORS

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Abstract

High neutron economy, on-power refuelling and a simple fuel bundle design result in unsurpassed fuel cycle flexibility for CANDU® reactors. These features facilitate the introduction and exploitation of thorium fuel cycles in existing CANDU reactors in an evolutionary fashion. Detailed full-core fuel-management simulations concluded that a once-through thorium fuel cycle can be successfully implemented in an existing CANDU reactor without requiring major modifications.

1. Introduction

The abundance of thorium in the earth's crust is about three times that of uranium. Hence, the thorium fuel cycle ensures a long-term nuclear fuel supply. For countries with abundant thorium reserves, the thorium fuel cycle in CANDU reactors would enhance both the sustainability of nuclear power and the degree of energy independence, using a single reactor type.

There are two major options for implementing the thorium fuel cycle in CANDU reactors. The first is the recycling option, in which the ^{233}U in the spent thorium fuel is recycled into the fresh fuel. The second is the once-through thorium (OTT) option, where the rationale for the use of thorium does not depend on recycling. Thorium recycling is not a near-term option because it requires extensive research and development efforts. Therefore, recent thorium fuel cycle studies conducted at AECL have focused on the OTT as the nearer-term option.

Two methods can be used to introduce the OTT fuel cycle into existing CANDU reactors. The first is a "mixed-core" approach where a large number of driver channels containing enriched-uranium fuel are used to support a relatively small number of channels dedicated to thorium irradiation. Because of the disparity in reactivity and power output between driver channels and thorium channels, very sophisticated fuel-management schemes will be required to shape the channel and bundle power distributions in the mixed core in order to achieve the nominal reactor power output. This approach is theoretically feasible, but its practicality has not been investigated in detail.

An alternative approach is to fuel the whole core with mixed-fuel bundles, which contain both thorium and enriched-uranium fuel elements in the same bundle. This "mixed-fuel bundle" approach is a practical means of utilizing thorium in existing CANDU reactors, while keeping the fuel and the reactor operating within the current safety and operating envelopes established for the natural-uranium fuel cycle.

Detailed fuel-management studies were conducted using the RFSP[1] code for a CANDU 6 reactor using the mixed-fuel bundle approach. The lattice parameters were calculated by WIMS-AECL[2] for CANFLEX® mixed-fuel bundles having slightly enriched uranium (SEU) fuel in the outer 35 elements and natural thorium in the central 8 elements.

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2. Fuel-Management Flexibility in CANDU

The on-power refuelling feature of CANDU reactors allows the reactors to operate with the optimal channel and bundle power distributions for a wide variety of fuel cycles. In general, the reactor is divided into different regions for fuel-management purposes. Each region may contain a different type of fuel with different fissile content. Reactor criticality and global power shape can be controlled by fuelling each region at a different rate. Local power peaking can be minimized by judiciously selecting individual channels to be refuelled, and by limiting the number of fresh fuel bundles inserted into a channel during each refuelling operation.

Figure 1 shows the RFSP model of a CANDU 6 reactor divided into three fuelling regions. The inner and the outer regions are further subdivided into smaller zones having slightly different fuelling rates in order to optimize the reactor global power shape. Figure 2 shows the configuration of the fuel elements in a CANFLEX fuel bundle where the natural-thorium fuel in the 8 inner elements is surrounded by slightly enriched uranium (SEU) fuel in the outer 35 elements. There is a high degree of flexibility in the choice of the amount and the nature of the fissile material in the enriched driver fuel elements to achieve specific goals in different fuel cycles. The combination of on-power fuelling with a simple and flexible fuel bundle design offers many options for burning thorium in existing CANDU reactors.

3. Options for Burning Thorium in CANDU Reactors

Two options have been developed for burning thorium fuel in an existing CANDU 6 reactor. In Option 1, only one fuel type was used throughout the entire core, and the adjuster rods were removed. The reference fuel design is a CANFLEX fuel bundle with 1.8 wt % slightly enriched UO_2 fuel in the outer 35 elements and natural ThO_2 fuel in the inner 8 elements. The initial fissile content was chosen to maximize the burnup of the thorium fuel elements without exceeding the current limits on maximum channel and bundle power.

Adjuster rods provide flux and power flattening with natural-uranium fuel, but they are not needed for this purpose with enriched fuel. In fact, they would over-flatten and reduce the power in the centre of the channel, resulting in an undesirable asymmetric double hump in the axial flux and power distributions in CANDU reactors using enriched fuel. The flux and power distortions caused by the adjuster rods can be eliminated by using a sophisticated fuelling scheme[3], or by using a small amount of burnable poison in the fuel bundle.

