# Lattice Characteristics that Influence the Change In Reactivity with Coolant Voiding in CANDU Lattices

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ABSTRACT

The reactivity change in CANDU following coolant voiding is determined by a delicate balance of reactor physics phenomena. These in turn depend, most sensitively, upon the relative volumes of coolant and moderator, the relative temperature of the coolant and moderator and the fuel enrichment. The influence of these parameters is explained in terms of classic four-factor reactor theory.

A proper simulation of the void effect can only be obtained from full core calculations. However, the simpler approach of using a lattice cell code such as WIMS-CRNL does allow the magnitude of the void effect to be estimated.

WIMS-CRNL results that predict the way the void effect changes with fuel enrichment and channel geometry are presented and shown to be in qualitative agreement with the simple four-factor explanation. The geometry changes include moderator volume, coolant-to-fuel volume ratio and coolant displacers.

It is shown that one way that loss of coolant results in a positive void effect is due to the loss of scattering inside the fuel bundle. If this loss can be reduced, a less positive void effect would be expected. Coolant displacers could be used to replace the innermost fuel pins with a solid scattering material which is not removed when the coolant is voided. WIMS-CRNL results confirm these expectations.

As all methods of changing the size of the void effect result in changes to the absolute reactivity, corresponding burnup changes are to be expected. WIMS-CRNL calculations demonstrate that, with the exception of coolant displacers, a significant reduction in the magnitude of the positive void coefficient is accompanied by large burnup losses.

For completeness some experimental data are presented. These data indicate the way that the void effect changes with lattice pitch,the agreement between WIMS-CRNL and experimental data for the total void effect, and the effect of coolant displacers.

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# Lattice Characteristics that Influence the Coolant Void Reactivity in CANDU Lattices.

## 1. Introduction

The effect of changing fuel enrichment and fuel channel geometry on the coolant void effect are assessed. Variations in fuel channel geometry have been made by:

- Changing the volume of the moderator by either altering the lattice pitch or by increasing the outer diameter of the calandria tube.
- Changing the relative amounts of fuel and coolant
- Increasing the bundle subdivision
- Replacing the central fuel pins by a fixed neutron scattering material

Not all of the changes in channel geometry or bundle design that have been considered would be physically possible. The intent was to determine the magnitude of the effect of changes in particular parameters to assess possible directions for future work.

For completeness some experimental information and comparison between calculation and experiment are included.

All the calculated results were obtained with the WIMS-CRNL lattice code using the UK nuclear data library.[1,2]

## 2. Background

### 2.1. Modelling Problems

The accurate calculation of the effects of coolant voiding in a CANDU reactor is complex, involving both spatial and temporal effects. Fuel properties can vary significantly along the length of the fuel channel, especially with enriched fuels. The effects of coolant voiding depend on the physical scenario being modelled and on the configuration of the primary heat transport system.

It is not possible to model such complicated effects using only a lattice code such as WIMS-CRNL. However, WIMS-CRNL can be used to estimate the overall change in reactivity on voiding a core which contains everywhere the same fuel. Results from mid burnup are then the only ones that in any way represent the behaviour of a real reactor and approximate the behaviour of an equilibrium core.

2.2. WIMS-CRNL Leakage Spectrum

The use of a cell code to calculate the full core reactivity is complicated by the sensitivity of the void reactivity to the method of calculation. With WIMS-CRNL the sensitivity is most affected by the choice of the leakage spectrum. For the calculations presented here the spectrum is that obtained by using a spectrum characterised by the reactor geometric buckling.

Other work indicates that with this spectrum the void effect at mid-burnup is in quite good agreement with full-core equilibrium calculations. While the burnup dependence has been indicated for some cases the results are not realistic as they refer to a full core at that burnup and are intended only to illustrate the trends. In some cases only zero-burnup data are presented and again this is meant to illustrate trends and is not usually representative of any practical situation.

2.3. Phenomena which contribute to the void effect

It is of interest to identify the major phenomena contributing to the void effect. For this purpose it is convenient to divide the neutron energy spectrum into three ranges

- Fast, covering the energy range above 0.8 Mev.
- Resonance, covering the energy range from 0.8 Mev down to 4 ev.
- Thermal, below 4 ev.

2.3.1. Fast Energy Range

The major contributor to the void effect in the fast energy range is the fission of U-238. On voiding the coolant, fewer fission neutrons are scattered to lower energy. As a result there is an increase in the number of fast fissions leading to an increase in reactivity. This contribution to the void effect becomes larger as the lattice pitch decreases and the number of fast fissions increase. Coming primarily from U238 this contribution is not significantly affected by enrichment or burnup.

2.3.2. Resonance Energy Range

The major contributor to the void effect in the resonance energy range is neutron absorption in the principal resonance absorber, usually U238. This contribution can be most simply described in terms of the resonance escape probability p. p can be considered as a function of two terms, the slowing down power $\xi\Sigma_s$ and the effective resonance integral for the fuel bundle I.

$$p \approx \exp - \left[ \frac{N}{\xi\Sigma_s} * I \right]$$

Where N is the number of absorbing nuclei per unit volume and the slowing down power $\xi\Sigma_s$ is the product of the average logarithmic energy decrement per collision and the macroscopic scattering cross section of the lattice cell.

The macroscopic scattering cross section has two principal components, that due to the coolant and that due to the moderator. For normal or larger lattice pitches, the latter contribution is the larger of the two.

The effective resonance integral is dependent on the effective surface area of the fuel. This area is a function of the coolant scattering cross section because the coolant provides an internal source of resonance neutrons.

On loss of coolant then, the coolant scattering cross section decreases leading to a decrease in the effective resonance integral and an increase in the resonance escape probability and hence reactivity. The reduction in the coolant scattering cross section reduces the slowing down power $\xi\Sigma_s$ leading to a decrease in the resonance escape probability and hence reactivity. The balance between the resonance integral and slowing down power effects depends upon the relative amounts of coolant and moderator. Coming primarily from U238, this contribution is not significantly affected by burnup or enrichment.

### 2.3.3. Thermal Energy Range

The contribution from the thermal energy range can be described most conveniently in terms of the thermal utilization f, the ratio of the number of thermal neutron absorptions in the fuel to those in the lattice cell, and "eta", the ratio of the number of fast neutrons produced per thermal neutron absorbed in the fuel.

