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Void Coefficient of Reactivity Associated with the Island Region of the HFIR

R. D. Cheverton

ABSTRACT

Changes in neutron multiplication caused by voids in the island of the HFIR have been calculated and measured experimentally. The results indicate that with only water initially in the island the maximum change in neutron multiplication (Δk_{max}) associated with island voids is 0.032 with a corresponding void fraction of 70%. With a simulated 300 g Pu target in the island Δk_{max} was 0.016, and the corresponding void fraction was 42%.

In view of these large changes in neutron multiplication, calculations were made to determine what additional materials could be used in the island to reduce Δk_{max} and what the associated decrease in peak thermal flux would be. The results indicated that of the materials considered the use of beryllium in the water island resulted in the smallest decrease in flux for a specified Δk_{max}. To reduce Δk_{max} to 0.01 required 26% by volume of beryllium in the island; the corresponding reduction in thermal flux, as compared to an all-water island, was about 10%. In order to reduce Δk_{max} to 0.01 with a 300 g Pu target in the island, the aluminum-to-water ratio of the target had to be increased from 0.54 to about 1.5 with an associated decrease in target-averaged thermal flux, as compared to the original target, of 17%.

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VOID COEFFICIENT OF REACTIVITY ASSOCIATED WITH THE ISLAND REGION OF THE HFIR

Introduction

Much of the neutron moderation in the HFIR takes place in the water island and beryllium reflector, resulting in the desired peak thermal fluxes in these two regions. To provide the necessary nonthermal leakage to these non-fuel-bearing regions it is necessary for the fuel region to be undermoderated, and as a consequence neutron multiplication is very sensitive to temperature and density changes of the materials in the island and reflector regions. Since the beryllium reflector region has considerably less water in it than the island, water density changes in the island have a much greater effect on reactivity.[1] Thus, this report will be concerned with the island region only.

Preliminary calculations[1] and experiments[2] indicated that the temperature and void coefficients of the all-water island were positive for initial changes in density; for larger changes the coefficients became negative, the maximum change in reactivity being about +2.5% with a corresponding water density reduction in the island of about 50%. This characteristic exists, presumably, because in a sense the island is overmoderated (with void fractions less than about 50%), and because absorption in the water has a significant effect on the effective albedo of the island region. As the water density is first decreased, the decrease in absorption is more effective than the change in moderation. At about 50% voids the changes in moderation and absorption compensate for each other, and for larger void fractions the moderation effect is controlling. An illustration of this behavior for the HFIR is depicted by the calculated[1] and experimental[3] curves in Fig. 1 which are applicable to the case of an all-water island only. When the plutonium target is in the island, the maximum positive change in reactivity is considerably less.

According to Stone,[4] a practical HFIR control system will not be able to handle reactivity additions* greater than about 1% without serious damage to the core. Thus, a decision was made[5] to investigate possible modifications to the island that would limit the maximum reactivity addition associated with island voids to about 1%.

There appear to be two basic ways to reduce the maximum reactivity addition attributed to voids in the island. With reference to Fig. 1, one obvious, although not entirely practical, way is to include permanent voids

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*For the purpose of Stone's analysis it was assumed that reactivity was introduced corresponding to a 25 msec ramp and left in. This simulated voids entering the island with the coolant flow and remaining in the island.