The second option illustrates the flexibility of existing CANDU reactors to accommodate both thorium fuel and adjuster rods. In Option 2, each of the three regions shown in Figure 1 contains a different type of thorium fuel bundle. The fuel in the 196 outer-region channels is the same as that used in Option 1. The fuel in the 124 inner-region channels is identical to that in the outer-region channels, except that the central ThO_2 element contains 6.0 wt % of gadolinium to shape the axial flux distribution. The gadolinium-doped bundles are used only in the inner-region, which is under the influence of the adjuster rods.

The 60 periphery channels in Option 2 contain thorium bundles designed to achieve burnups of over 50 MW.d/kgHE. These high-burnup thorium bundles use natural ThO_2 in all 43 fuel elements. However, the initial fissile content in the outer 35 elements is increased from 0 wt % to 1.7 wt % using 20 wt % enriched uranium. These high-burnup thorium bundles are located strategically at the edge of the core to utilize a large percentage of the leakage neutrons to produce power. This arrangement significantly increases the amount of thorium fuel in the core and improves the overall fuel efficiency of the thorium-burning reactor.

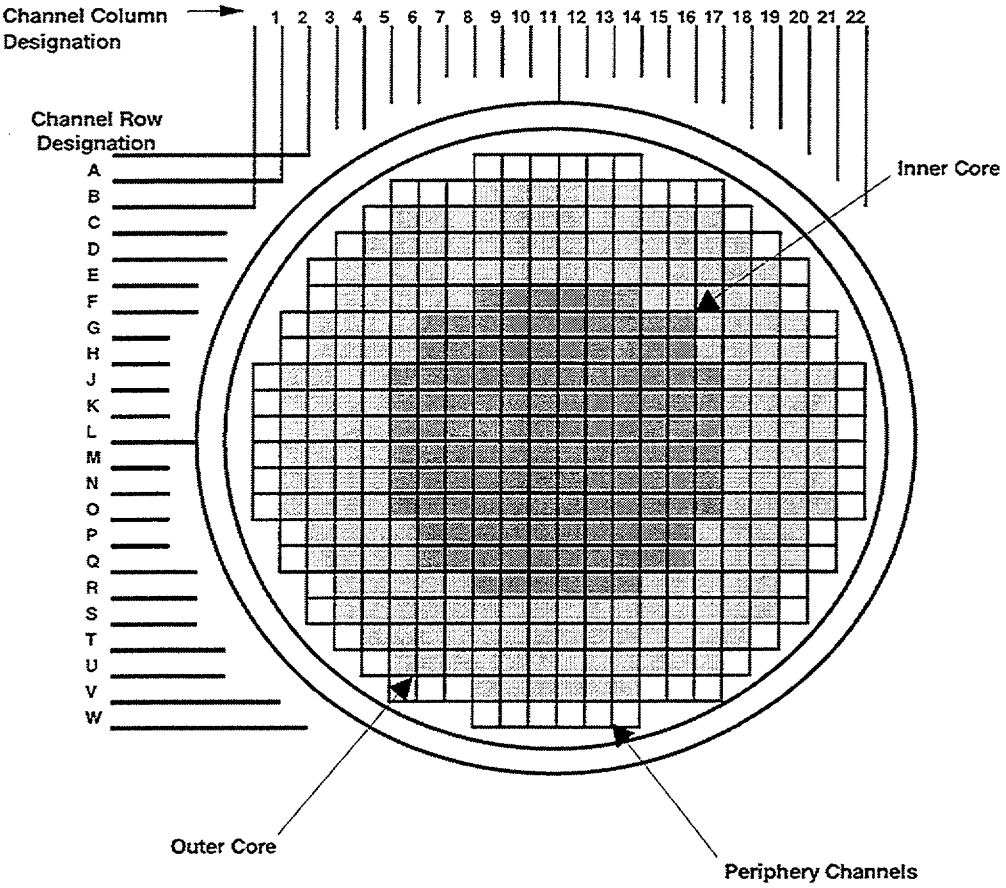

Figure 1 : Reactor Core Model of a CANDU 6

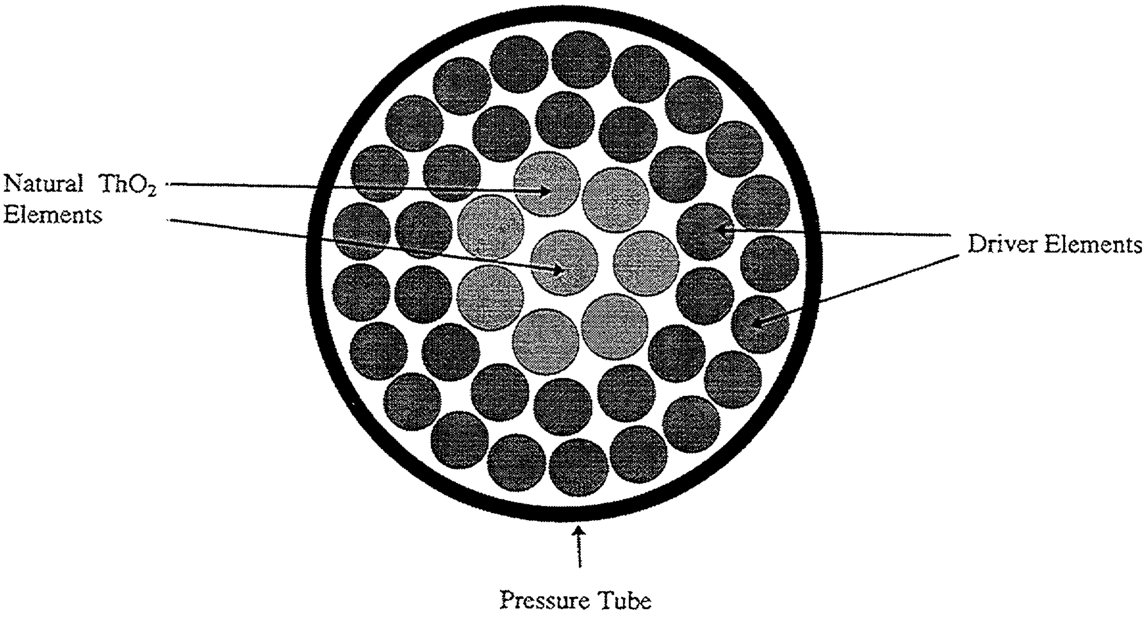

Figure 2 : Configuration of Fuel Elements in a CANFLEX Bundle

4. Lattice Properties of Mixed-Thorium Fuel

Table 1 gives the initial fuel composition of the three types of thorium fuel bundles used in the current study. The basic physics properties of these fuel lattices, such as the variation of lattice k-infinity, of fissile content and of lattice coolant-void reactivity, are shown in Figures 3, 4 and 5, respectively as functions of bundle-average fuel burnup. Although natural-UO_2 and natural-ThO_2 fuel bundles are not used in this study, their physics properties are also shown in these figures for comparison purposes.

