

THE USE OF GRAPHITE FOR THE REDUCTION OF VOID REACTIVITY IN CANDU REACTORS

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ABSTRACT

Coolant void reactivity can be reduced by using burnable poison in CANDU reactors. The use of graphite in the fuel bundle is introduced to reduce coolant void reactivity by adding an appropriate amount of burnable poison in the central rod. This study shows that sufficiently low void reactivity which is controllable by Reactor Regulating System (RRS) can be achieved by using graphite used fuel with slightly enriched uranium. Zero void reactivity can be also obtained by using graphite used fuel with a large central rod. A new fuel bundle with graphite rods can substantially reduce the void reactivity with less burnup penalty compared to previously proposed low void reactivity fuel with depleted uranium.

1. INTRODUCTION

In order to reduce coolant void reactivity in CANDU reactors, the use of depleted uranium in a fuel bundle was proposed⁽¹⁾ based on the understanding of neutronic behavior of the CANDU lattice under nominal and voided conditions.

When depleted uranium is used in a fuel bundle, however, the fraction of power shared by depleted uranium is very small since fissile content of depleted uranium is small and burnup penalty is not so small because depleted uranium acts as an absorber. Also, by using depleted uranium, a large amount of actinide isotopes are produced as radioactive wastes.

To resolve above problems, graphite is introduced to the bundle instead of depleted uranium. The fuel bundle consists of intermediate and outer fuel elements containing slightly enriched uranium, a central graphite rod poisoned with burnable poison (dysprosium) and surrounding graphite rods as an inner ring. That is, the depleted uranium rods from the previously proposed fuel are replaced by graphite rods. Graphite rods inside the fuel bundle act as moderator/reflector under normal condition which give better neutron economy. When void occurs, these graphite rods support central burnable poison to suppress positive reactivity by thermalizing fast neutrons.

Above concept was evaluated for the standard CANFLEX⁽²⁾ and large central rod fuel bundles with slightly enriched uranium. In this paper, the use of graphite in the fuel bundle is focused instead of using depleted uranium.

2. PRINCIPLE OF COOLANT VOID REDUCTION⁽¹⁾

In CANDU reactor, the change of neutron spectrum brings positive reactivity on voiding. 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 due to the location of the fissile material in the fuel bundle.

The production of new negative reactivity components due to voiding is focused rather than attempting to reduce the magnitude of the positive void reactivity components. This is achieved by making use of redistribution of 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, where the thermal neutron flux increases on voiding. From this feature, the use of depleted uranium and burnable poison in the central rod was proposed for low void reactivity.

Natural dysprosium was selected due to the optimum burnout rate which satisfies several conditions. In this paper, the use of graphite and burnable poison is introduced to improve fuel cycle economy with low void reactivity.

3. WIMS CALCULATIONS

The simulations are carried out with the WIMS-AECL code⁽³⁾. The Winfrith library is used for the neutron cross sections. The neutron spectrum is calculated in thirty-three energy groups. The PIJ option is used to model the fuel elements discretely in the WIMS calculations.

The Winfrith library has only dysprosium-164 data for dysprosium isotope. Therefore, DY164 data is considered as natural dysprosium for WIMS calculations.

Reactivity of the lattice that would produce a critical reactor was obtained from the previous analysis of the CANDU 6 reactor. The k-infinity of the critical lattice was 1.045. The excess reactivity of 45 mk is accounted for the reactor leakage as well as all the absorptions, other than those occurring in the fuel channels, in the reactor.

Two fuel bundle designs are used to evaluate for the specific targets of coolant void reactivity. The first is standard CANFLEX 43-element fuel bundle design (Fig. 1(a)). The second is 43-element fuel bundle design with a large central rod (Fig. 1(b)). The amount of dysprosium in the central rod was adjusted to give the desired void reactivity.