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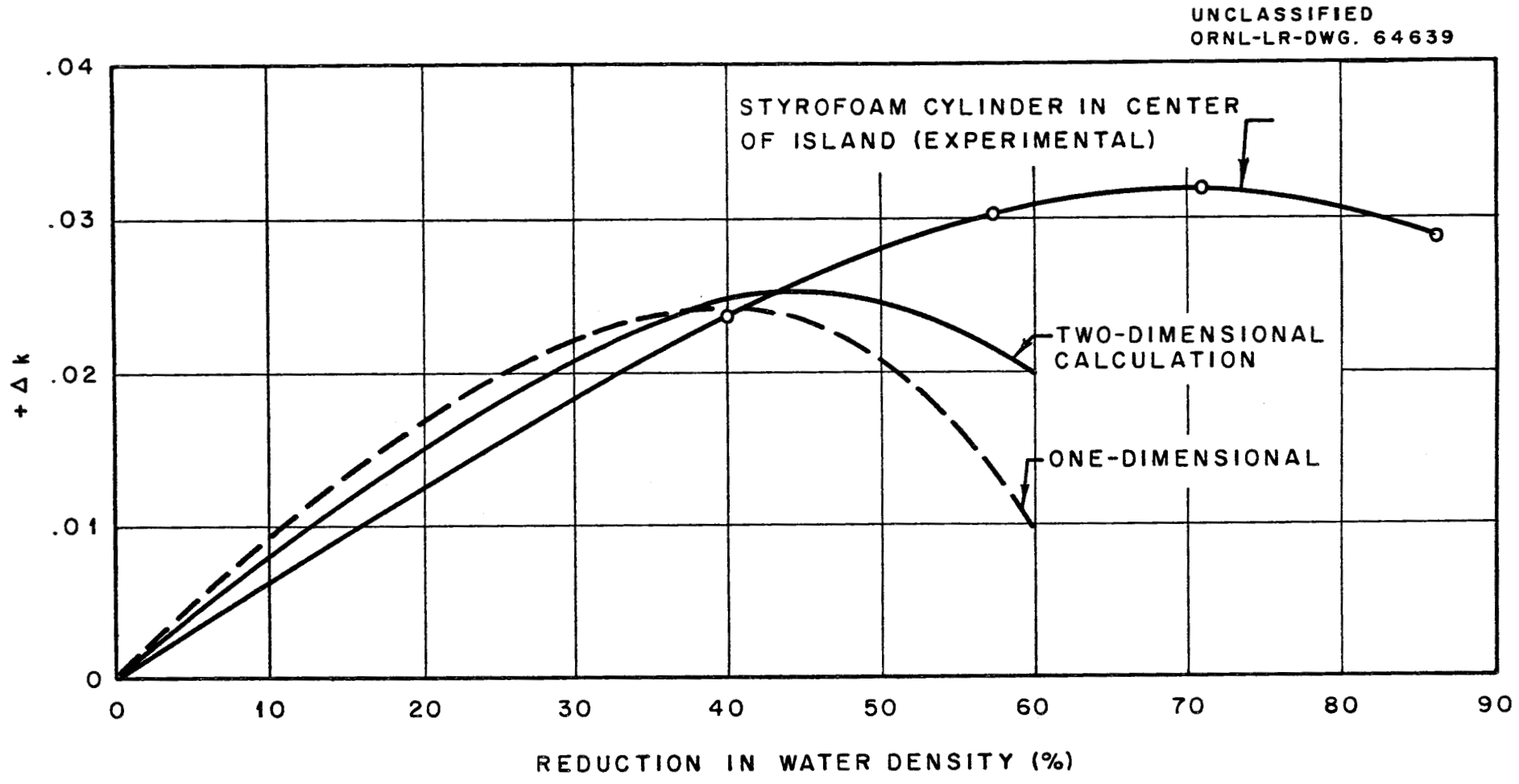

Fig. 1. Change in Neutron Multiplication Attributed to Voids in Island (No Target).

in the island; the other is to add a permanent absorber so that the fractional change in island absorption would be less with decreasing water density. However, the big disadvantage associated with the singular use of these methods is a significant decrease in the peak thermal flux in the island. Thus the problem reduces to one of determining a practical combination of materials in the island that will reduce the positive change in neutron multiplication significantly and have the least effect on the peak thermal flux.

Materials Considered

Plutonium Target. The plutonium target being considered for irradiation in the island of the HFIR contains initially 300 g Pu^{242} (as an oxide) dispersed in 31 aluminum rods that are 3/8 in. in diameter and 20 in. long. For the purpose of this study it was assumed that these rods would be supported in aluminum, slotted, hexagon tubes, clustered together within a target region about 4.0 in. in diameter, the total metal-to-water ratio in the target region (within the 4.0-in. diameter) being about 0.5. The absorption cross section used in the calculations for the plutonium and subsequent heavy isotopes was 40 barns, a value that is considered to be about the minimum for normal irradiation of the first-cycle material.

Other Island Materials. Very likely there will be times when it is desirable to replace the plutonium target with minute quantities of special materials so as to achieve the maximum possible flux. However, if at this time it is deemed necessary to limit the maximum reactivity addition associated with the optimum void fraction to the same value achieved with the normal plutonium target, it will be necessary to add other materials to the island. If used for prolonged periods, these materials must be compatible with water at high velocity ($\sim$ 40 ft/sec) and possibly with high heat fluxes ($\sim 1 \times 10^6$ Btu/hr-ft^2). It is also desirable that the materials have reasonably small absorption cross sections, although the term "reasonably" cannot be accurately defined until after the void coefficient problem has been investigated. Materials that generally satisfy these requirements are aluminum, beryllium, zirconium, and magnesium; and since there is some question concerning the possibility of zirconium-and magnesium-water reactions, the oxides of these two metals were also considered. In the case of beryllium the buildup of Li^6 was considered because of its neutron poisoning effect.