The initial fissile content of the high-burnup thorium bundles has been carefully chosen so that the depletion rate of the fissile material is almost the same as the conversion rate of the fertile ^{232}Th into fissile ^{233}U. Consequently, the reactivity and the fissile content of the high-burnup thorium bundles are almost constant throughout the entire lifetime. These high-burnup thorium bundles can theoretically reside indefinitely in the reactor. The attainable fuel burnup is limited only by the mechanical integrity of the fuel bundle.

The main purpose of the gadolinium is to shape the axial flux distributions so that the resulting bundle flux and power distributions are similar to those in the thorium-burning reactor without adjuster rods. Figure 6 shows that the gadolinium effectively eliminates the bundle power distortion caused by the adjuster rods. As expected, the effect of gadolinium on lattice reactivity is evident only during the initial stage of the fuel lifetime. The fast burnout rate of gadolinium suppresses the reactivity of the fresh bundle without causing significant burnup penalty over the lifetime of the fuel. This effect also reduces the channel and bundle power ripples caused by refuelling. The presence of a neutronic poison, gadolinium, in the central element also reduces coolant-void reactivity [4]. This results in a significant reduction in the core-averaged coolant-void reactivity.

Table 1: Initial Fuel Composition (kg/bundle) of Mixed SEU-Thorium Bundles

	1.8% SEU-Th No Gd Whole core, Option 1 Outer Core, Option 2	1.8% SEU-Th 6% Gd (central pin) Inner Core, Option 2	1.7% SEU-Th No Gd Periphery Channels Option 2
Ring 1			
^{235}U	0	0	0
^{238}U	0	0	0
^{232}Th	0.510	0.510	0.510
Gd(natural)	0	0.0306	0
Ring 2			
^{235}U	0	0	0
^{238}U	0	0	0
^{232}Th	3.590	3.590	3.590
Ring 3			
^{235}U	0.102	0.102	0.087
^{238}U	5.578	5.578	0.349
^{232}Th	0	0	4.700
Ring 4			
^{235}U	0.153	0.153	0.131
^{238}U	8.367	8.367	0.523
^{232}Th	0	0	7.050
Total			
^{235}U	0.256	0.256	0.218
^{238}U	13.944	13.944	0.872
^{232}Th	4.100	4.100	15.850
Gd(natural)	0	0.0306	0