WIMS calculations are done for the standard CANFLEX and for the large central rod fuel bundles of 1.2 wt %, 1.4 wt %, 1.7 wt % and 2.0 wt % enriched uranium having an appropriate amount of burnable poison in the central rod. The fuel bundles consist of outer two rings containing slightly enriched uranium, central depleted uranium or graphite rod poisoned with burnable poison and surrounding depleted uranium or graphite rods as inner rings.

3.1 Standard CANFLEX Geometry

The effects of using depleted uranium (0.25 wt %) and graphite in the LVRF (Low Void Reactivity Fuel) designs are investigated using the standard CANFLEX fuel. Table 1 shows the variations of discharge burnup, void reactivity and MLHGR (Maximum Linear Heat Generation Rate) versus amount of burnable poison in the central rod. In the case of depleted uranium, the average discharge burnup of ring 3 and ring 4 elements is shown in parentheses. The discharge burnups of the graphite used fuel are larger than those of depleted uranium used fuel.

Using depleted uranium and 1.2 wt % enriched uranium fuel, zero void reactivity can not be achieved and discharge fuel burnup is significantly reduced. However, using graphite, zero void reactivity can be achieved and discharge fuel burnup is relatively large. For the same void reactivity case (1.9 mk) in Table 1, the energy output per fuel bundle from graphite used fuel is 2.0 times of that from the reference fuel (depleted uranium used fuel).

The other calculations are done for higher enriched uranium fuel in order to increase discharge burnup. They have similar tendency with Table 1. In the cases of both fuels for higher enrichment, zero void reactivity can not be achieved.

3.2 A Large Central Rod Geometry

The effects of using depleted uranium and graphite in the LVRF designs are investigated using the 43-elements fuel design with a large central rod to make zero void reactivity with sufficient burnup. Table 2 shows the variations of discharge burnup, void reactivity and MLHGR versus amount of burnable poison in the central rod. The discharge burnups of graphite used fuel are larger than those of depleted uranium used fuel.

Using depleted uranium and 1.2 wt % enriched uranium fuel, zero void reactivity can be achieved but the discharge fuel burnup is significantly reduced. Using graphite, zero void reactivity can be also achieved but the discharge fuel burnup is relatively high. In this case, discharge burnup of zero void reactivity fuel is almost same as that of the current natural uranium fuel. However, since the uranium mass of graphite fuel is less than that of current fuel, the energy output per bundle with zero void reactivity (103.2 MWD) is small compared to that of current natural uranium fuel in CANDU reactors.

The other calculations are done for higher enriched uranium fuel in order to increase discharge burnup. They have similar tendency with Table 2.

4. RESULTS AND DISCUSSIONS

Reduction in the void reactivity that is potentially held up in the coolant will limit the reactivity excursion during a LOCA. If zero 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. Low void reactivity (2 mk) which is sufficiently controlled by RRS (specially, Zone Control Unit) when LOCA occurs, is focused. In this case, behavior of large LOCA may be similar to that of small LOCA in current CANDU reactors. Zero void reactivity is also to be target with a large central rod.

Figure 2(a) shows the relationships between discharge burnup and U^{235} enrichment for low void reactivity fuel with the standard CANFLEX geometry. In the 1.2 wt % enriched uranium fuel, the discharge burnup of the graphite used fuel is 2.4 times of that of the depleted uranium used fuel. In the 2.0 wt % enriched uranium fuel, however, the discharge burnup of the graphite used fuel is 1.3 times of that of the depleted uranium used fuel. Figure 3(a) shows the relationships between discharge burnup and U^{235} enrichment for low void reactivity fuel with the large central rod. In the 1.2 wt % enriched uranium fuel, the discharge burnup of the graphite used fuel is 1.8 times of that of the depleted uranium used fuel. In the 2.0 wt % enriched uranium fuel, however, the discharge burnup of the graphite used fuel is 1.3 times of that of the depleted uranium used fuel. Figure 4(a) shows the relationships between discharge burnup and U^{235} enrichment for zero void reactivity fuel with the large central rod. In the 1.2 wt % enriched uranium fuel, the discharge burnup of the graphite used fuel is 4.0 times of that of the depleted uranium used fuel. In the 2.0 wt % enriched uranium fuel, however, the discharge burnup of the graphite used fuel is 1.4 times of that of the depleted uranium used fuel.