In the calculations made to investigate the effects of the above materials, the materials were homogenized over a cylindrical region (in the center of the island) having a 12-cm diameter (2 cm less than the island diameter) and a length equal to the active core length.

Calculation Methods and Results

Void coefficients in the island were calculated using both one-dimensional, 34-group and two-dimensional, two-group reactor codes; fast-group cross sections for the two-dimensional calculations were obtained from the

corresponding multigroup calculations. As shown in Fig. 1, preliminary results (for the case of uniform voids in the island) indicated that the one-dimensional calculations gave about the same maximum change in neutron multiplication as the two-dimensional calculations. (The two-dimensional calculations considered the uniform island voids to be located only within the active length of the core.) Even though the two methods did not agree very well on the optimum void fraction, the one-dimensional calculation was used most extensively, with a few two-dimensional calculations being made for spot checks. Curves similar to those in Fig. 1 were obtained for different volume fractions of beryllium, aluminum, zirconium, and zirconium oxide* in the water island, and in the case of the plutonium target for plutonium loadings of zero, 200, and 300 g. The results of the former calculations are presented in Fig. 2 as the percent reduction in peak thermal flux attributed to the change in island composition vs the maximum positive change in neutron multiplication achieved with that composition. Except for the case where true voids were added to the island the fluxes were calculated for zero voids and w compared to the peak thermal flux in an all-water island with zero voi.

The results presented in Fig. 2 indicate that with the exception of true voids the use of beryllium in the island results in the least reduction in flux for a specified maximum change in k. For a maximum permissible reactivity addition of 1% the reduction in flux is about 10, 18 and 23%, respectively, for beryllium, zirconium oxide (plus the associated aluminum), and aluminum. It is also observed that more beryllium than zirconium oxide and more zirconium oxide than aluminum on a volume basis must be used to achieve the same acceptable reactivity addition.

The results of the above void coefficient calculations, plus an examination of appropriate nuclear characteristics of the materials concerned, implies that the reduction in flux and the maximum reactivity addition are a simple function of the moderating ratio ($\xi\Sigma_s/\Sigma_a$) of the materials. As shown in Fig. 3 this appears to be the case, making it possible to estimate the effects of other materials by knowing their moderating ratios. Using Fig. 3 and the curve representing the two-dimensional results in Fig. 2 for proper normalization, it was estimated that for a 1% maximum reactivity addition the loss in flux would be approximately 11, 16, and 20%, respectively, for beryllium containing an equilibrium amount of Li^6 poison, magnesium oxide dispersed in and clad with aluminum in the same proportions as for zirconium oxide, and pure zirconium metal. The equilibrium concentration of Li^6 in the beryllium was estimated to be 1×10^{-6} atoms/barn-cm. Since the lithium reaches about 90% of its equilibrium value in only ten days it must be taken into consideration, if beryllium is used in the island for an extended period.

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*For the purpose of establishing atom densities it was assumed that ZrO_2 would be dispersed in an aluminum matrix, with ZrO_2 representing 80% of the "atoms". It was further assumed that 1/4-in.-diam rods of this material would be clad with 0.010-in. aluminum.