The thermal utilization tends to increase on voiding as the loss of parasitic absorption in the coolant reduces the thermal neutron absorption in the cell. Any processes that tend to increase the fuel neutron absorption will reduce the effect of voiding the coolant. Included in this category are fuel enrichment, burnup and increased lattice pitch. In $D_2O$ cooled lattices the small $D_2O$ thermal neutron absorption cross section results in the contribution from f to the void effect being small.

The change in "eta" on coolant voiding depends on the change in the thermal neutron spectrum which in turn depends on the relative temperature of the coolant and moderator. It is convenient to describe the thermal neutron spectrum in terms of two parameters, the epithermal index, r, that measures the proportion of neutrons in the spectrum which are not part of a Maxwellian distribution and the effective neutron temperature, T, which identifies the peak of the Maxwellian distribution.

On voiding the coolant the epithermal index increases. The effect on the effective neutron temperature of voiding the coolant depends upon the physical temperature of the moderator and coolant. If the moderator and coolant temperatures are the same, as is often the case with zero energy experiments, then the effective neutron temperature will increase on voiding. However, when the coolant is hotter than the moderator then the effective temperature will decrease on voiding.

For uranium fuels, the effect of the change in T usually predominates with a reduction in T causing an increase in "eta", and hence reactivity, and vice-versa. The increase in r becomes important for relatively large values of r such as can occur with tight pitches or enriched fuel and has the effect of decreasing "eta" and hence the reactivity.

The majority of the calculated results presented later are for the situation of hot coolant. In this case at normal or larger pitches, the thermal contribution to the void effect will be positive, reducing with pitch or increasing enrichment and eventually becoming negative.

In fuels containing significant amounts of plutonium, the thermal contribution to the void effect through "eta" is always negative for the situation where the coolant is hotter than the moderator. This is due to the reduction in the neutron absorption in the Pu239 and Pu241 resonance at about 0.3ev. As fuel is irradiated and plutonium is produced this effect would be expected to decrease the void effect.

## 2.4. Predicted Void Effect Variations

The largest contribution to the change in the infinite multiplication factor $k_\infty$ comes from the resonance and fast effects. Consequently the change in $k_\infty$ on voiding the coolant is effectively independent of enrichment. Defining the void effect as $\delta k_\infty / k_\infty$ then results in the prediction that, with fresh fuel, the void effect should decrease with increasing enrichment due to the increase of $k_\infty$.

As the fuel is irradiated, the initial uranium enrichment reduces, causing the void effect to increase with burnup. At the same time plutonium builds in, causing the void effect to decrease with burnup. These two opposite effects can combine to produce three basic variations of the void effect with irradiation

- Decreasing initially as plutonium is produced then levelling out and maybe increasing as the U235 burns out

- Increasing initially as the U235 burns out then peaking and decreasing as the plutonium is produced

- Essentially constant, with the effects due to uranium depletion and plutonium production in balance

The effect of changing the lattice pitch on the void effect arises primarily from the resonance escape probability. Because of the overwhelming contribution of the moderator to the slowing down power at normal or larger lattice pitches, the change in the slowing down power is small compared to the change in resonance integral, and the net effect is an increase in reactivity. However as the lattice pitch is decreased, the change in the slowing down power on coolant voiding becomes more important leading, at fairly tight pitches, to a decrease in the reactivity.

## 3. Experimental Information

### 3.1. Change in Buckling on Voiding

The change in buckling on voiding a lattice can be obtained from experiments performed in the ZED-2 zero energy reactor and similar facilities. The measured change in buckling upon voiding gives an indication of the change in reactivity, a positive change in buckling indicating an increase in reactivity. The results presented in Figure 1 are for natural uranium in a variety of bundle designs and indicates the change in the void effect as the moderator volume is reduced.[3,4,5] The variation with moderator volume is in qualitative agreement with the expectations of section 2.4. Down to a moderator volume of about 500 $cm^3$ the moderator dominates the total slowing down power resulting in a positive and slowly decreasing void effect. At moderator volumes below 500 $cm^3$ the coolant dominates the slowing down power, and the void effect decreases rapidly even becoming negative.

### 3.2. Comparison of Calculated and Experimental Void Effect

Sixteen natural uranium and nine plutonium uranium fueled lattices have been used for this comparison. For all these lattices the buckling has been measured with both $D_2O$ and voided coolant.

When the measured buckling is used by the lattice code, the calculated value of the effective multiplication factor, $k_{eff}$, should equal one. The difference between the calculated $k_{eff}$ with voided and $D_2O$ cooled channels should then be equal to zero.

Figure 2 is a plot of this difference in $k_{eff}$ against the ratio of the fuel to moderator volume. The scatter in the results arises partly from experimental error, ≈±5 mk, and partly from the different coolant volumes associated with the different fuel bundle designs. A regression line fitted to these data is:

$$k^v_{eff} - k^c_{eff} = -1.99 + 40.63 \left[ \frac{Vf}{Vm} \right]$$

where the superscripts v and c refer to voided and cooled.
This line is just statistically significant and has a standard error of estimate of ±1.83 mk.

For the standard CANDU 600 this line predicts that WIMS -CRNL overestimates the void effect by 0.57±1.83 mk.

### 3.3. Experimental and Calculated Coolant Displacer effects

Experiments to investigate the effect of coolant displacers were performed in ZED-2.[6] There were two sets of experiments in which the void effect was inferred by substituting one test bundle into a critical reference core.

The first set of experiments was based on a 37-element fuel bundle. The void effect was measured for the following bundle configurations:

- the 37-element bundle
- the 37-element bundle with the central seven elements removed (37/1)
- the 37-element bundle with the central seven elements replaced by an air filled tube (37/2)
- the 37-element bundle with the central seven elements replaced by a $D_2O$ filled tube (37/3)

The second set of experiments was based on a 61-element fuel bundle. The void effect was measured for the following bundle configurations:

- the 61-element bundle
- the 61-element bundle with the central seven elements replaced by an air filled tube (61/1)
- the 61-element bundle with the central 19 elements removed (61/2)
- the 61-element bundle with the central 19 elements replaced by an air filled tube (61/3)
- the 61-element bundle with the central 19 elements replaced by a $D_2O$ filled tube (61/4)

Where fuel elements were replaced by a tube, the contents of that tube were not changed when the coolant was voided. The numbers following the description of the configurations refer to the data in figure 3.

The coolant displacers result in a considerable reduction in the void effect. Figure 3 compares reduction in the void effect as measured with that predicted by WIMS-CRNL. While WIMS-CRNL slightly overestimates the reduction in void effect, the results give confidence that the code predicts quite adequately the effect of coolant displacers.