Figures 2(b), 3(b) and 4(b) show the relationships between energy output per bundle and U^{235} enrichment for three types of fuel bundles. In the 1.2 wt % enrichment, the energy outputs per fuel bundle from graphite used fuels are much better than those from depleted uranium used fuels. However the benefits of graphite fuels reduce at higher enrichments as known from behavior of discharge burnups. In the 2.0 wt % enrichment, the energy outputs per fuel bundle from graphite used fuels are almost same as those from depleted uranium used fuels.

Figures 2(c), 3(c) and 4(c) show the relationships between MLHGR and U^{235} enrichment for three types of fuel bundles. Although figures show that graphite fuel always results in slightly higher MLHGR, the increase of MLHGR due to the replaced graphite rods is less than 5% and can be ignored.

From the above results, as enrichment of fuel increases, the discharge burnup of the depleted uranium used fuel increases significantly because the conversion ratio of depleted uranium is increased because of sufficient fast neutrons. Zero void reactivity can not be achieved in standard CANFLEX geometry. Low void reactivity can be achieved by using graphite fuel with less burnup penalty. In a large central rod geometry, zero void reactivity fuel with the graphite rods is also more effective than that with the depleted uranium rods.

As for the bundle dimensional stability, the following two parameters are considered. One is the dissolution of graphite through chemical reaction with oxygen in the form of CO or CO₂ gases, which consequently leads to the increase in the element internal pressure. The other is the axial expansion of the elements into different lengths at each ring due to the difference in power and neutron flux. The former parameter is considered to be insignificant because of low temperature and no fission gas production. The latter should be evaluated and reflected for the design optimization of the fuel bundle which has graphite-filled elements for low void reactivity.

5. CONCLUSION

Graphite used fuel is found to improve fuel economy compared with the depleted uranium used fuel for low void reactivity. This new fuel bundle reduces void reactivity substantially with less burnup penalty compared to previously proposed fuel bundle⁽¹⁾.

In the case of low void reactivity which can be sufficiently controlled by RRS when LOCA occurs, the use of graphite in fuel bundle is much better than that of depleted uranium. In the case of zero void reactivity, the use of graphite in fuel bundle is also more economical than that of depleted uranium in fuel bundle. If low (or zero) void reactivity is required for CANDU reactors, the fuel cost might be reduced by using graphite for the low void reactivity fuel.

REFERENCE

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Table 1. Variation of Discharge Burnup and Void Reactivity for 1.2 wt % Enriched Fuel (CANFLEX)

Dy Content in Central Rod	Estimated Discharge Fuel Burnup (MWD/T)		Void Reactivity at Mid Burnup (mk)		Energy Output per Bundle (MWD)		MLHGR***	
	Dep. U*	Graphite**	Dep. U	Graphite	Dep. U	Graphite	Dep. U	Graphite
0 %	15907(18287)	20336	11.5	9.7	295.9	286.7	58.89	61.66
10 %	5386(6561)	17173	2.3	8.3	100.2	242.1	60.24	62.45
20 %	4524(5520)	12520	2.0	3.2	84.1	176.5	60.30	62.66
25 %		10515		1.9		148.3		62.70
30 %		9403		1.4		132.6		62.73
40 %	3966(4826)	8300	1.9	1.0	73.8	117.0	60.34	62.76
100 %	3378(4056)	6529	1.5	0.0	62.8	93.5	60.39	62.77