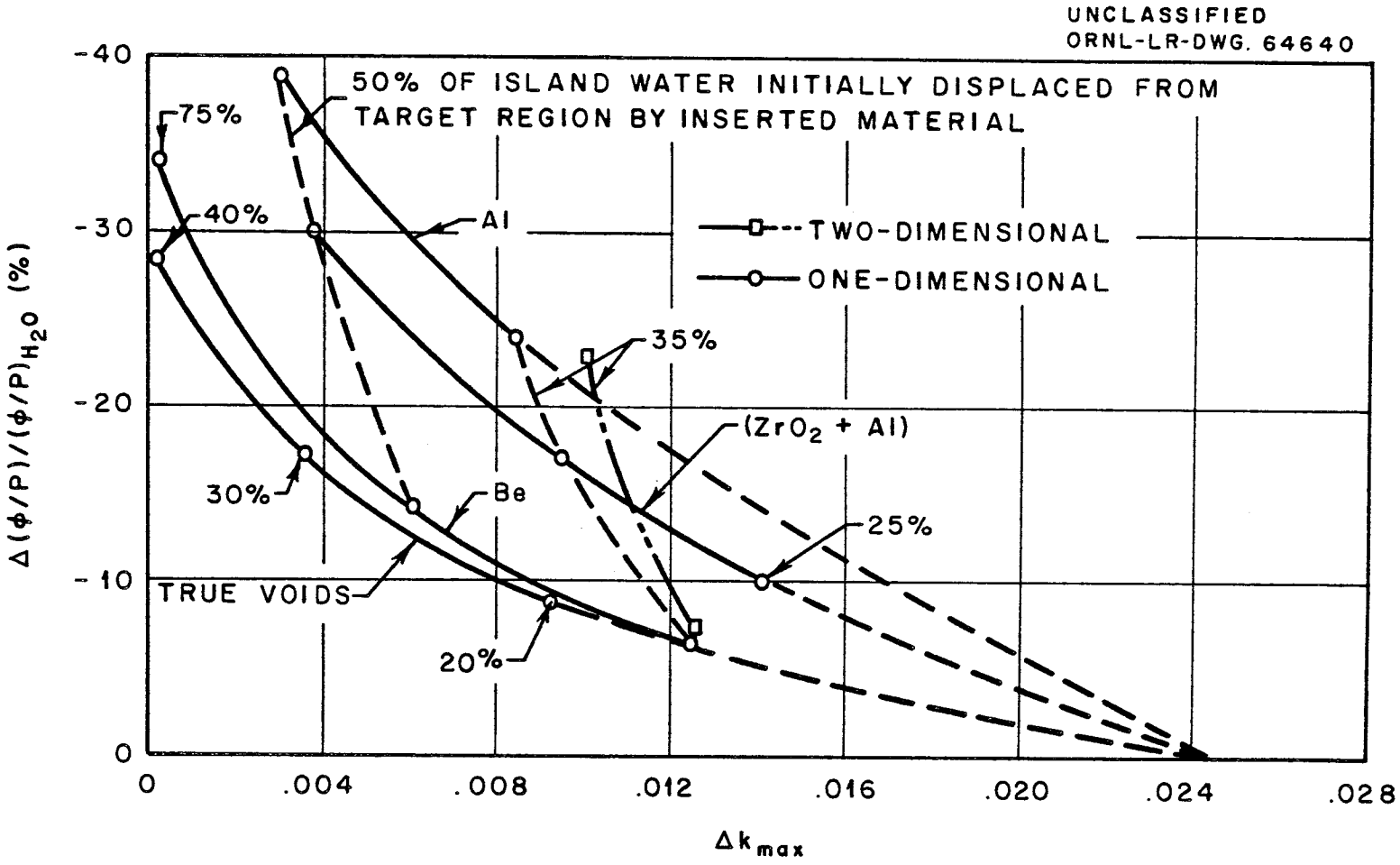

Fig. 2. Percent Reduction in Maximum Thermal Flux (as Compared to All-Water Island) as a Function of Maximum Δk_{max} Associated with Optimum Void Size (Water Density Reduction) for Various Solids in Water.