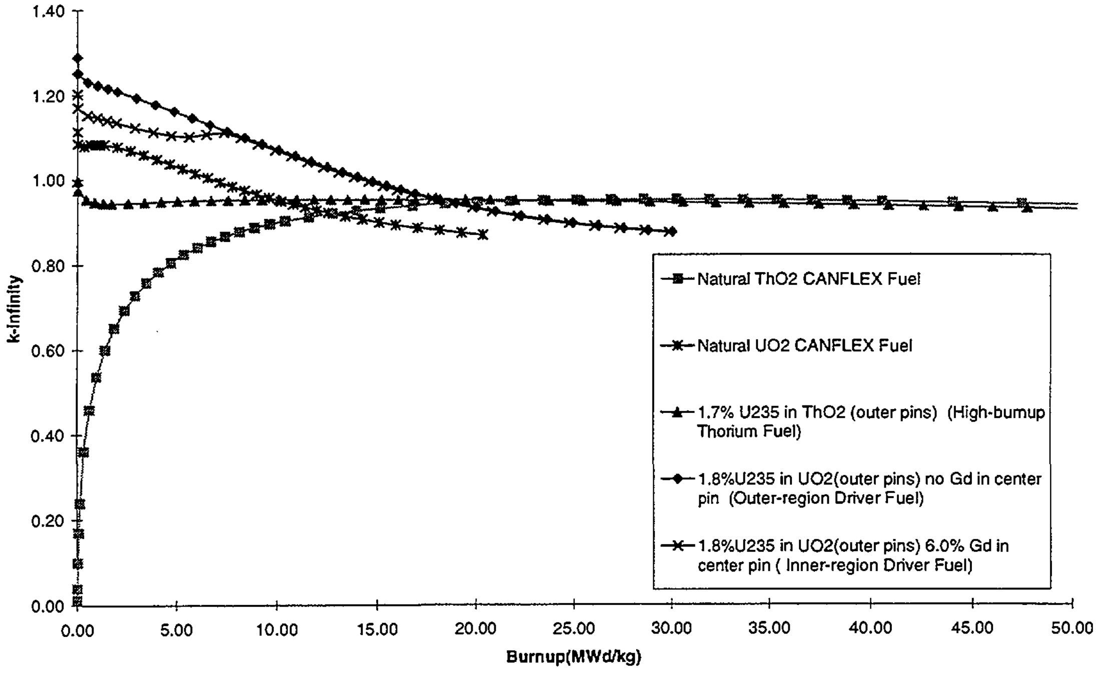

Figure 3: Lattice k-infinity vs. Fuel Burnup

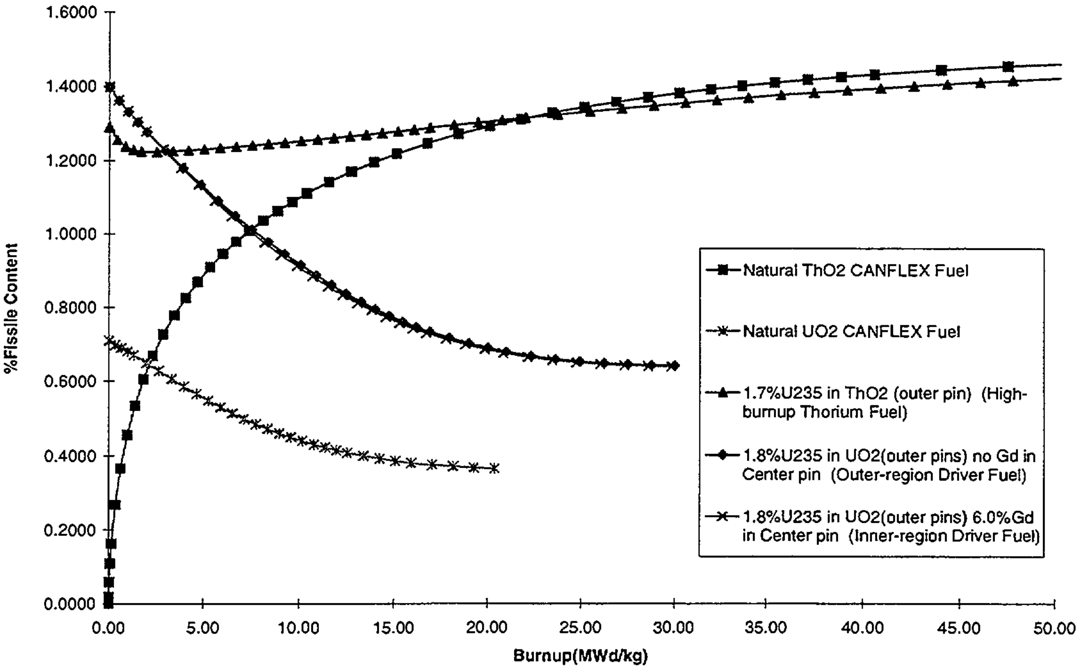

Figure 4 : Fissile Content vs. Fuel Burnup

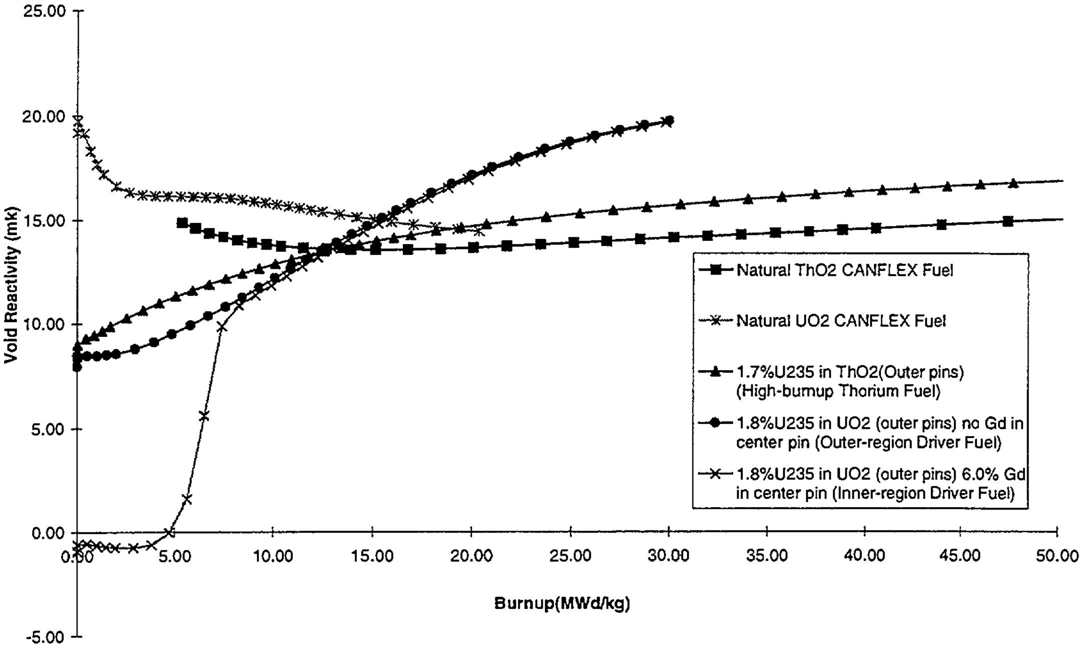

Figure 5: Lattice Void Reactivity vs. Fuel Burnup

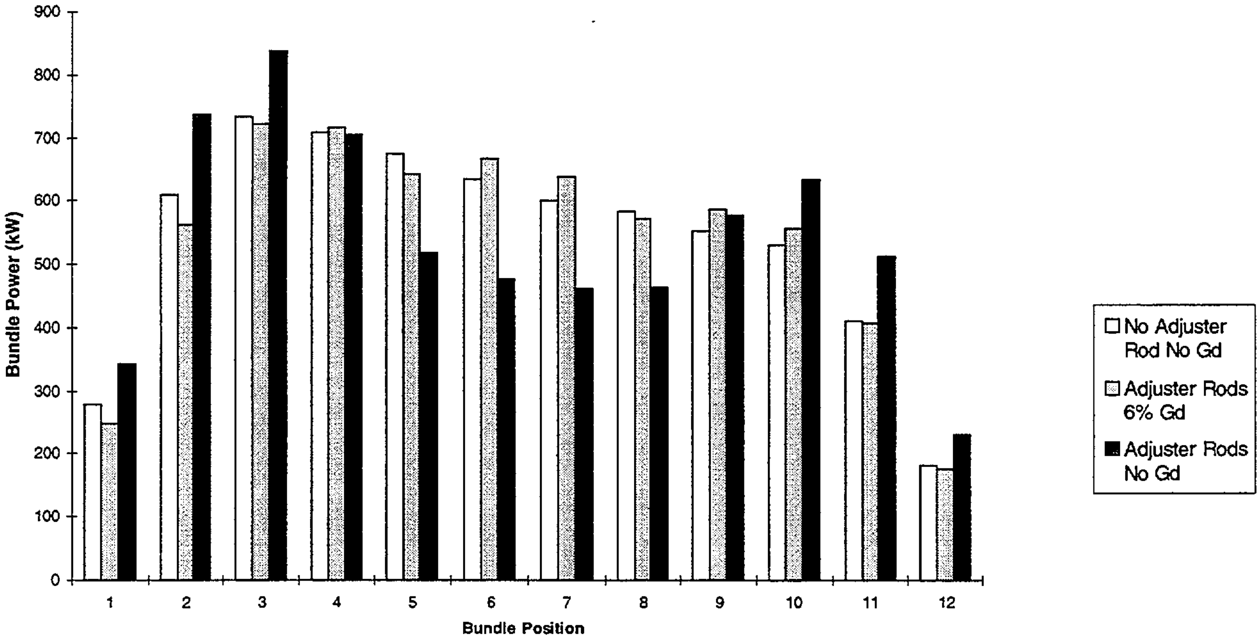

Figure 6: Effect of Adjuster Rods and Gadolinium on Time-Average Bundle Power Distribution