* : Fuel with Depleted Uranium

** : Fuel with Graphite

*** : Maximum Linear Heat Generation Rate Based on a Bundle Power of 1000kW

() : The Average Discharge Burnup of the Ring 3 and Ring 4

Table 2. Variation of Discharge Burnup and Void Reactivity for 1.2 wt % Enriched Fuel (A Large Central Rod)

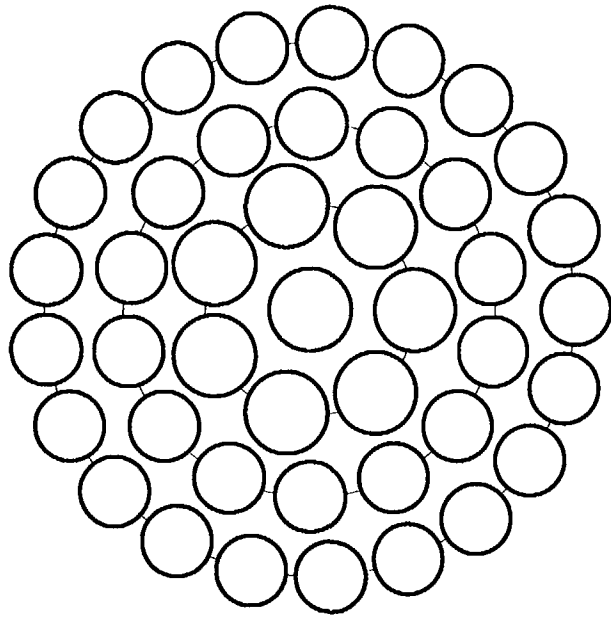
Dy Content in Central Rod	Estimated Discharge Fuel Burnup (MWD/T)		Void Reactivity at Mid Burnup (mk)		Energy Output per Bundle (MWD)		MLHGR***	
	Dep. U*	Graphite**	Dep. U	Graphite	Dep. U	Graphite	Dep. U	Graphite
0 %	16127(18412)	20360	11.6	9.9	296.1	287.1	59.01	61.66
1 %	10569(12439)		6.6		194.0		60.44	
1.5 %	6469(7803)		2.4		118.8		60.70	
2 %	3196(3926)		0.6		58.7		60.87	
5 %	188(234)	16357	-0.7	8.3	3.5	230.6	61.22	62.74
7 %		14153		5.9		199.6		62.91
8 %		12721		4.3		179.4		62.97
9 %		10929		2.5		154.1		63.03
10 %		9022		0.9		127.2		63.07
11 %		7463		0.1		105.2		63.11
12 %		6297		-0.7		88.8		63.14