## 4. Calculated Results

### 4.1. The Reference Case

The reference WIMS-CRNL case describes a standard, CANDU 600, 37-element fuel bundle with either natural uranium or enriched uranium. The coolant density is 0.806gm/cm$^3$ and the physical temperatures of the fuel, coolant and moderator are 687°C, 290°C and 71°C, respectively.

### 4.2. Definition of the Void Effect

The reactivity change as a result of voiding the coolant is defined as described earlier in terms of the effective multiplication constant k, calculated using the reactor geometric buckling. The void effect is then

$$\left[ \frac{1}{k_v} - \frac{1}{k_c} \right] * 1000 \quad \text{(mk)}$$

where the subscripts refer to voided and cooled.

As noted earlier only the results at mid burnup represent a real situation. In some cases the results are presented for a range of burnups while in others only results at zero burnup are given. For those changes to the reference case that have large effects on the burnup, the burnup is also indicated. In all cases the intent is to provide sufficient information to adequately illustrate a particular point.

### 4.3. The Effect of Uranium Enrichment

The calculated void effect is plotted against burnup in figure 4 for a range of initial fuel enrichments. The three variations of the void effect with burnup described in section 2.4 are all represented in this figure. The build up of plutonium is the dominant effect initially with natural uranium while the burnout of uranium dominates the 1.2% and 1.3% enriched results. The remaining result at 1% enrichment demonstrates the situation where the plutonium and uranium effects balance.

For an entire core of fresh fuel the void effect decreases with increasing enrichment. However at equilibrium, fraction of exit burnup equal to 0.5, the void effect increases with increasing enrichment although the range of values is smaller.

### 4.4. The Effect of Changing the Moderator Volume

For the results presented, the moderator volume was varied by changing the lattice pitch. Similar although not identical results are obtained when the volume is changed by increasing the size of the calandria tube.

The void effect is plotted in figure 5 against the moderator volume at zero burnup for natural and 1.2% enriched uranium. The general features are similar for each fuel and match the shape of the experimental buckling curve shown earlier. The rapid decrease in the void effect sets in when the slowing down in the coolant becomes comparable with that in the moderator.

The effect of changing the moderator volume on the attainable burnup is shown in figure 6. The curves are rather similar to those in figure 1 however the burnup becomes zero at or before the moderator volume needed to reduce the void effect to zero.

An alternate presentation of the results is shown in figure 7 where the zero burnup void effect is plotted against the attainable burnup.

### 4.5. The Effect of Changing the Fuel And Coolant Volumes

A number of calculations were performed at the reference lattice pitch in which the coolant and fuel volumes were changed. The changes were achieved by:

- Varying the outside radius of the fuel cladding while changing the density of the cladding so that its mass and neutron absorption cross section were kept the same

- Varying the fuel radius while maintaining the same clad thickness, the clad density was changed to keep its mass and neutron absorption cross section the same

Obviously these changes are not physically possible.

The void effect at zero burnup is shown in figures 8 and 9 for natural and 1.2% enriched $UO_2$. The void effect is most sensitive to the coolant volume. At the reference pitch the coolant volume primarily influences the void effect through the resonance integral. Smaller coolant volumes imply smaller enhancement of the resonance integral above its value with voided coolant. Changes in the fuel volume affect the neutronic behaviour at all energies. Only quite small changes to the void effect can be made by changing these volumes and the changes in exit burnup are similarly small.

### 4.6. The Effect of Changing the Number of Fuel Elements

Some calculations were done for fuel bundles having different numbers of fuel elements while maintaining the fuel,cladding and coolant volumes and all other details of the lattice at the reference case values. Fuel bundles having 45,56 and 71 fuel elements were examined.

The effect on the total void effect was very small, at most 0.6mk, and the changes in exit burnup were similarly small. Because the results are so small they are not presented in detail.

### 4.7. The Effect of Coolant Displacers

To investigate the reduction in the void effect that could be obtained with coolant displacers, the central seven elements of the 37-element reference fuel bundle were replaced by a graphite filled zirconium tube of two centimetre inside diameter. Calculations were performed for both natural and 1.2% enriched fuel.

In figures 10 and 11 the void effect is plotted against burnup for the reference fuel bundle and the displacer fuel bundle for, respectively, the two fuel enrichments. Significant reductions in the void effect were achieved with only small reductions in burnup.

The reference fuel bundle used in these calculations has both uniform fuel enrichment and uniform fuel element diameter. There is a significant decrease in fuel rating from the outer ring of fuel elements to the central fuel element. Consequently the contribution of the individual fuel elements to the bundle average burnup is greater for the outer ring of fuel elements than the inner ones. In advanced fuel designs in which either or both enrichment and geometry grading may be used the fuel rating would be expected to be more uniform across the bundle. Consequently the inner elements would contribute more to the burnup than was the case for a uniform bundle design. It may be expected, then, that the burnup loss with coolant displacers would be greater for graded bundles than the results quoted here for a uniform bundle.

## 5. Summary

The effect on the void effect of changing the fuel enrichment and some aspects of fuel channel design have been presented.

The accurate calculation of the effects of coolant voiding is complex, involving both spatial and temporal effects. While a lattice cell code such as WIMS-CRNL can not represent all of these effects it can be used to estimate the overall reactivity change in a core which contains everywhere the same fuel. Results at mid-burnup approximate the behaviour of an equilibrium core.

Calculations with WIMS-CRNL are further complicated by the choice of the leakage spectrum. To best represent the void effect at equilibrium the spectrum used was that characterised by the reactor geometric buckling.

Changing the relative volumes of the fuel and coolant or increasing the bundle subdivision while maintaining the fuel and coolant volumes does not cause the coolant void effect to be changed significantly. Increasing the fuel enrichment results in small increases in the void reactivity of the equilibrium core. Reducing the moderator volume can cause a significant decrease in the void reactivity. The reduction in burnup that accompanies this reduction in the void effect is so large that this is not a practical option.

Replacing the innermost fuel elements with a fixed scattering material is the most promising method for reducing the void effect. While with the geometries studied it was not possible to produce a zero void coefficient quite significant reductions were achieved with only modest burnup penalties.

