

THE USE OF DEPLETED URANIUM FOR
THE REDUCTION OF VOID REACTIVITY IN CANDU REACTORS

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ABSTRACT

Coolant void reactivity in CANDU reactors can be reduced or even eliminated by adding an appropriate amount of burnable poison in the inner elements of CANDU fuel bundles. The additional amount of U-235 that is required to compensate for the burnable poison can be reduced by using depleted uranium in the inner fuel elements.

1.0 INTRODUCTION

Inherent in all CANDU designs beginning with the NPD plant, designers and physicists sought to contain positive reactivity excursions following design basis loss-of-coolant accidents (LOCA) and mitigate its consequences through sophisticated design concepts involving early detection, rapid response and defense-in-depth approaches.

Because of these design concepts, present CANDU reactors keep the LOCA consequences within acceptable limits. However, the desire to improve the economics of the CANDU plants has resulted in simpler designs that exploit the economy of scale, i.e., larger reactor cores and reactors with more flux and power flattening. These requirements tend to increase void reactivity insertion rate on LOCA because of the higher neutronic decoupling of the two Primary Heat Transport (PHT) loops. To achieve such design simplification and superior economics and yet keep the LOCA consequences within acceptable limits, an alternative approach is required. This involves a reduction in the void reactivity holdup and consequently a reduction in the reactivity insertion rate for a fixed voiding rate.

1.1 Void Reactivity as a Design Parameter

Reduction in the void reactivity that is potentially held up in the coolant will limit the reactivity excursion during a LOCA. If low void reactivity is included as an optimization parameter in future CANDU plant design, many of the concepts which are required in the present plant design in order to minimize LOCA consequence can be simplified. The overall simplification in plant design can result in large economic improvements by reducing the capital cost significantly. Some of the design areas that can be simplified are:

- single PHT loop with unidirectional coolant flow in all channels;
- no interlacing of feeders;
- gravity-driven instead of spring-assisted shutoff rods.

The cost reduction associated with these simplifications will amount to several tens of millions of dollars. The cost of reducing void reactivity is due mainly to the extra U-235 enrichment required to compensate for the burnable poison that is used in the Low Void Reactivity Fuel (LVRF) designs. This increase in fuelling cost should be compared against the reduction in capital cost in order to arrive at an optimum level of void reactivity from the cost viewpoint.

2.0 METHODOLOGY OF COOLANT VOID REDUCTION

2.1 Simulation Method

The simulation of the lattice neutronics was carried out with the WIMS-AECL code (version 90-04-18). The Winfrith (version 90-06-09) library was used for the neutron cross section database. The neutron spectrum was calculated in thirty-three energy groups. The group structure was chosen according to the energy bounds of major reaction rates that are expected in the CANDU lattice. The PIJ option was used to model the fuel elements discretely in the WIMS calculations.

The effect of neutron leakage on the neutron spectrum was calculated on the basis of reactor leakage. This procedure was used in order to interpret the WIMS results as being valid for the reactor. The reactivity of the lattice that would produce a critical reactor was obtained from previous analysis for the CANDU 6 reactor. The k-infinity of the critical lattice was 1.045. The excess reactivity of 45 mk accounted for the reactor leakage as well as all the absorptions, other than those occurring in the fuel channels, in the reactor.

2.2 Methods of Void Reactivity Reduction

Most of the neutronic processes in CANDU that are responsible for producing positive reactivity on voiding are brought about by a change in neutron spectrum. The role of neutron absorption in the coolant is negligible, however, coolant void causes a significant redistribution of flux in the fuel channel. This flux redistribution can have a major impact on the thermal reaction ratio depending upon the location of the fissile material in the fuel bundle. The second component of the spectrum change is in the epithermal range, i.e., those that increase fast fission in U-238 and decrease resonance absorption in U-238. A reduction in these positive reactivity components would therefore require either,

- a. a reduction in the size or a reversal of the spectrum change upon voiding, or
- b. reduction in the reactivity effect of the spectrum change if the spectral effects are left unchanged, or
- c. creation of negative reactivity to counteract the positive components.

Approach (a) required a change in the neutron scattering properties of the coolant which is equivalent to replacing the heavy water coolant with another material of lower scattering cross section. To produce a reversal in the spectrum change on voiding would require a significant reduction in moderator volume. This approach requires a change of the basic CANDU lattice.

Approach (b) requires a significant change in the fuel bundle geometry, in particular, in the surface-to-volume ratio of the fuel pins. This approach will require significant fuel development effort.

Because both approach (a) and approach (b) require significant development effort beyond present-day CANDU technology, approach (c) is the only credible method available to CANDU reactors in the near term. In approach (c), rather than attempting to reduce the magnitude of the positive void reactivity components described above, the focus is placed on the production of new negative reactivity components due to voiding. This is achieved by making use of the redistribution of the thermal neutron flux that occurs across the fuel bundle upon voiding. The negative reactivity component is created by placing neutron absorbing material in the central region of the fuel bundle, where the thermal neutron flux increases on voiding. The production of negative reactivity due to the increased neutron absorption in these materials on voiding, caused by an increase in the thermal neutron flux, can be made sufficiently high to completely offset the positive reactivity component that is produced on voiding.

2.3 Choice of Absorber Material

The following criteria were used in considering the suitability of a burnable poison for void reduction:

- a. The burnout rate of the absorber should be such as to maintain the required void reactivity reduction through the life of the fuel.
- b. The burnout rate should match the reduction in lattice reactivity such as to minimize the parasitic load of the absorber integrated over the life of the fuel.
- c. The burnout rate should also minimize the power of a fuel channel, over the fuel life, relative to neighbouring fuel channels. This is necessary in order to offset the increase in the peak element power density by restricting the absorber to the inner fuel elements of the bundle.
- d. Absorbers that are known to be chemically, physically and neutronicallly compatible with the fuel should be given preference. In particular, naturally occurring isotopes of fission products were used as the first choice for evaluation.