* : Fuel with Depleted Uranium

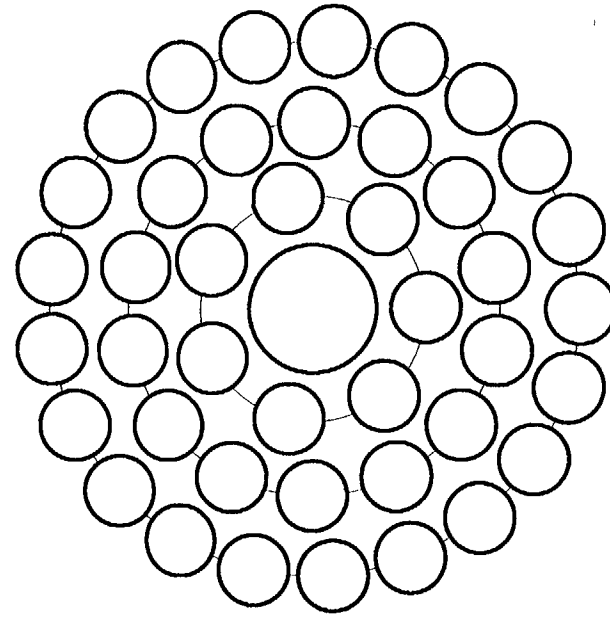
** : Fuel with Graphite

*** : Maximum Linear Heat Generation Rate Based on a Bundle Power of 1000kW

() : The Average Discharge Burnup of the Ring 3 and Ring 4

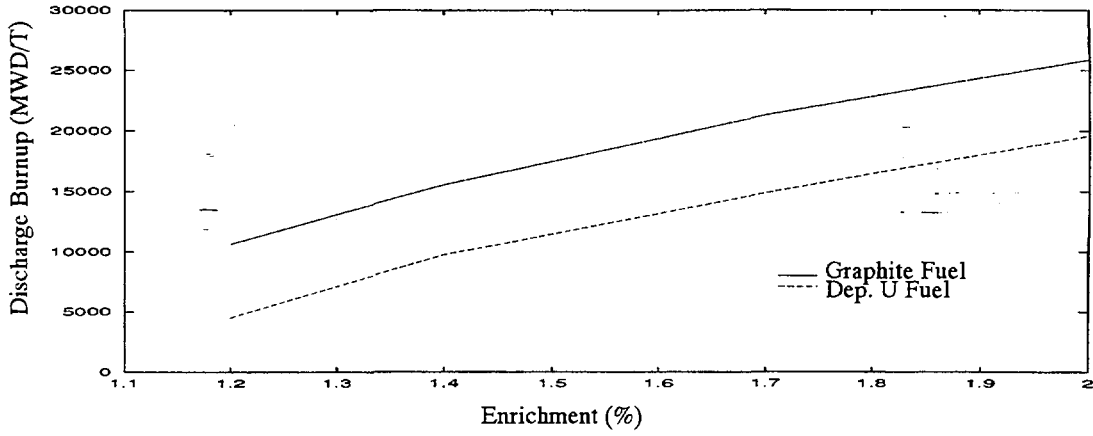