## REFERENCES


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5. AECL-2606, "Lattice Measurements with 28 Element Natural $UO_2$ Fuel Assemblies; Part 1: Bucklings for a range of Spacings with Three Coolants", K.J. Serdula. 1966

6. CRNL-1542, "Measurement of Reduced Coolant Void Effect for Annular Fuel Bundles", P.M. French, R.T. Jones, 1976

**FIGURE 1.** Change in Measured Buckling on Voiding against the Moderator Volume

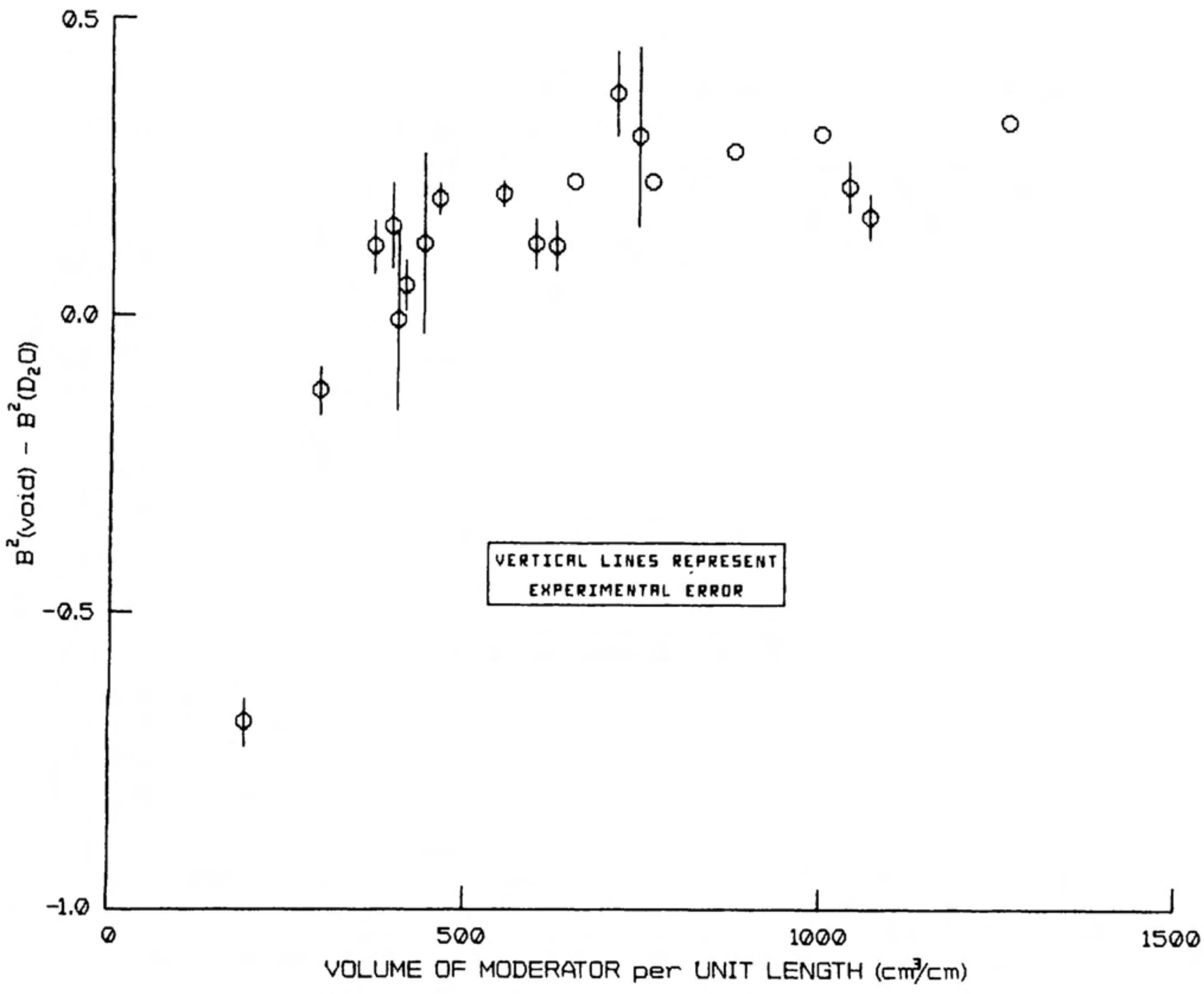