Several absorbers were evaluated as candidates for use in void reactivity reduction. It was found that relatively low cross section absorbers - such as natural cobalt, hafnium and indium - did not burn out fast enough to minimize the parasitic load at high fuel burnups. On the other hand, the familiar burnable poisons such as gadolinium and boron had unacceptably high burnout rates. The closest match to the optimum burnout rate was obtained with natural dysprosium, which is also physically and chemically compatible with the uranium fuel.

2.4 Using Depleted Uranium to Reduce Cost of Void Reactivity Reduction

Because coolant void reactivity in CANDU reactors, using low void reactivity fuel, can be reduced to any desired value, even below zero, it becomes possible to consider coolant void reactivity as a design parameter which can be used for the overall optimization of the CANDU power plant. The fuelling cost in CANDU reactors using LVRF depends on the design discharge fuel burnup as well as the targeted void reactivity. It is convenient to express the cost of void reduction as the increase in U-235 enrichment required to achieve the targeted void reactivity while maintaining the design discharge fuel burnup.

The increase in U-235 enrichment requirement can be viewed as a reduction in the resource utilization advantage that CANDU reactors have over the Light

Water Reactors (LWRs). Therefore, there is considerable incentive to improve the LVRF designs by reducing the cost of void reduction. The improvement can be achieved by:

- a. decreasing the dysprosium requirement for a given void reactivity reduction,
- b. decreasing the incremental U-235 enrichment required for a given amount of dysprosium.

The dysprosium requirement can be decreased by replacing some of it by another absorber, U-238, in the form of depleted uranium from the tailings, i.e., waste product, of fuel enrichment plants for LWRs. Another advantage of using depleted uranium is the expected high conversion ratio because of the relatively hard neutron spectrum in the inner fuel pins. Fissile plutonium formation in the depleted uranium would offset the lack of U-235 in the inner fuel pins and contribute significantly to the overall energy produced by the fuel bundle.

The use of depleted uranium can therefore reduce the dysprosium requirement for a required void reduction. It also reduces the U-235 requirement for a given fuel discharge burnup since the energy produced in the depleted uranium is essentially free.

The efficacy of the dysprosium to reduce void reactivity should also be increased in the presence of depleted uranium because of the lack of fissile material in the inner pins. The flux rise in the inner pins on voiding will not result in a significant increase in fission rate. This should reduce the dysprosium requirement for a given void reactivity reduction.

2.5 Low Void Reactivity Fuel Bundle Designs

The following fuel bundle designs were used in the WIMS simulations to evaluate the U-235 requirements for specific targets of discharge fuel burnup and coolant void reactivity:

- a. standard 37-element fuel bundle design,
- b. standard CANFLEX 43-element fuel bundle design, and
- c. 43-element fuel bundle design with a large central pin.

Depleted uranium and dysprosium were used in the inner two rings, i.e., innermost seven fuel pins of the standard 37-element design. The amount of dysprosium in the inner seven pins and the U-235 enrichment in the outer 30 pins were adjusted to give the desired void reactivity and discharge fuel burnup.

The same procedure was used for the standard CANFLEX design, where depleted uranium and dysprosium were used in the inner eight fuel pins. The CANFLEX design is expected to perform better than the standard 37-element design because it can accommodate more depleted uranium in the inner eight fuel pins, which are larger than the remaining fuel pins in the outer two fuel rings. Also, the larger number of fuel pins in the outer fuel rings, i.e., 35 in the CANFLEX design vs 30 in the standard 37-element design, reduces the Maximum Linear Heat Generation Rate (MLHGR) in the fuel elements for a given bundle power output.

Figure 1 shows a 43-element fuel design, which is similar to the standard CANFLEX design except for the large central fuel pin. Depleted uranium is used in the inner eight fuel pins. However, the size of the central pin

allows the dysprosium to be located only in the central pin, where the void reduction effect is maximum and the parasitic load under nominal conditions is minimum. This fuel design is therefore expected to be the most cost-effective low void reactivity fuel design.

The above fuel designs were chosen because they require only minimum development effort based on present-day CANDU technology. More advanced LVRF designs, which have more than 43 fuel pins in order to improve void reactivity reduction and reduce MLHGR, are being considered.

3.0 WIMS SIMULATIONS OF LOW VOID REACTIVITY FUEL DESIGNS

3.1 Effects of Depleted Uranium

The effects of using depleted uranium in the LVRF designs were investigated using the 43-elements fuel design with a large central pin. Table 3.1 gives the U-235 contents in the four fuel rings for two cases:

- a. depleted bundle, where depleted uranium (0.25 wt% U-235) is used in the inner two fuel rings and Slightly Enriched Uranium (SEU) is used in the outer two fuel rings, and
- b. regular bundle, where SEU is used in all fuel rings.

Both fuel bundles give the same discharge fuel burnup of 21,000 Mwd/teU. However, the bundle-averaged fuel enrichment for the depleted bundle is 1.12 wt% U-235, which is lower than the 1.20 wt% U-235 required for the regular bundle. Also, the void reactivity for the depleted bundle is 13.3 mk, which is significantly lower than the corresponding value of 15.7 mk for the regular bundle.

Figure 2 shows the thermal neutron flux distribution within the two fuel bundles. The low flux level in the central pin, i.e., fuel 1, suggests that placing an absorber in the central pin will give the least U-235 enrichment penalty under nominal operating conditions.

Figure 3 shows the change in thermal neutron flux distribution within the fuel bundles due to coolant voiding. It is clear that the thermal flux increases in all the fuel rings upon voiding. However, the increase is smallest, i.e., less than 1%, in the outermost ring. The largest increase, about 12%, occurs in the central pin for both bundles. This suggests that the maximum void reactivity reduction effect will be achieved by putting the absorber in the central pin.