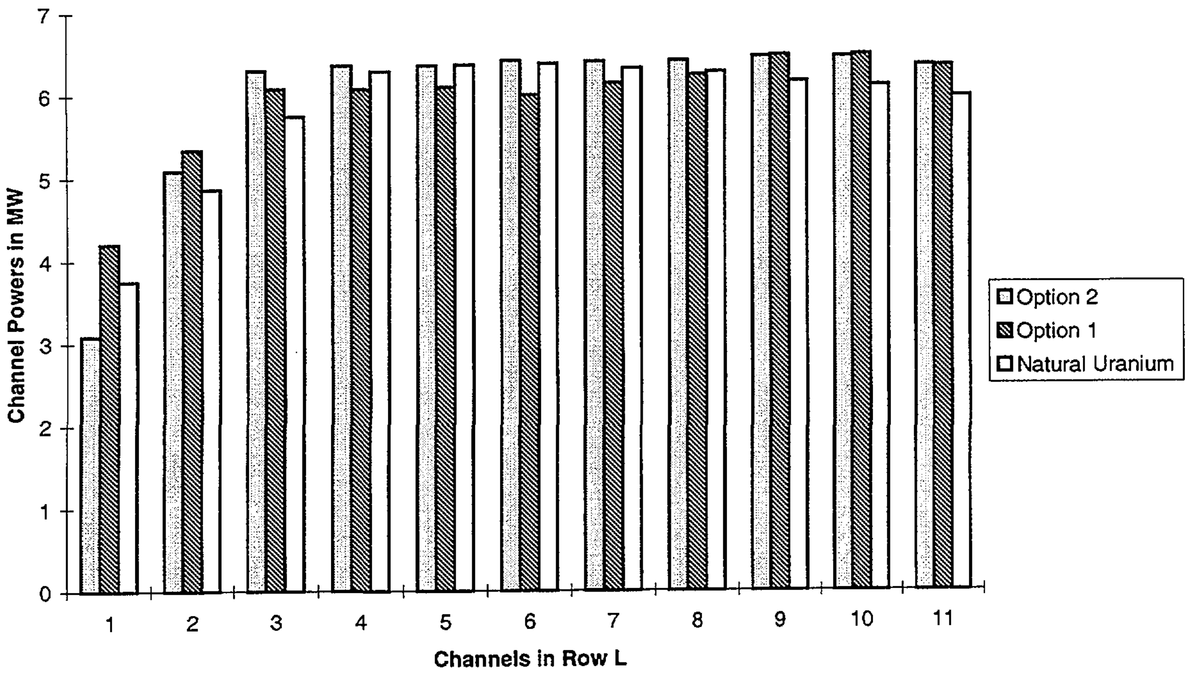

Figure 7: Time-Average Channel Power Distributions

Table 2 : Summary of WIMS/RFSP OTT Fuel-Management Studies in a CANDU 6 Reactor

	Option 1 (without Adjuster Rods)	Option 2 (with Adjuster Rods)
Uranium Utilization (MgNU/GW(e).a)	130	138
Percentage of Thorium in Reactor Core (by volume)	25	36
Core-Average Fuel Burnup (MW.d/kgHE)	22.1	20.3
Core-Average Thorium Burnup (MW.d/kgHE)	10.4	9.1
Fuelling rate (Bundles per Full-Power-Day)	5.5	6.0
Fuelling Scheme (*bundle-shift*)	2	2
Maximum Channel Power (kW) (Time-Average)	6491	6505
Maximum Bundle Power (kW) (Time-Average)	741	739
Maximum Channel Power (kW) (Instantaneous)	6855	6849
Maximum Bundle Power (kW) (Instantaneous)	785	781
Reactor Leakage (mk)	30.6	25.8
Full Core Coolant-Void Reactivity (mk)	12.6	10.6