FIGURE 2. Void Effect Error against Vf/Vm

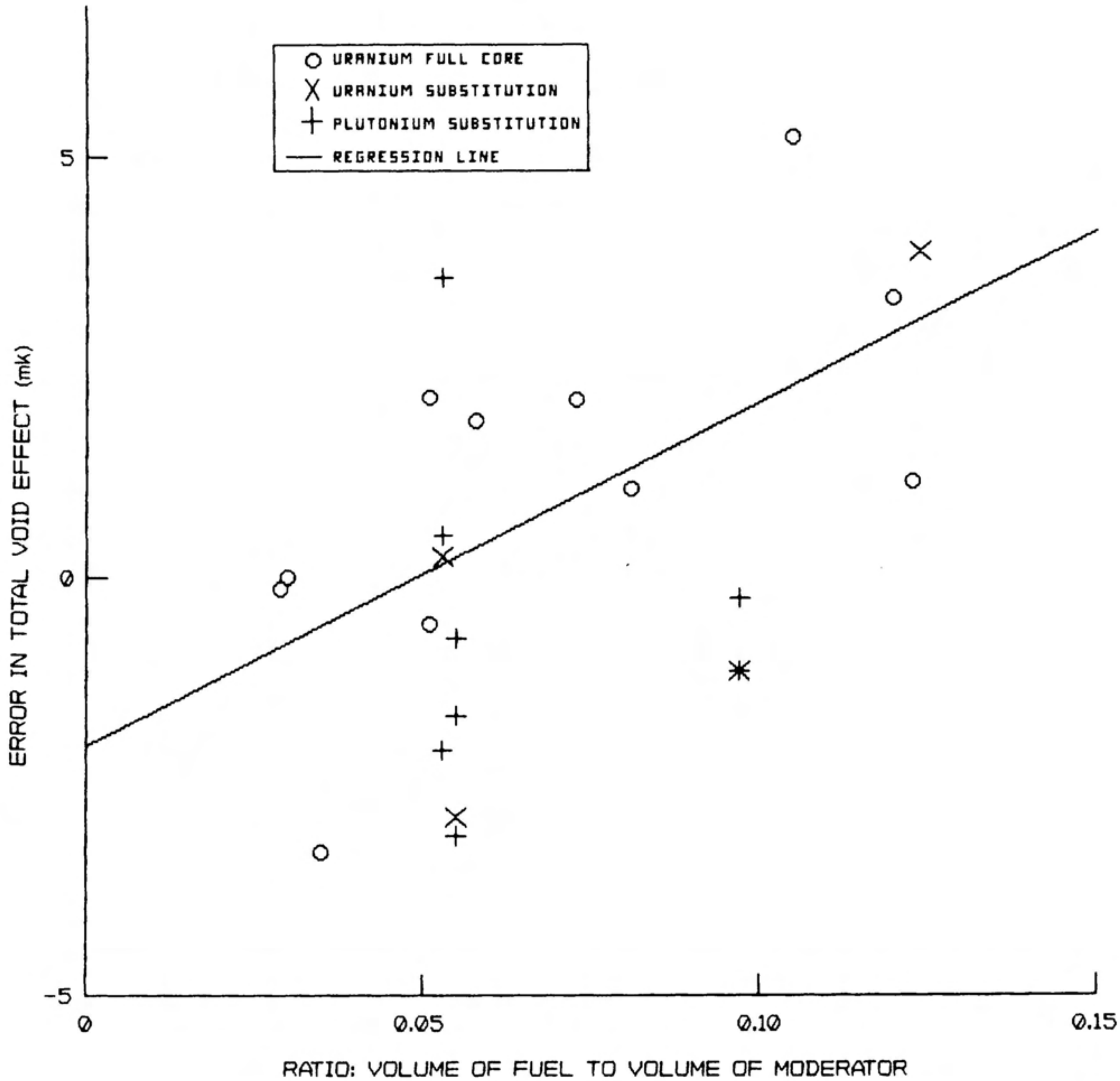

FIGURE 3. Void Effect Reduction with Coolant Displacers

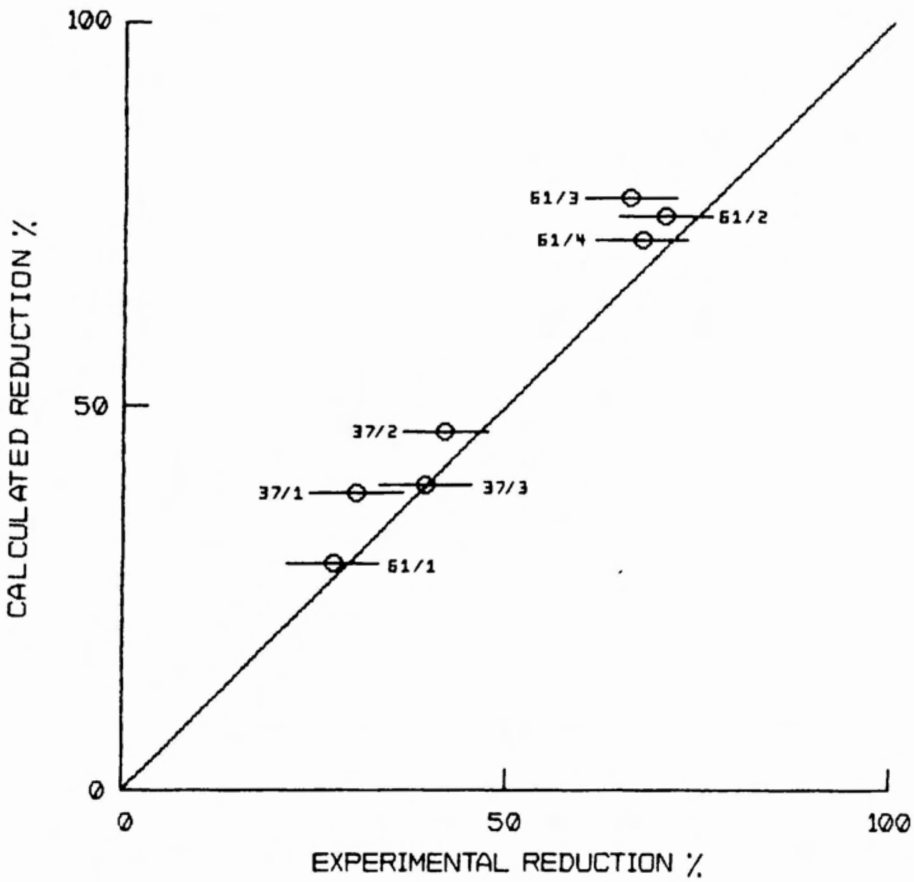

FIGURE 4. Void Effect against Burnup for Different Enrichments

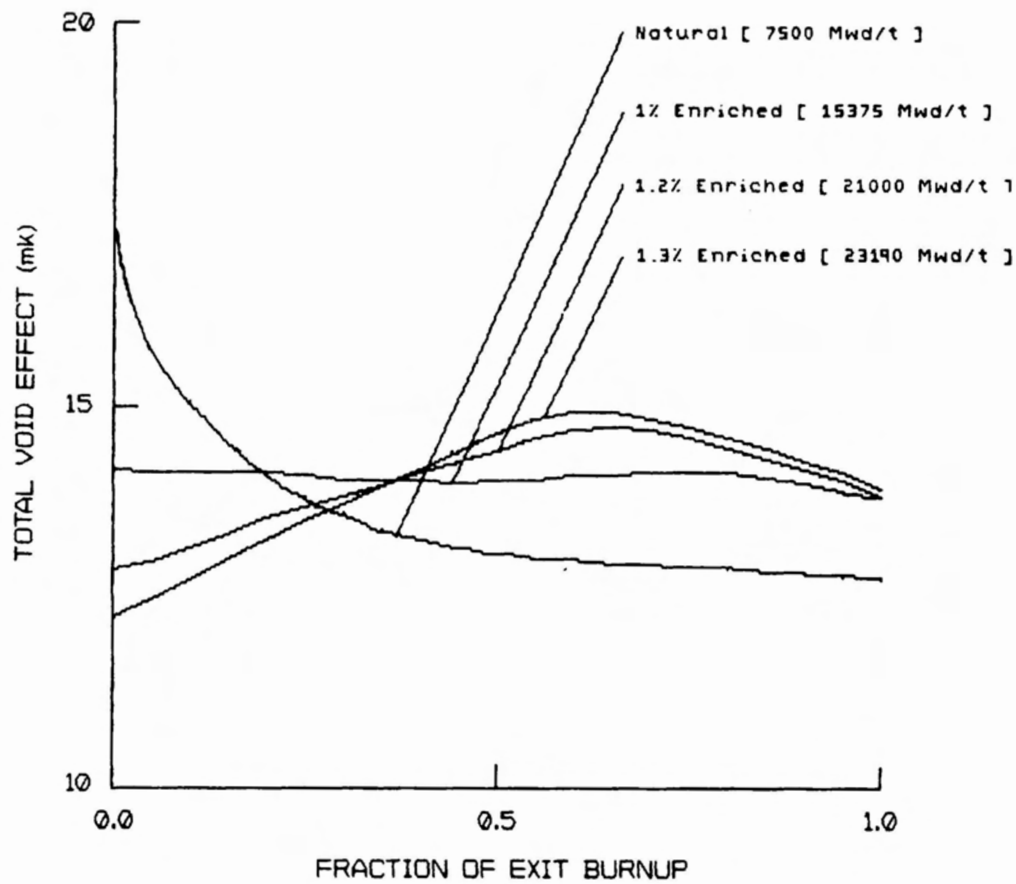

FIGURE 5. Void Effect against Moderator Volume

( zero burnup )