Table 3.1 U-235 (wt%) in Depleted and in Regular Fuel Bundle Designs Giving 21,000 Mwd/te Burnup					
	Ring 1	Ring 2	Ring 3	Ring 4	Bundle Average
Depleted	0.25	0.25	1.57	1.57	1.12
Regular	1.20	1.20	1.20	1.20	1.20

3.2 Detailed WIMS Reaction Rates

Optimization of the LVRF designs requires an understanding of the neutronic behaviour of the CANDU lattice under nominal and voided conditions. The

information can be obtained from the reaction rates calculated by WIMS for the depleted and for the regular bundles.

Table 3.2 shows the nu*fission rates by fuel ring in the depleted uranium fuel bundle. Table 3.3 shows the nu*fission rates in the regular fuel bundle. In the regular fuel bundle, as compared with the depleted uranium bundle, both the group 1 and group 2 reaction rates are higher in fuel rings 1 and 2. The nu*fission rates are concentrated in the outer fuel pins in the depleted uranium bundle.

Table 3.2 Nu*fission Rates in a Depleted Uranium Fuel Bundle at Equilibrium Fuel Burnup				
Group #	Nu*fission Rates (mk)			
	Fuel 1	Fuel 2	Fuel 3	Fuel 4
1	6.7	15.7	27.7	37.1
2	41.6	107.7	289.8	517.1

Table 3.3 Nu*fission Rates in a Regular Fuel Bundle at Equilibrium Fuel Burnup				
Group #	Nu*fission Rates (mk)			
	Fuel 1	Fuel 2	Fuel 3	Fuel 4
1	8.7	19.6	26.3	34.7
2	61.0	159.6	159.4	474.5

Table 3.4 shows the absorption rates by fuel ring in the depleted uranium fuel bundle. Table 3.5 shows the absorption rates in the regular fuel bundle. The fast group reaction rates are quite similar in the two bundle designs. As was the case with the nu*fission rates, the thermal group absorption rates are more concentrated toward the outer fuel rings in the depleted uranium fuel bundle.

Table 3.4 Absorption Rates in a Depleted Uranium Fuel Bundle at Equilibrium Fuel Burnup				
Group #	Absorption Rates (mk)			
	Fuel 1	Fuel 2	Fuel 3	Fuel 4
1	12.4	30.2	50.0	88.5
2	36.9	96.0	221.7	417.1

Table 3.5 Absorption Rates in a Regular Fuel Bundle at Equilibrium Fuel Burnup				
Group #	Absorption Rates (mk)			
	Fuel 1	Fuel 2	Fuel 3	Fuel 4
1	13.6	32.9	48.9	86.7
2	46.0	122.2	206.1	396.1

The ratio of production/absorption, i.e., eta, in the fuel rings in the two bundles is shown in Table 3.6. The variation of eta between fuel rings in the regular fuel bundle reflects the differences in the fuel burnup between fuel rings. In the depleted uranium fuel bundle, eta is less than 1.0 in the inner two rings. In the third and fourth fuel rings, eta is greater than 1.0 because of the relatively high enrichment level.

Table 3.6 ETA for the Regular and Depleted Uranium Bundles at Equilibrium Burnup					
Bundle Type	ETA				
	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Bundle-Averaged
Regular	1.1707	1.1523	1.1203	1.0545	1.0951
Depleted	0.9785	0.9778	1.1685	1.0962	1.0950

Table 3.7 shows the change in the nu*fission rates in the depleted uranium fuel bundle due to voiding. Table 3.8 shows the change in the nu*fission rates in the regular bundle due to voiding. In both bundle designs, the fast group production rates increase on voiding in all fuel pins. The increases are similar in the two designs. The changes in the thermal group nu*fission rates show the effect of the distribution of enrichment on void reactivity. In both bundle designs, the nu*fission rate drops in ring 4, with the largest decrease occurring in the regular bundle design. In ring 3, the nu*fission rate increases, with the largest increase occurring in depleted uranium bundle. In the inner two fuel rings the trend is reversed. The nu*fission rates increase more in the regular bundle design. The net effect of the changes in the nu*fission rates, in the two designs, is to increase the nu*fission rate in the regular bundle slightly more than in the depleted uranium bundle.

Table 3.7 Change in Nu*Fission Rates in a Depleted Uranium Fuel Bundle due to Voiding at Equilibrium Fuel Burnup				
Group #	Nu*Fission Rates (mk)			
	Fuel 1	Fuel 2	Fuel 3	Fuel 4
1	+ 0.5	+ 1.4	+ 2.0	+ 2.5
2	+ 3.4	+ 4.6	+ 8.9	- 8.7

Table 3.8 Change in Nu*Fission Rates in a Regular Fuel Bundle due to Voiding at Equilibrium Fuel Burnup				
Group #	Nu*Fission Rates (mk)			
	Fuel 1	Fuel 2	Fuel 3	Fuel 4
1	+ 0.6	+ 1.5	+ 1.9	+ 2.5
2	+ 6.3	+ 8.6	+ 6.3	- 10.9

Table 3.9 shows the change in the absorption rates in the fuel rings of the depleted uranium bundle due to voiding. Table 3.10 shows the change in the absorption rates in the fuel rings of the regular bundle due to voiding. In both bundle designs, the fast group absorption rates drop, by similar amounts in all fuel rings. The thermal group absorption rates increase in the inner three rings and drop in the outer ring in both designs. With the exception of ring 3, the changes in the absorption rates are largest in the regular bundle design. The net result of the changes in the absorption rates in the depleted uranium bundle is a slight increase in the absorption rate in the fuel on voiding. In the regular bundle design, the net change in the absorption rates in each fuel pin produces a drop in the absorption rate in the fuel.