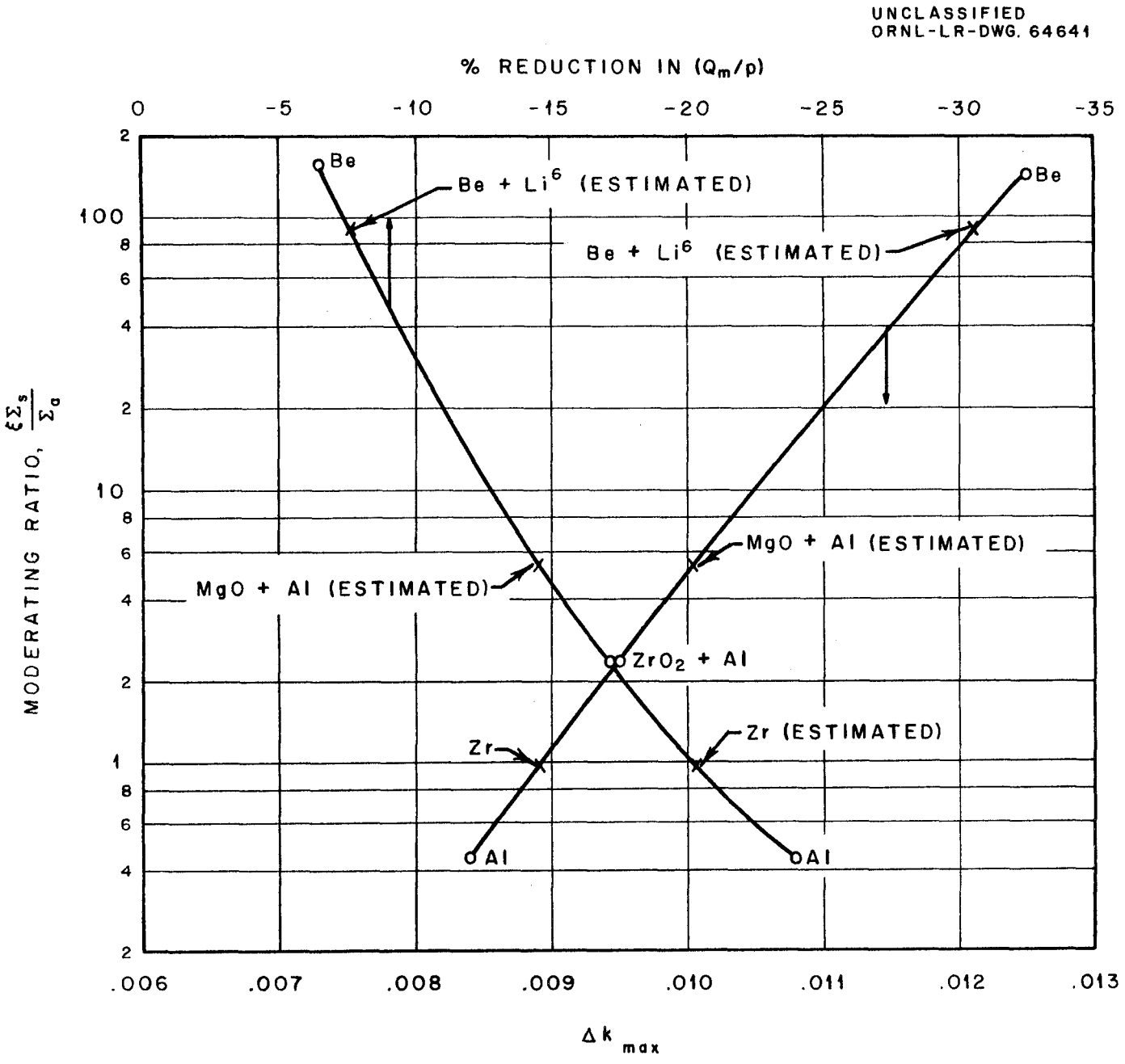

Fig. 3. Peak Thermal Flux and Δk_{max} for Various Materials Displacing 35% by Volume of the Island Water in a Centrally Located Volume 50 cm Long by 12 cm in Diameter Vs. the Moderating Ratio of the Material. (One-Dimensional Calculations)

In the above calculations the solid material added to the island was homogenized over a central cylindrical region 2 cm smaller in diameter than the island. Some idea of how Δk_{max} is affected by a change in this diameter can be obtained by a comparison of one of the above aluminum cases with the plutonium target calculation that had no plutonium in the aluminum target. Figure 4 shows that for 26% by volume of aluminum in the island (corresponds to 50% aluminum within the 10-cm-diam area and 35% aluminum within the 12-cm-diam area) a reduction in target diameter from 12 cm to 10 cm results in an increase in Δk_{max} of 0.0009, indicating a very slight advantage in using a larger target.

The above results imply that uniformly distributed voids are worth more than voids grouped closely in the center of the island and brings up a question concerning the experimental curve in Fig. 1. Since this curve was obtained by increasing the diameter of a Styrofoam cylinder in the center of the island, it is reasonable to believe on the basis of the above calculations that more uniformly distributed voids would result in larger changes in neutron multiplication. This possibility was studied analytically and also experimentally to some extent. The calculations[1] indicated that the Δk_{max} achieved with an optimum cylindrical void (~ 40% island void) was somewhat less than achieved with an optimum uniform void fraction (~ 45% island void). The same result appears to have been obtained in the HFIR critical experiments when void coefficients were measured with the centrally located Styrofoam cylinder (refer to Fig. 1) and with centrally grouped air-filled polystyrene tubes. In the latter case the voids were more uniformly distributed, and as indicated in Ref. 3 the void coefficient appeared to be slightly greater than for the Styrofoam over the range of zero to 40% voids covered with the air-filled tubes*. Similar results were obtained when the uniformity of the voids was increased by drilling longitudinal holes in a complete Styrofoam island.[6] In this case the full range of void fractions was covered, and the results indicated a slightly larger Δk_{max} for more uniformly distributed voids.