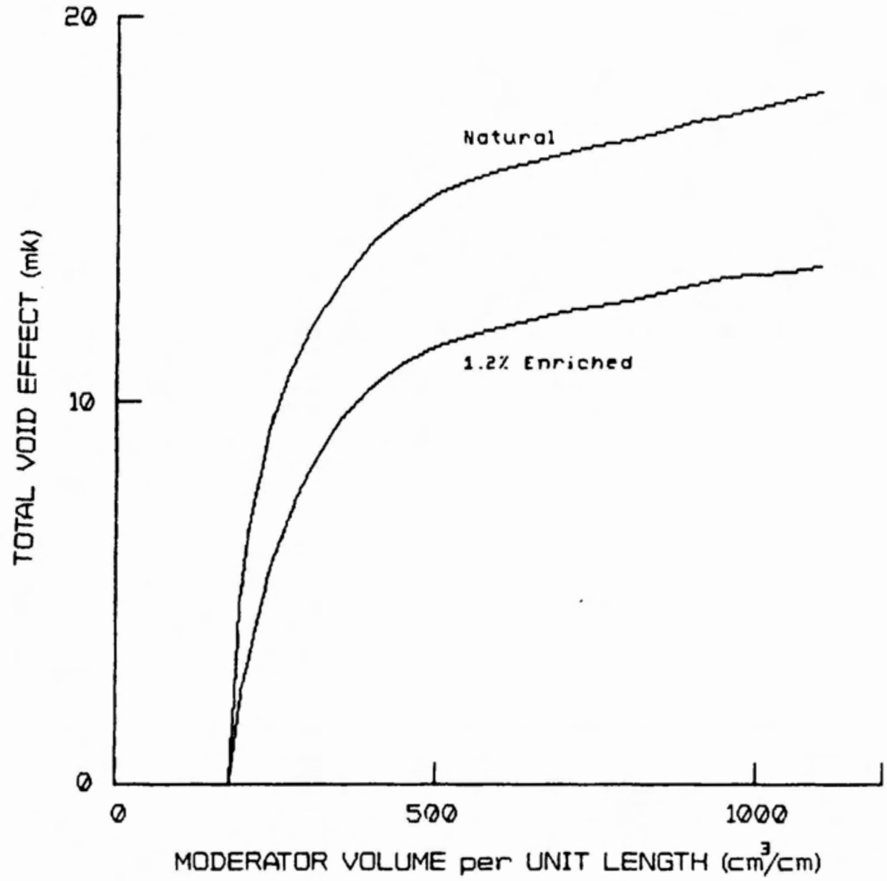

FIGURE 6. Exit Burnup against Moderator Volume

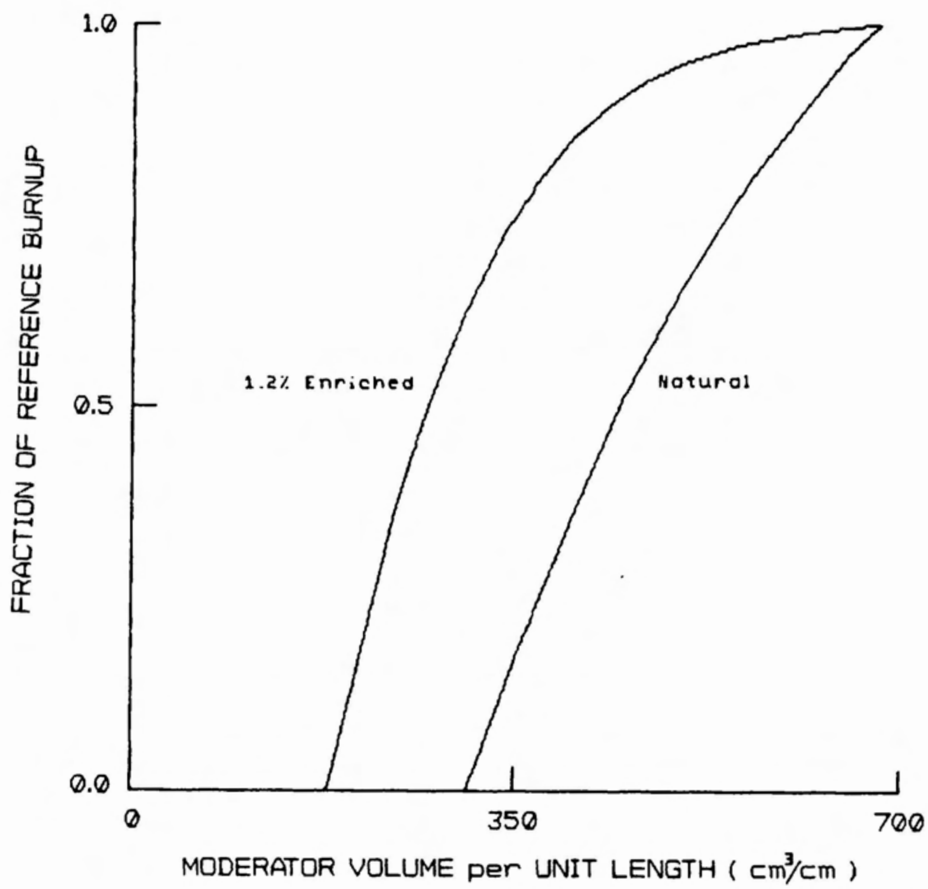

**FIGURE 7.** Void Effect against Burnup: Varying Moderator Volume