Table 3.9 Change in Absorption Rates in a Depleted Uranium Fuel Bundle due to Voiding at Equilibrium Fuel Burnup				
Group #	Absorption Rates (mk)			
	Fuel 1	Fuel 2	Fuel 3	Fuel 4
1	- 0.7	- 2.0	- 3.0	- 2.6
2	+ 3.4	+ 5.2	+ 7.4	- 5.9

Table 3.10 Change in Absorption Rates in a Regular Fuel Bundle due to Voiding at Equilibrium Fuel Burnup				
Group #	Absorption Rates (mk)			
	Fuel 1	Fuel 2	Fuel 3	Fuel 4
1	- 0.7	- 2.0	- 3.1	- 2.7
2	+ 4.8	+ 7.5	+ 2.8	- 7.7

The net changes in the absorption and nu*fission rates in the two designs lead to a change in eta for each fuel ring. These changes are shown in Table 3.11 for the two designs. The changes in each fuel ring are similar in the two designs; however, the bundle-averaged change in eta is lower in the depleted uranium bundle. The difference between changes in the bundle-averaged eta's for the two designs reflects the differences in the importance of the inner fuel rings. The lower eta values of the inner fuel rings in the depleted uranium bundle lead to a smaller increase in the bundle averaged eta.

Table 3.11 Relative Change in ETA for the Regular and Depleted Uranium Bundles due to Voiding at Equilibrium Burnup					
Bundle Type	ETA				
	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Bundle-Averaged
Regular	+ 2.7%	+ 2.3%	+ 1.8%	+ 0.5%	+ 1.5%
Depleted	+ 2.5%	+ 2.3%	+ 1.8%	+ 0.6%	+ 1.2%

3.3 Summary of Results

Tables 3.12 and 3.13 give the void reactivity and MLHGR of the depleted and regular bundles for the 43-element fuel design with large central pin for different amounts of dysprosium in the central pin. The U-235 enrichment was adjusted to give a constant discharge fuel burnup of 21,000 MWd/teU. The superior performance of the bundle design using depleted uranium is clearly shown in Figure 4. Void reactivity can simply be considered as a design parameter which can be achieved by using an adequate amount of U-235 to compensate for the required amount of dysprosium. For the LVRF design using depleted uranium, zero void reactivity can be achieved for a bundle averaged U-235 enrichment of 1.75 wt%. Without depleted uranium, it is impossible to achieve zero void reactivity by adding dysprosium to the central pin alone. The addition of dysprosium to the second fuel rings will reduce the void reactivity to zero but will result in a much larger U-235 enrichment requirement.

Table 3.12 The Effect of Dysprosium on Void Reactivity, Enrichment Requirements and Maximum Linear Heat Generation Rate in the Depleted Uranium Fuel Bundle				
Dy Content in Central Pin	Bundle- Averaged Enrichment	Enrichment in Rings 3 & 4	Lattice Void (mk)	MLHGR* (kW/m)
0	1.12%	1.57%	13.3	62.0
2.5%	1.36%	1.90%	8.1	64.5
5.0%	1.50%	2.10%	4.3	65.5
7.5%	1.63%	2.28%	1.9	66.2
10.0%	1.76%	2.47%	- 0.4	66.9

* based on a bundle power of 1000 kW.

Table 3.13
The Effect of Dysprosium on Void Reactivity,
Enrichment Requirements and Maximum Linear Heat Generation Rate
in the Regular Fuel Bundle

Dy Content in Central Pin	Bundle- Averaged Enrichment	Enrichment in Rings 3 & 4	Lattice Void (mk)	MLHGR* (kW/m)
0	1.20%	1.20%	15.7	51.9
2.5%	1.45%	1.45%	11.6	55.1
5.0%	1.65%	1.65%	8.4	56.6
7.5%	1.78%	1.78%	6.3	57.5
10.0%	1.92%	1.92%	3.8	58.5

* based on a bundle power of 1000 kW.