(a) The Standard CANFLEX Geometry

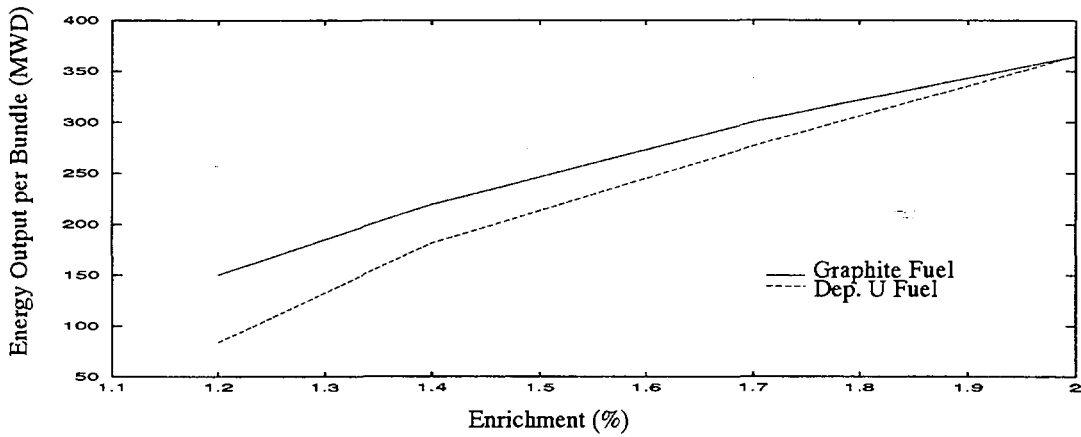


(b) A Large Central Rod Geometry

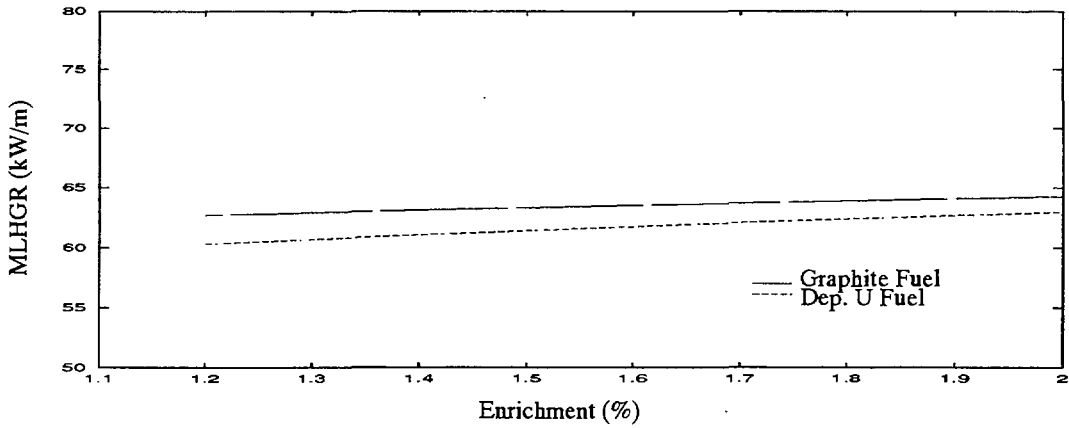
Figure 1. 43 Elements Bundle Design



(a) Discharge Burnup vs. Enrichment

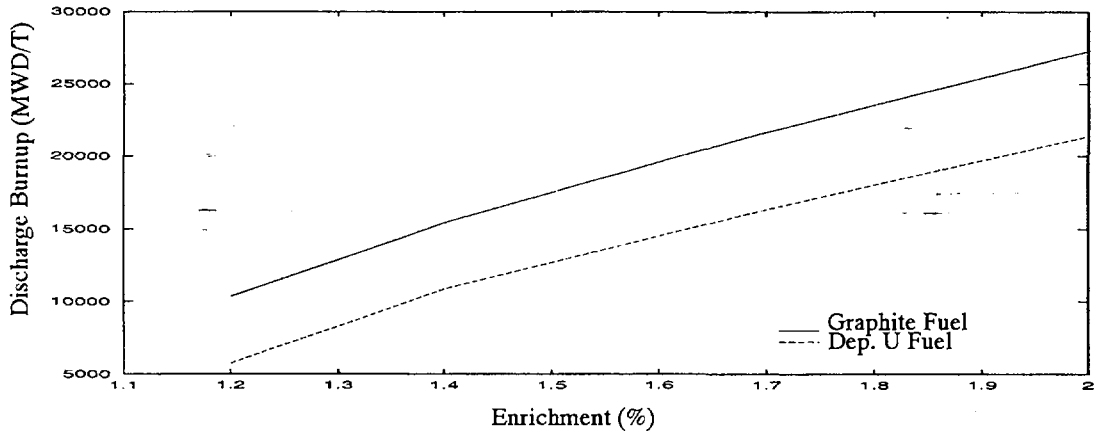