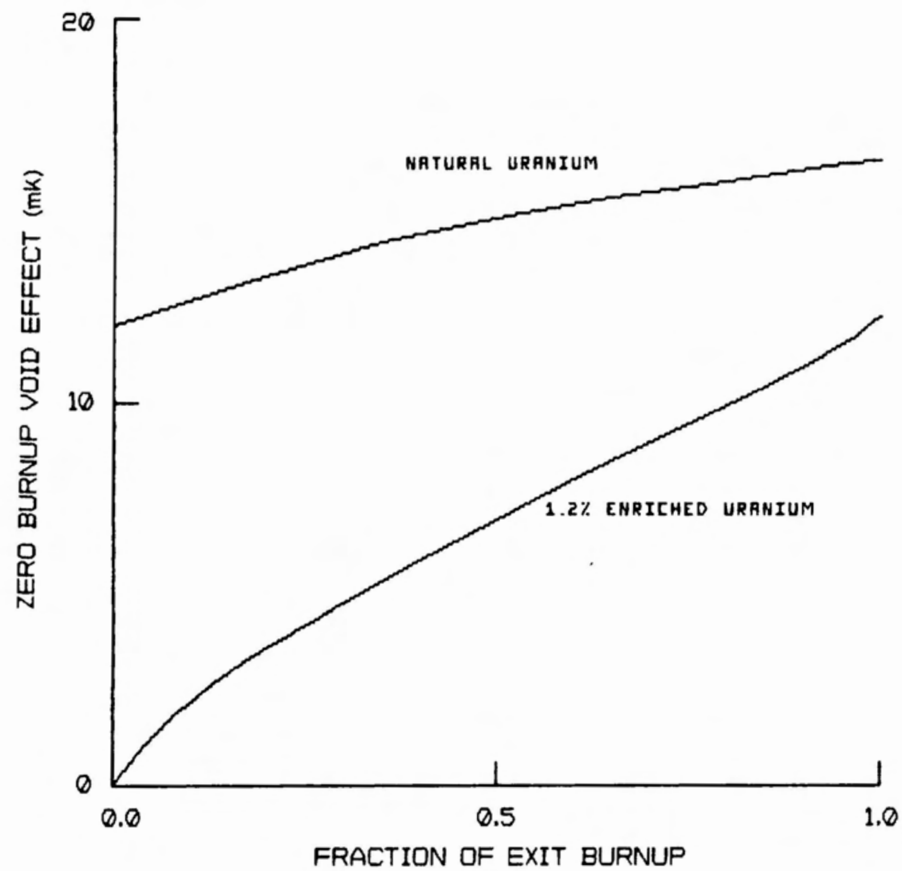

**FIGURE 8. Effect of Changing the Fuel & Coolant Volumes**

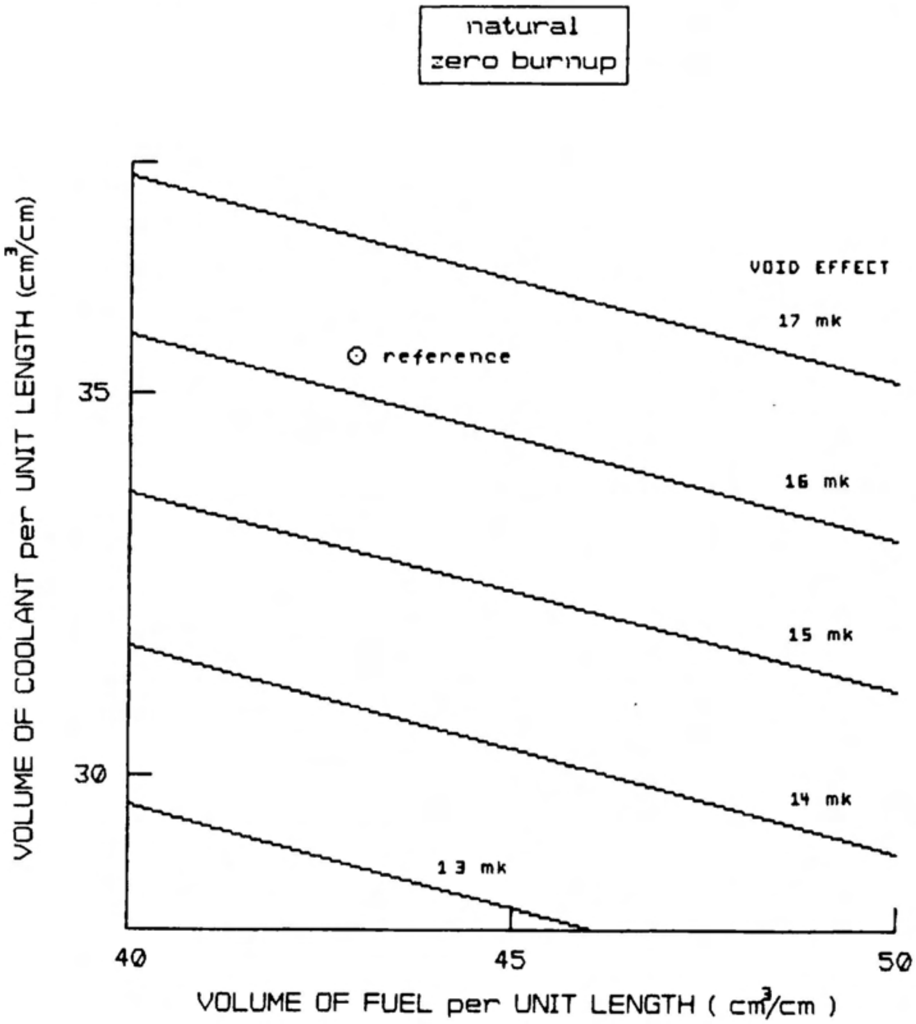

**FIGURE 9. Effect of Changing the Fuel & Coolant Volumes**