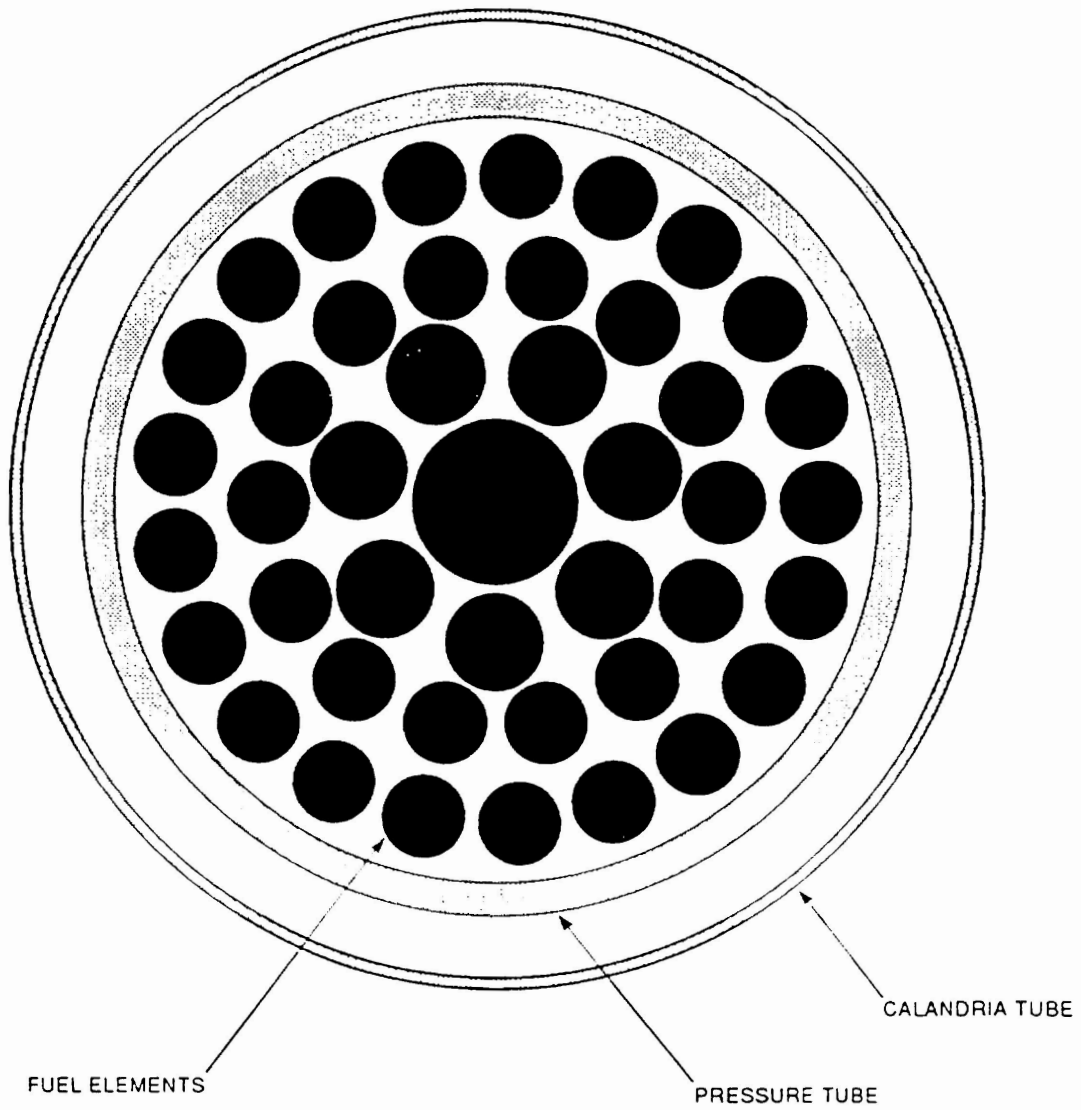
Figure 5 shows the relationships between void reactivity and U-235 requirement for different discharge fuel burnups for the standard CANFLEX fuel design. Depleted uranium and dysprosium were used in the inner eight fuel pins. The U-235 enrichments required to achieve zero void reactivity are 1.12 wt%, 1.44 wt%, and 1.82 wt% for fuel discharge burnups of 7,000 MWd/teU, 14,000 MWd/teU and 21,000 MWd/teU respectively.

Similar results are shown in Figure 6 for the standard 37-element fuel design. The U-235 enrichment required to achieve zero void reactivity are 1.18 wt%, 1.52 wt% and 1.92 wt% for discharge burnups of 7,000 MWd/teU, 14,000 MWd/teU and 21,000 MWd/teU respectively.

4. CONCLUSIONS

The use of depleted uranium in the inner pins of CANDU fuel bundles significantly reduces the U-235 enrichment penalty due to coolant void reactivity reduction and improves uranium utilization. The successful development of low void reactivity fuel bundles enables the CANDU reactor designers to design a CANDU with any targeted void reactivity, even negative void reactivity.