(b) Energy Output per Bundle vs. Enrichment

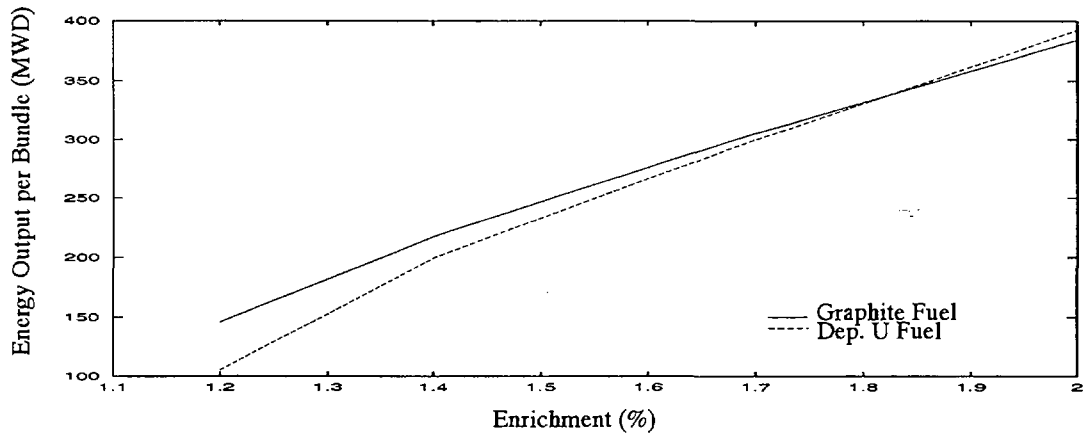


(c) Maximum Linear Heat Generation Rate vs. Enrichment

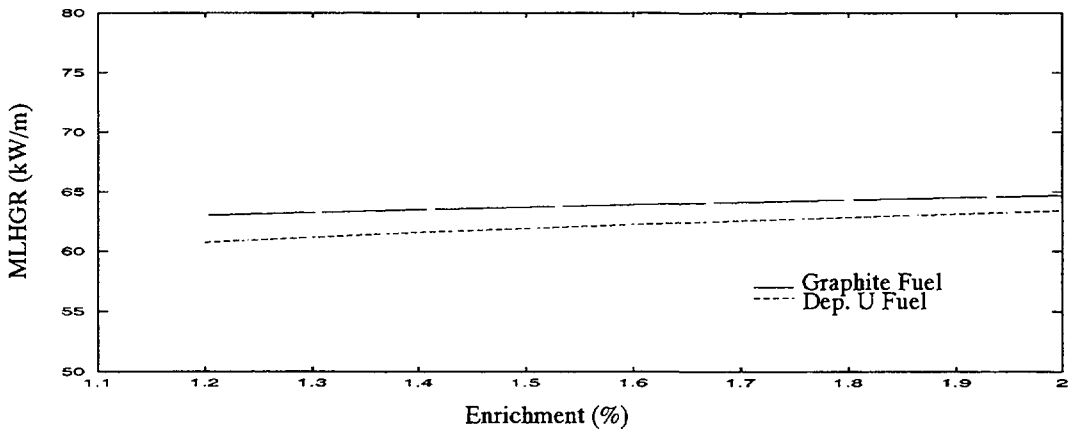
Figure 2. Physics Parameters for Low Void Reactivity Fuel (2 mk) with CANFLEX Geometry