One possible reason why the differences in Δk_{max} noted above are so small is that the corresponding volume fraction is sufficiently large (~ 70%) that the physical difference between uniform and non-uniform voids is small. Thus the particular location and shape of the optimum void within the island should not be very important, and the value of Δk_{max} given in Fig. 1 should be essentially the maximum attainable.

Results from the void coefficient calculations and from experiments that included the plutonium target in the island are presented in Fig. 5. The calculated curves indicate that the maximum change in k is not very dependent on the small amounts of plutonium present in the target and is equal to about 0.015 with an optimum void fraction in the island of 34%. The experimental results were obtained from an experiment that employed an

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*Magnuson[7] points out that the differences he reported might actually be within experimental tolerances.

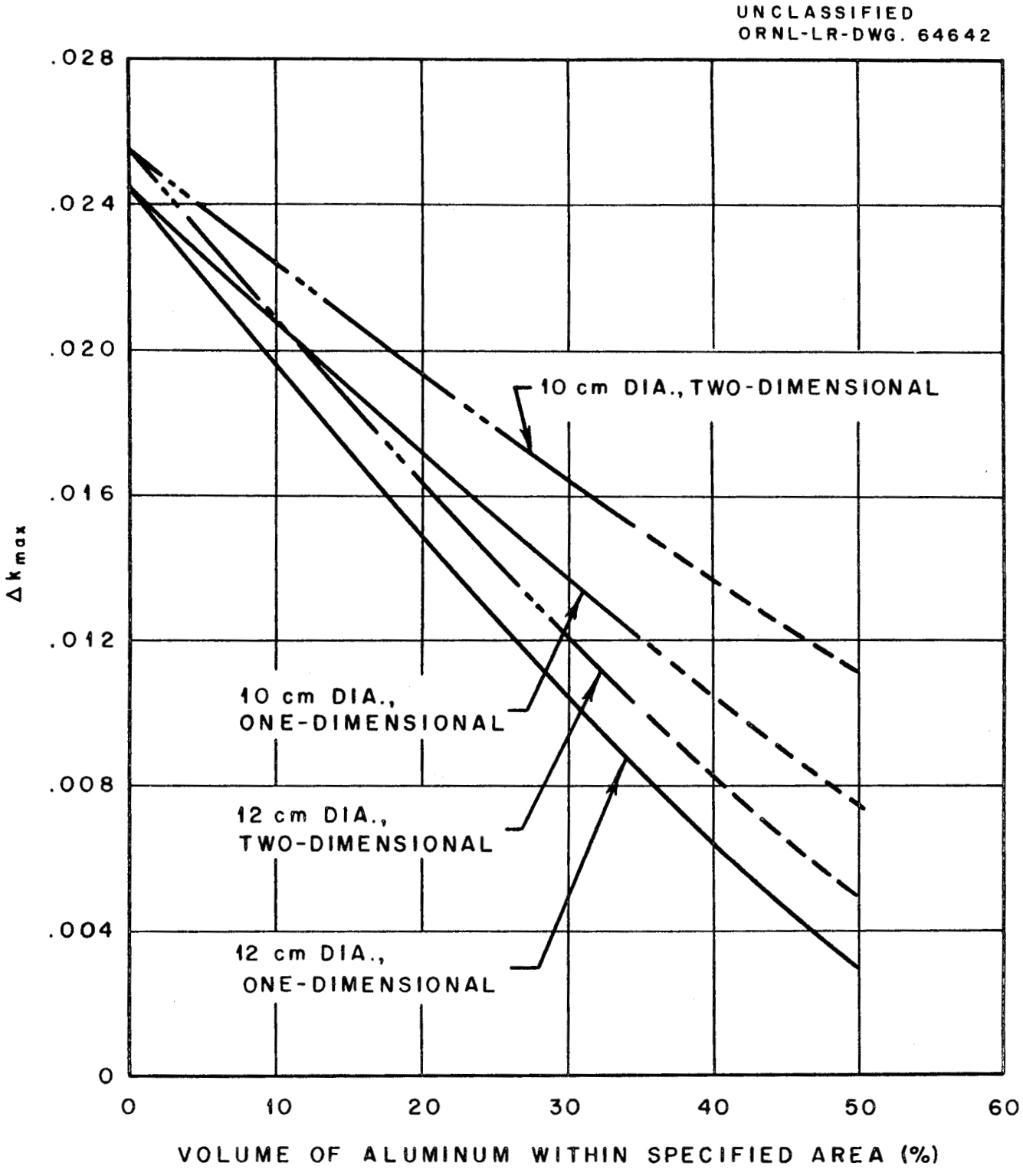

Fig. 4. Change in Neutron Multiplication Associated with the Optimum Void Fraction for Different Volume Fractions of Aluminum in a 10 and 12 cm Diameter Central Region of the 14 cm Diameter Water Island.