FIGURE 1



920236

43 ELEMENT BUNDLE DESIGN (LARGE CENTRAL ELEMENT)

THERMAL FLUX IN CANDU LATTICE AT MID BURNUP

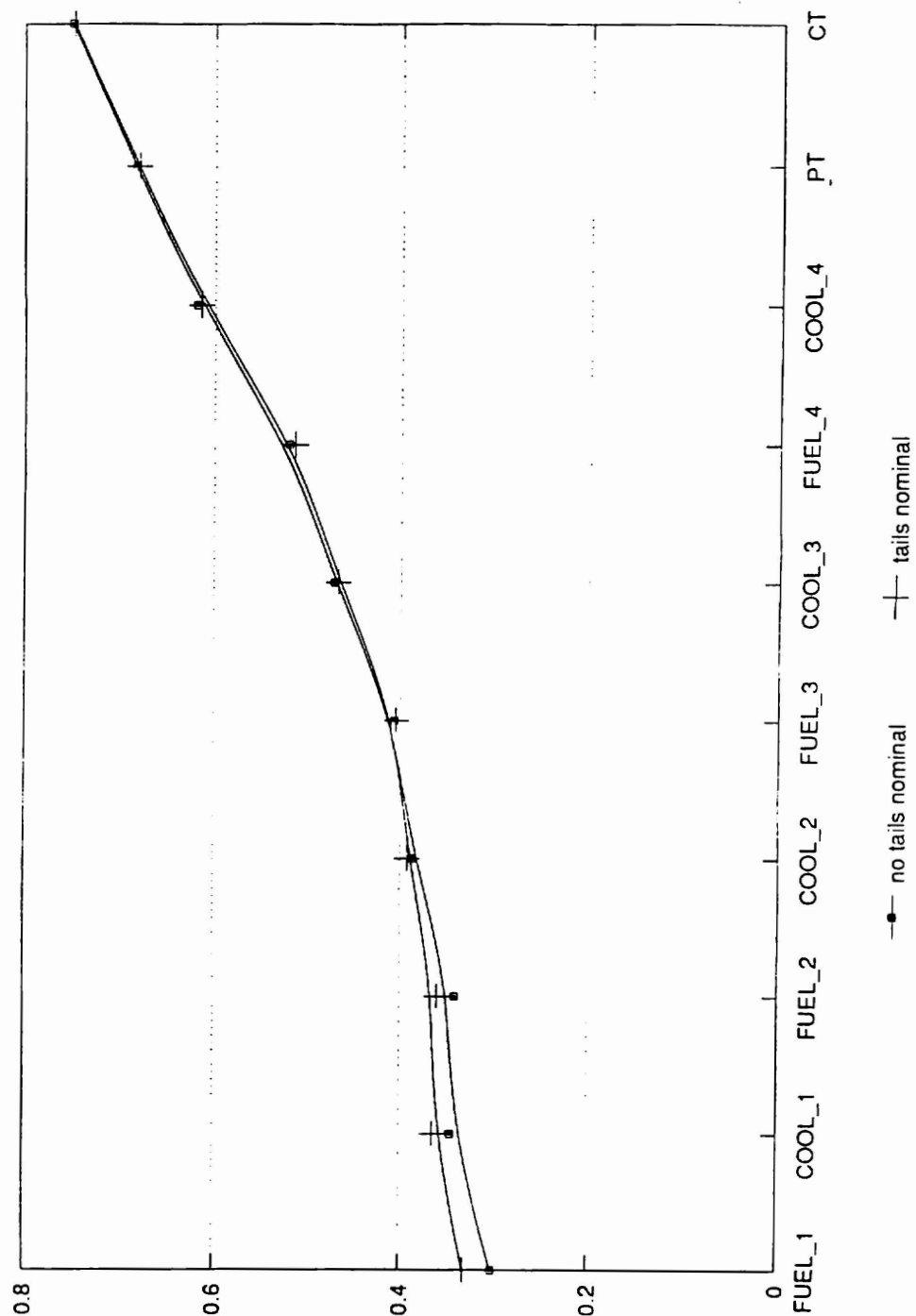