5. Characteristics of Thorium-Burning CANDU Reactors

The RFSP code was used to perform time-average core calculations for Options 1 and 2 using a uniform 2-bundle-shift fuelling scheme. Instantaneous core calculations were conducted using randomly generated age patterns. Figure 7 shows that the channel power distributions for the two thorium-burning reactors are very similar to those of a typical natural-uranium CANDU reactor. Figure 8 shows that the axial bundle power distributions in the thorium-burning reactors are flatter than those in a natural-uranium CANDU and are more skewed towards the coolant-inlet end. This skewed axial power profile should improve the thermalhydraulics performance. Major reactor physics results for both options are summarized in Table 2.

The fuelling rates, maximum channel power and maximum bundle power for both options are well within the limits established for current CANDU reactors using natural-uranium fuel. There is also a significant reduction in the coolant-void reactivity from that of a natural-uranium reactor under comparable conditions. Option 1 gives 21% better uranium utilization than that for a natural-uranium CANDU reactor. About half of the improved fuel efficiency is due to the removal of the adjuster rods. The other half can be attributed to the energy produced in the thorium fuel. Option 2, which uses the existing adjuster rods, gives 14% better uranium utilization than that for a natural-uranium reactor with the additional advantage of a significantly lower coolant-void reactivity.

6. Effect of Flux-Dependence on Thorium Physics Calculations

The dependence of the lattice parameters of thorium-bearing fuel on the flux and power history of the fuel was reported in a previous study [5]. This dependence arises because the creation of the fissile isotope ^{233}U from the fertile isotope ^{232}Th is flux-dependent. This process is analogous to the production of the fissile isotope ^{239}Pu from the fertile isotope ^{238}U in uranium-based fuel cycles. The major difference is that the equilibrium level of ^{233}U in ^{232}Th is about 1.5%, and it is sensitive to flux level, whereas the equilibrium level of ^{239}Pu in ^{238}U is only about 0.4%, and it is relatively insensitive to the flux level.