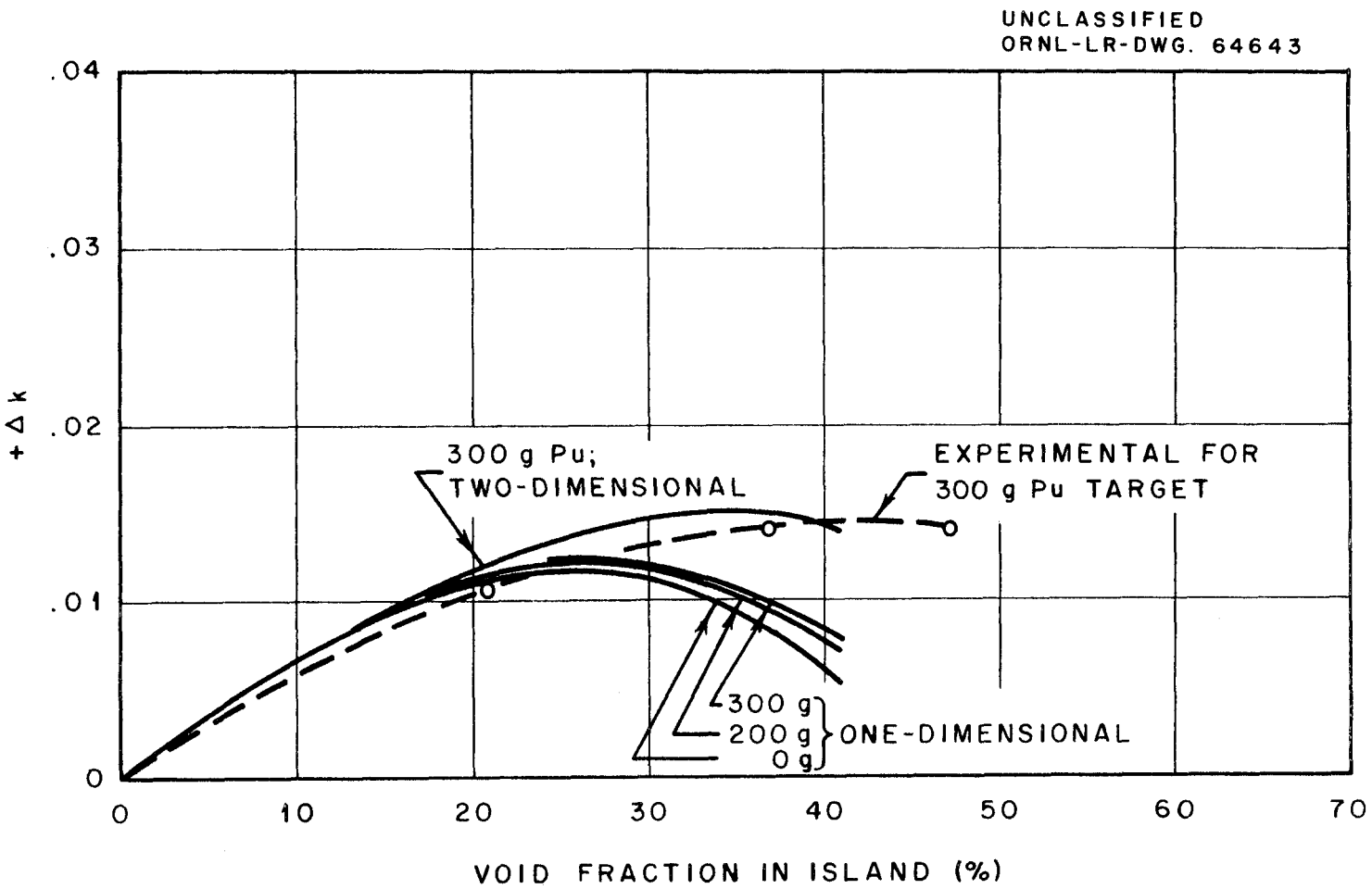

Fig. 5. Change in Neutron Multiplication Attributed to Uniform Reduction in Water Density Over Entire Island, Including Plutonium Target.

island target* that was essentially the same as that calculated except for the presence of a thin aluminum can that was used during the experiments for containing the voids. Using the aluminum curve in Fig. 2 to correct for the presence of this can, the corrected "experimental" value of Δk_{max} was 0.016.