FIGURE 2

FIGURE 3

CHANGE IN THERMAL FLUX DUE TO VOIDING

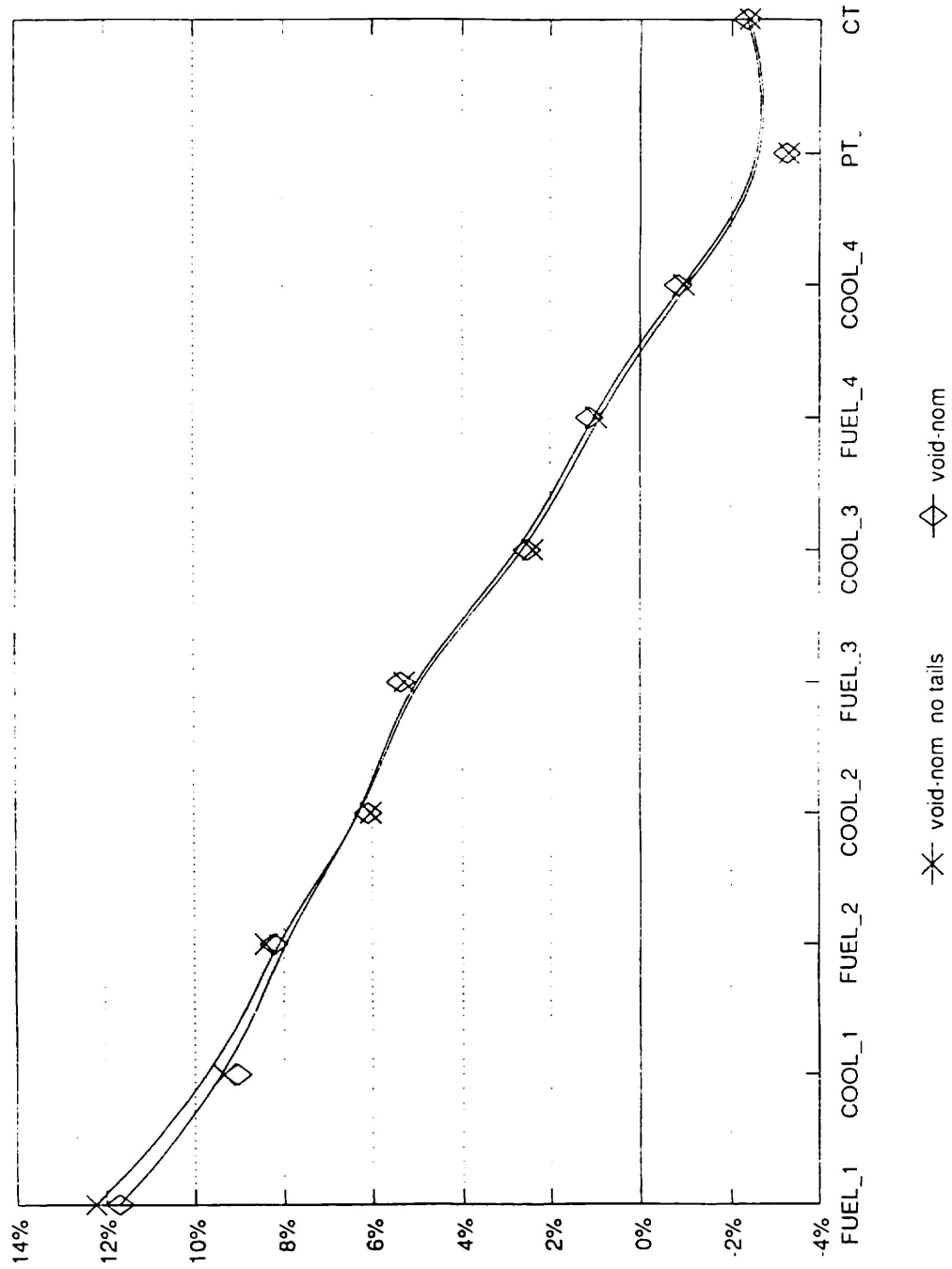
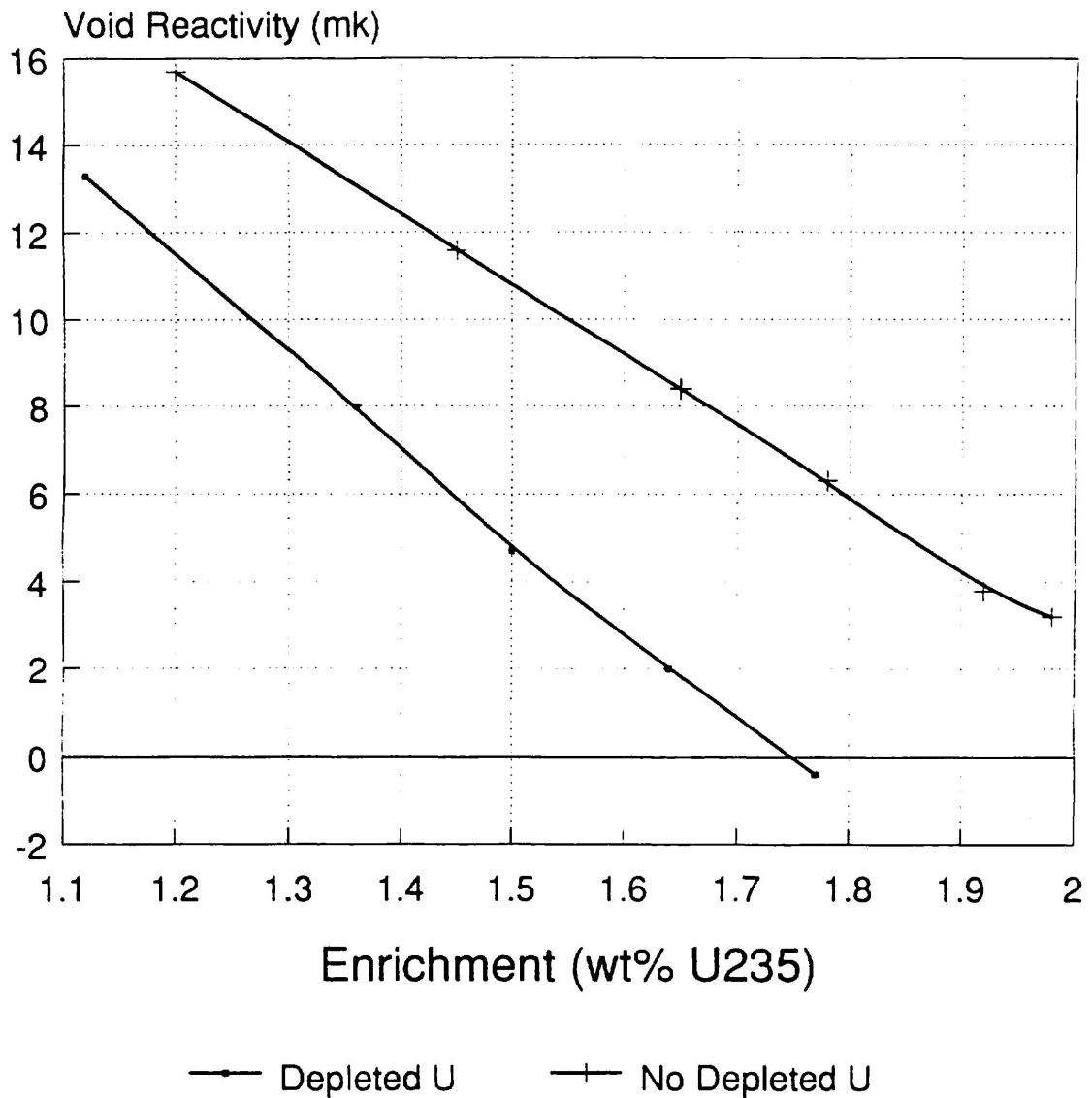