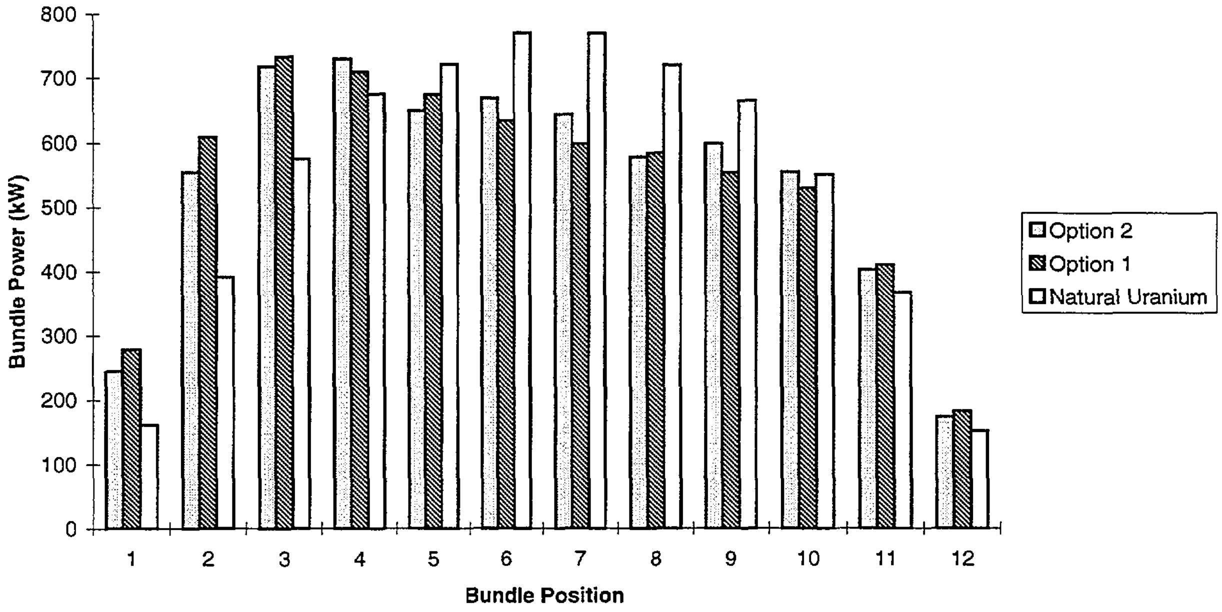

Figure 8: Time-Average Bundle Power Distributions in a High-Power Channel

The lattice parameters for the mixed SEU-Thorium fuels were calculated with WIMS-AECL using a constant cell-average thermal flux of 2.0×10^{14} n/cm^2.s. Those for the high-burnup thorium fuel were calculated using a constant cell-average thermal flux of 1.0×10^{14} n/cm^2.s. These flux levels are consistent with the flux levels obtained from RFSP core calculations. The results of the RFSP calculations are not expected to be significantly affected by the flux-dependence of the lattice parameters because the thorium-bearing fuel is placed in very low-importance regions. The high-burnup thorium fuel is located at the outermost channels and the thorium in the mixed SEU-Thorium fuel bundles is limited to the inner two fuel rings, where the thermal neutron flux level is relatively low.

WIMS-AECL calculations were performed to assess the effect of flux-dependence on the lattice k-infinity and fissile content of the mixed SEU-Thorium fuel up to a core-average fuel burnup of 22.1 MW.d/kgHE for Option 1 and 20.3 MW.d/kgHE for Option 2. Two methods for incrementing the fuel burnup were used:

- the fuel burnup was calculated by simulating the shifting of a thorium fuel bundle from the inlet to the outlet using a typical time-average axial flux profile and resident time at each position calculated by RFSP, and
- the fuel burnup was calculated by using a constant cell-average thermal flux level consistent with the time-average axial flux profile.

The results are summarized in Table 3. As expected, there are small differences between these two sets of calculations. However, the variations in the ^{233}U content are not significantly greater than the variations in the fissile plutonium content. The sum of ^{233}U and ^{233}Pa is the important quantity at discharge and is generally quite constant for each case type. For the cases with the axial thermal neutron flux distribution modelled, the flux level drops appreciably for the final irradiation period. During this irradiation, the decay of ^{233}Pa to ^{233}U is enhanced and the level of ^{233}U at discharge is greater than in the constant flux situation. This increases the k-infinity somewhat and also reduces the amounts of the other fissile nuclides that were used up. The maximum discrepancy in the lattice k-infinity is less than 10 mk at discharge. The uncertainty in the mixed SEU-Thorium fuel lattice properties is expected to be small and should not have a significant impact on the results of the reactor core calculations.

Table 3 : Effect of Flux Dependency on Lattice Reactivity and Fissile Contents (g/bundle) in Mixed SEU-Thorium Fuel Bundle

	WIMS calculations based on Core-Average Constant Cell Flux	WIMS calculations based on RFSP Time-Average Axial Flux Profile
Option 1		
Core-Average Burnup (MW.d/kgHE)	22.1	22.1
WIMS k-infinity	0.898	0.904
^{235}U	20.6	20.5
^{233}U	48.9	50.7
^{233}Pa	4.6	3.1
^{239}Pu + ^{241}Pu	46.8	47.1
Option 2 (outer-region fuel)		
Core-Average Burnup (MW.d/kgHE)	20.3	20.3
WIMS k-infinity	0.916	0.922
^{235}U	26.6	26.6
^{233}U	47.0	48.6
^{233}Pa	4.2	2.8
^{239}Pu + ^{241}Pu	46.6	46.8

The RFSP code was used to conduct time-dependent refuelling simulations in the Option 1 core for a period of 100 full-power-days using lattice parameters that are consistent with the power history of individual fuel bundles. These local lattice parameters are based on WIMS-AECL calculations using a very efficient computational scheme[6]. The maximum channel power and maximum bundle power during this simulation period using history-dependent lattice parameters are 6.8 ± 0.1 MW and 780 ± 10 kW respectively. These results are very similar to those calculated by the RFSP code using traditional non-history-based lattice parameters.

7. Conclusions

The current study represents only a first look at practical fuel-management strategies for the OTT fuel cycle. Two options for implementing the OTT fuel cycle in existing CANDU reactors were identified. For both options, the uranium utilization is better than that of the natural-uranium fuel cycle. The reactor and the fuel perform within existing envelopes without requiring major modification to the current reactor design. Coolant-void reactivity is significantly lower than that of a natural-uranium reactor under comparable conditions.

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