(a) Discharge Burnup vs. Enrichment

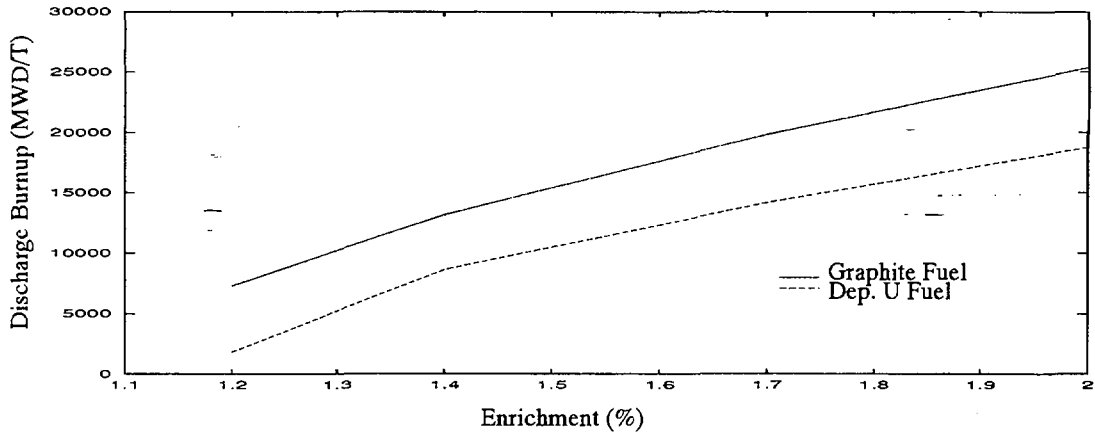


(b) Energy Output per Bundle vs. Enrichment

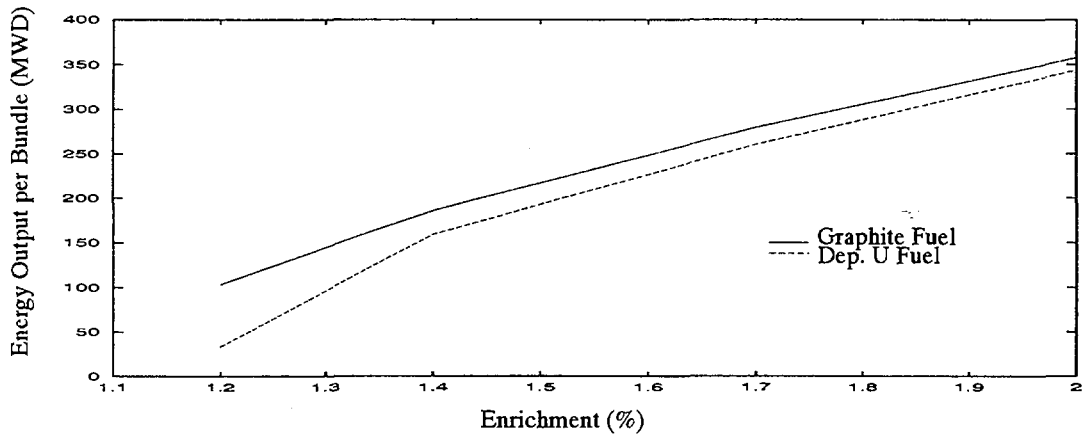


(c) Maximum Linear Heat Generation Rate vs. Enrichment

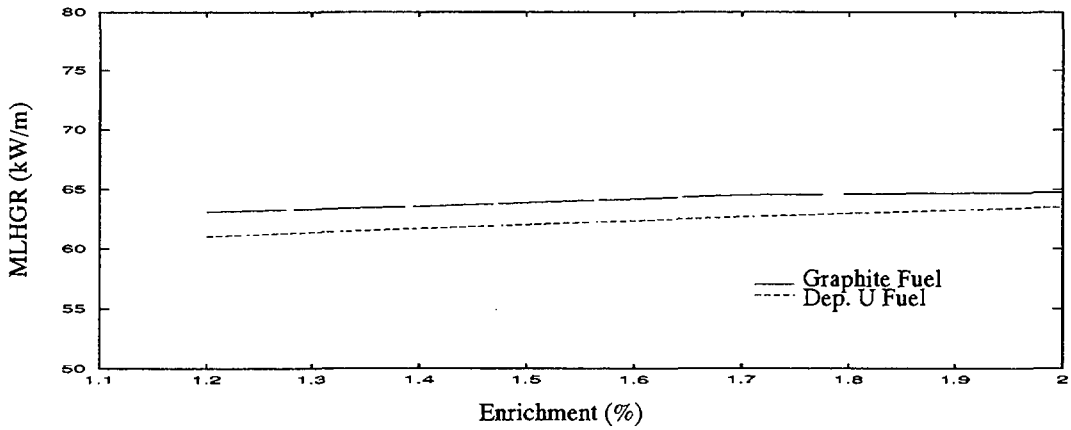
Figure 3. Physics Parameters for Low Void Reactivity Fuel (2 mk) with Large Central Rod



(a) Discharge Burnup vs. Enrichment



(b) Energy Output per Bundle vs. Enrichment



(c) Maximum Linear Heat Generation Rate vs. Enrichment

Figure 4. Physics Parameters for Zero Void Reactivity Fuel (0 mk) with A Large Central Rod