FIGURE 4

Void Reactivity vs Enrichment

43-Element Design with Large Central Pin

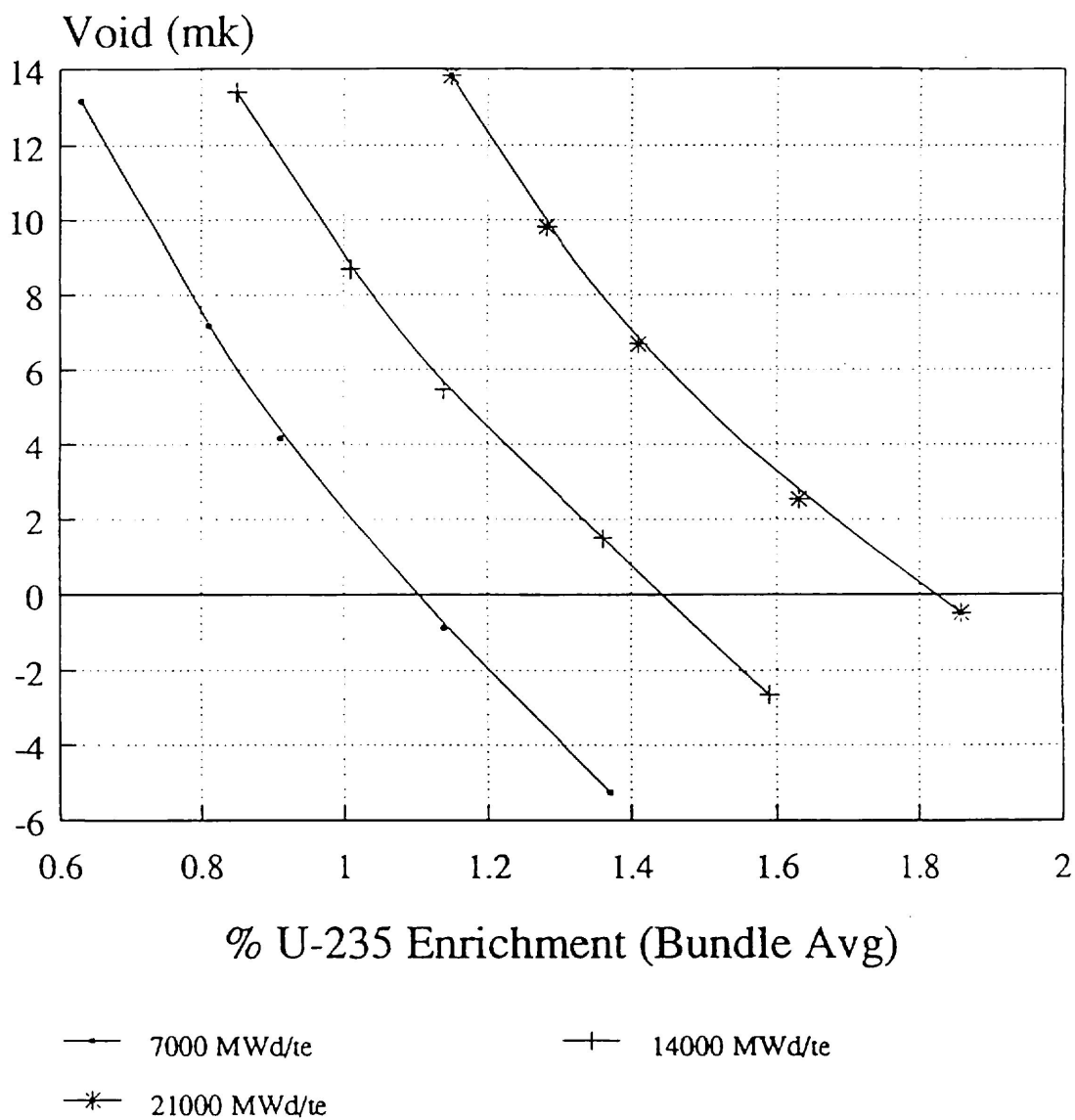
Effect of Depleted U in inner 8 Pins



bundle averaged discharge fuel burnup
is 21,000 MWd/teU for all cases
void reactivity at critical k-infinity

FIGURE 5

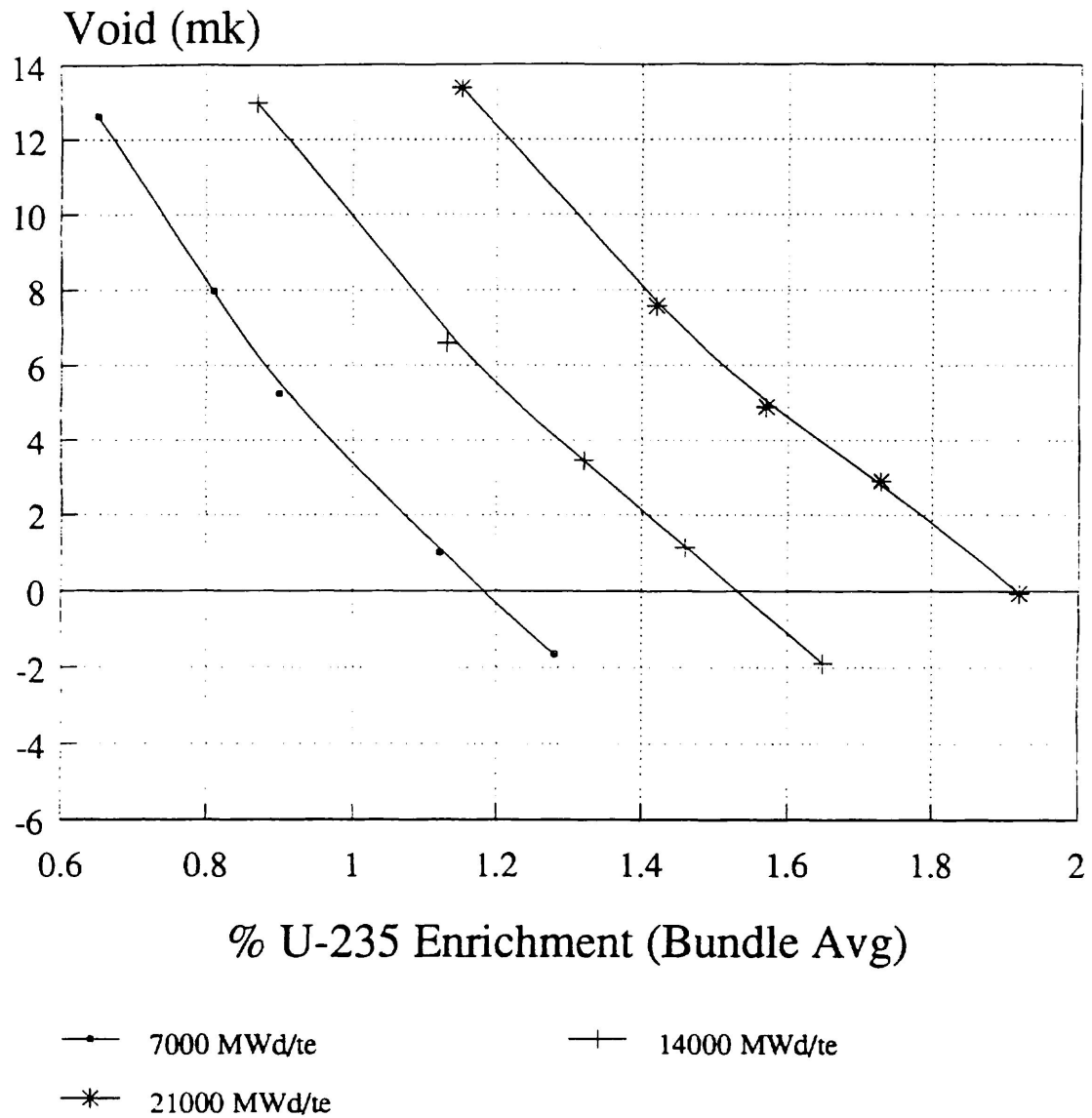
Lattice Void Reactivity vs Enrichment
43-elements CANFLEX Design for
different exit fuel burnups



Void Reactivity at Critical k-infinity
Uranium Tails & Dy in Central 8 pins

FIGURE 6

Lattice Void Reactivity vs Enrichment
37-elements Design for
different exit fuel burnups



Void Reactivity at Critical k-infinity
Uranium Tails & Dy in Central 7 pins