If it is eventually decided that the probable frequency of occurrence of the optimum target void in a manner similar to that described earlier in this report is such to necessitate a lower limit on Δk_{max}, then more aluminum should be added to the target. Using the aluminum curves in Fig. 4, it is estimated that increasing the metal-to-water ratio of the target from 0.54 to about 1.5 would reduce Δk_{max} to 0.010, and as shown in Fig. 6 would reduce the average flux in the 300 g target by about 17%.

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*The target used in the critical experiment was slightly different than the calculated target in that it had a 40% greater absorption cross section and also had a fission cross section ($\Sigma_f V$) of about 9.3 cm^2. In view of the calculated results in Fig. 2 it is not anticipated that the difference in targets is significant.

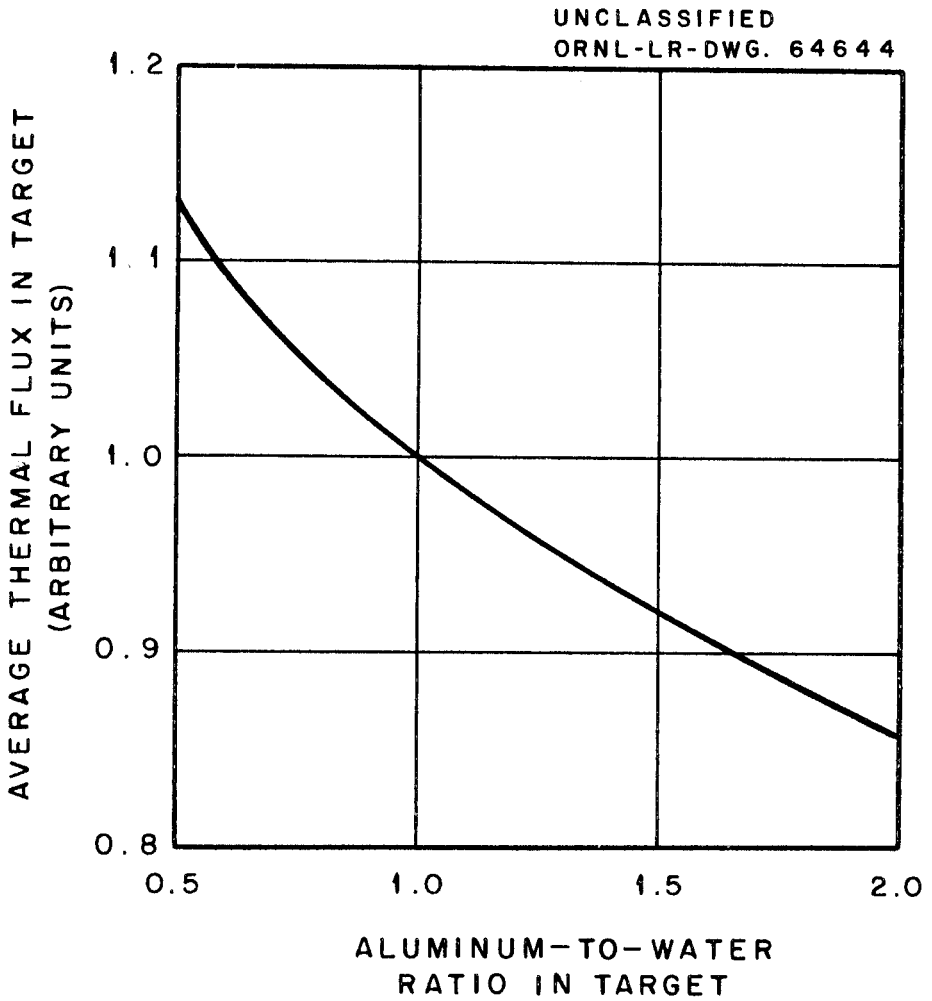

Fig. 6. Average Thermal Flux in the 300g Pu Target Vs. Aluminum-to-Water Ratio in the Target.

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