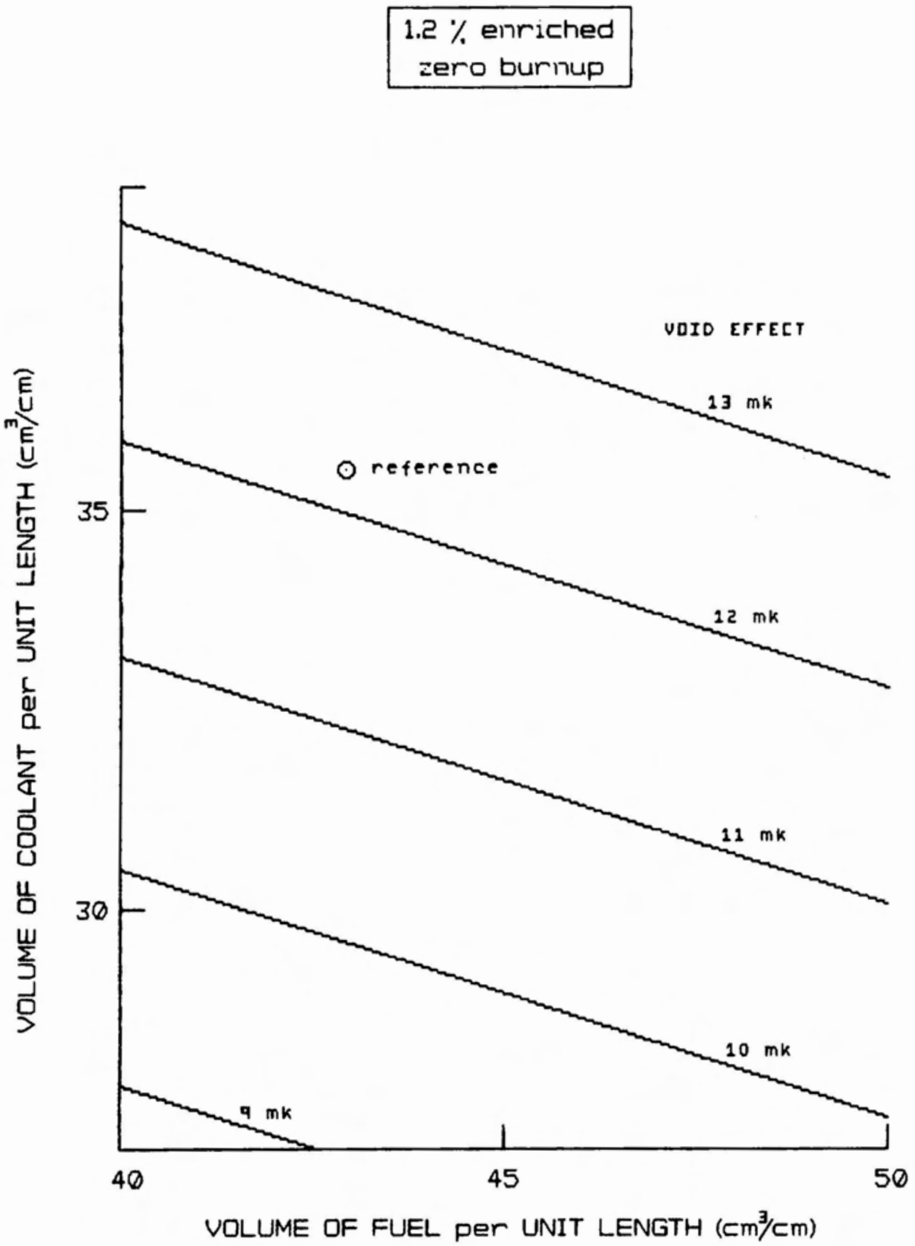

**FIGURE 10. Effect of a Coolant Displacer on the Void Effect**

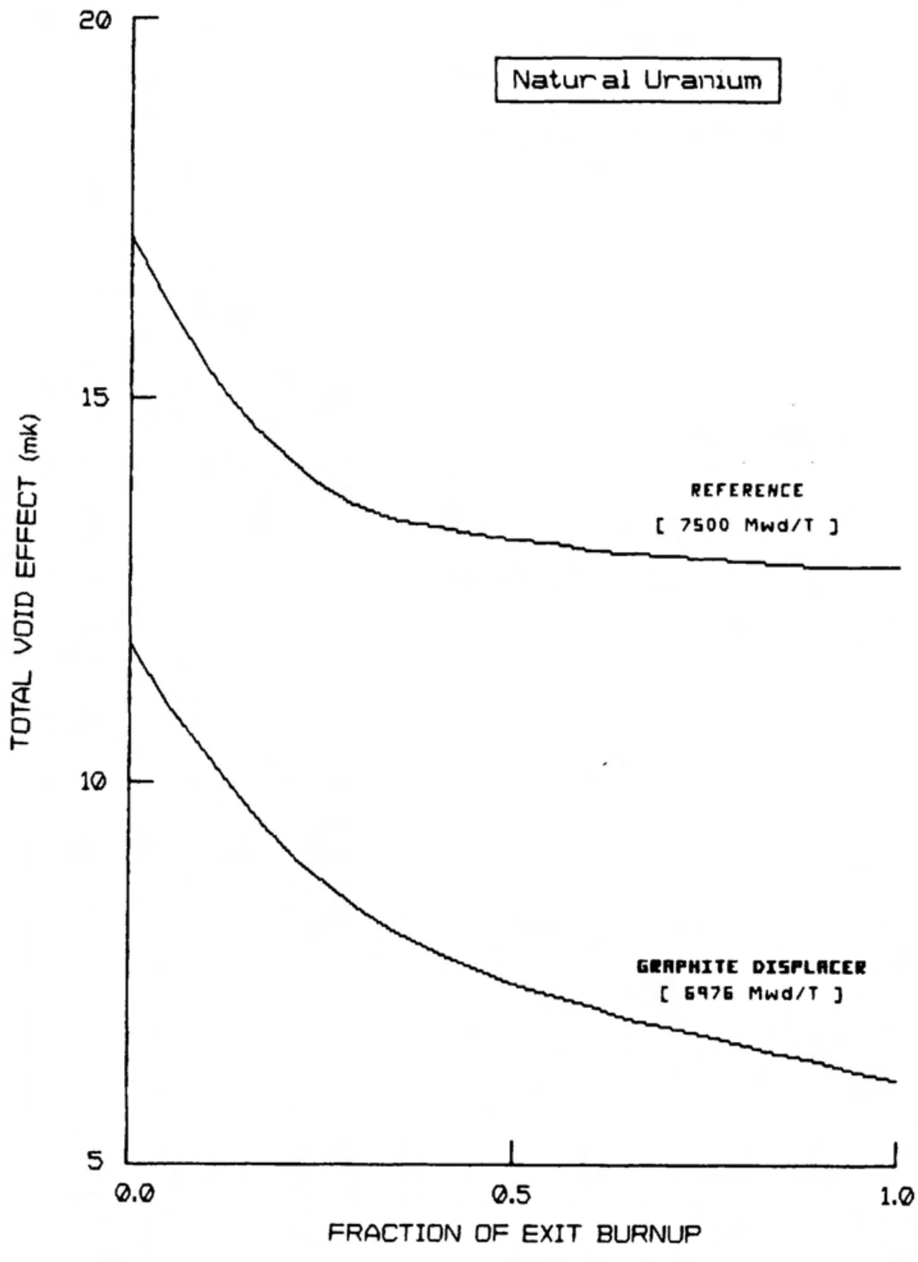

FIGURE 11. Effect of a Coolant Displacer on the Void Effect