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SUBJECT: Studies of Improvement of Power Density in ORR Loops

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FROM: M. L. Tobias and D. R. Vondy

ABSTRACT

Using a simplified model, calculations have been made concerning the possible effects of voids upon the power density in ORR loop experiments. It is concluded that the power density may be markedly increased if voids and channels are plugged with moderator material such as graphite or beryllium.

DISCLAIMER

STUDIES OF IMPROVEMENT OF POWER DENSITY IN ORR LOOPS

M. L. Tobias and D. R. Vondy

General Discussion

Despite the fact that fluxes obtainable in the ORR are much higher than those in the LITR, it has been found that fuel solution loops in the ORR do not display a markedly increased power density compared with those used in the LITR. The principal point of contrast between these loops appears to lie in one important construction difference, namely, that the fuel solution containers in the LITR were surrounded by graphite whereas those in the ORR are not. Further, there exists an air gap about 1/2 inch thick between the outer shell and the fuel solution container which was not present in the loops used earlier. Behind the fuel container, neutron reflection is afforded only by the piping and other hardware associated with the fuel loop which are heavily interspersed with air gaps. It appeared that the power in the loop was being lowered by two interconnected effects. First, the air gaps may lower the reactor flux in the loop vicinity due to neutron streaming through these passages, and second, fission neutrons generated in the fuel container are poorly reflected and moderated by surrounding material because of the high percentage of nearby void space.

Only the second of these effects has been studied here, but the results show substantial improvement in power density is possible if the voids are replaced by moderator material. The following simple model of the actual situation was used. First, the fuel container was taken to be a 3-in.-dia x 8-in.-long cylinder of 10 g U^{235} in H_2O surrounded by a half-in. gap.

The derivative of the flux was taken to be zero on the far side of the gap, and the flux was assumed zero on the container face away from the reactor. The boundary condition at the face in contact with the reactor was that of a constant flux, with the ratio of the fast to slow fluxes used as a parameter. The nuclear calculations were two-group diffusion calculations which were handled in two ways which gave results in good agreement. In the first way, it was assumed that the effect of the void of the half-inch gap was the same as if the void were homogeneously dispersed in the fuel solution. The second way likewise disperses the void throughout the fuel solution, but uses the methods of Behrens[1] where the geometry effects as well as the dilution effects of the void are included. In addition, the effect of placing a graphite or beryllium reflector 6 inches thick against the cylinder face away from the reactor were computed. The results are shown in Fig. 1. It is seen that the average power density per unit thermal flux at the reactor face varies linearly with fast-to-thermal flux ratio. This ratio is in the neighborhood of 2 for the ORR but varies with the reactor configuration used for an experiment and is quite variable with position as well. The void fraction in the present case is of the order of 40%, so that good agreement is found between the results of Behren's theory and the simple dilution method. The best reflector from the standpoint of power improvement is clearly beryllium. However, graphite would probably be preferred because of the relative ease with which it may be used.

The question of whether any benefit may be obtained from surrounding the loop with heavy water instead of light water (as at present) has also been examined. Again on the basis of a crude model of the actual situation, the variation of power per unit thermal flux has been determined as a function of fast-to-slow flux ratio at the reactor face. Referring to Fig. 2, light water is seen to be superior at high values of this ratio while heavy water is better at low values. Near a ratio of 2, the powers obtainable are quite close. In any case, no very great advantage is likely to be obtained by using heavy water.

Details of the equations used for determining the void effects may be found in Appendix I. The treatment of the problem of the use of heavy water in place of light water is discussed in Appendix II.

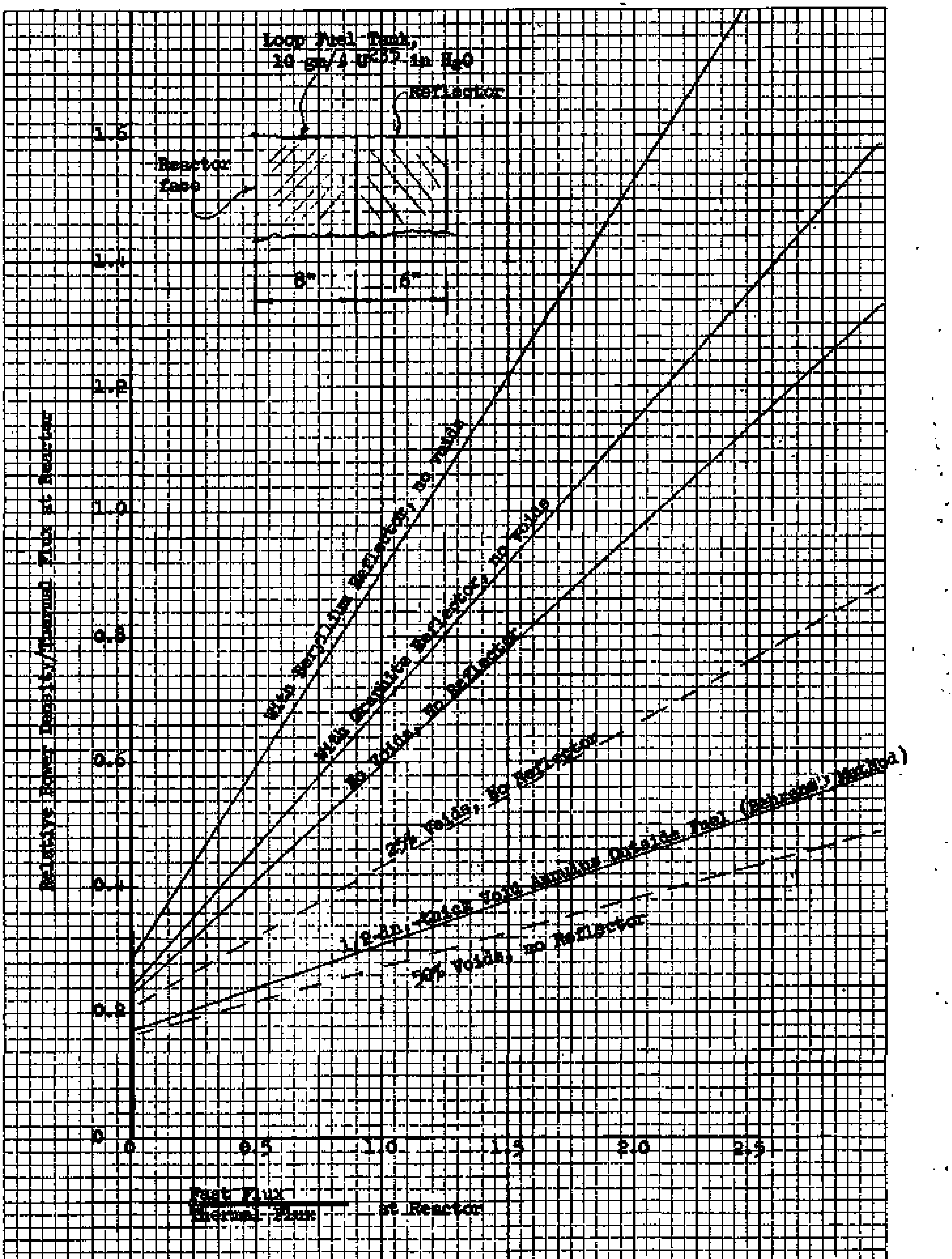

Fig. 1. Power Density in GRR Loop

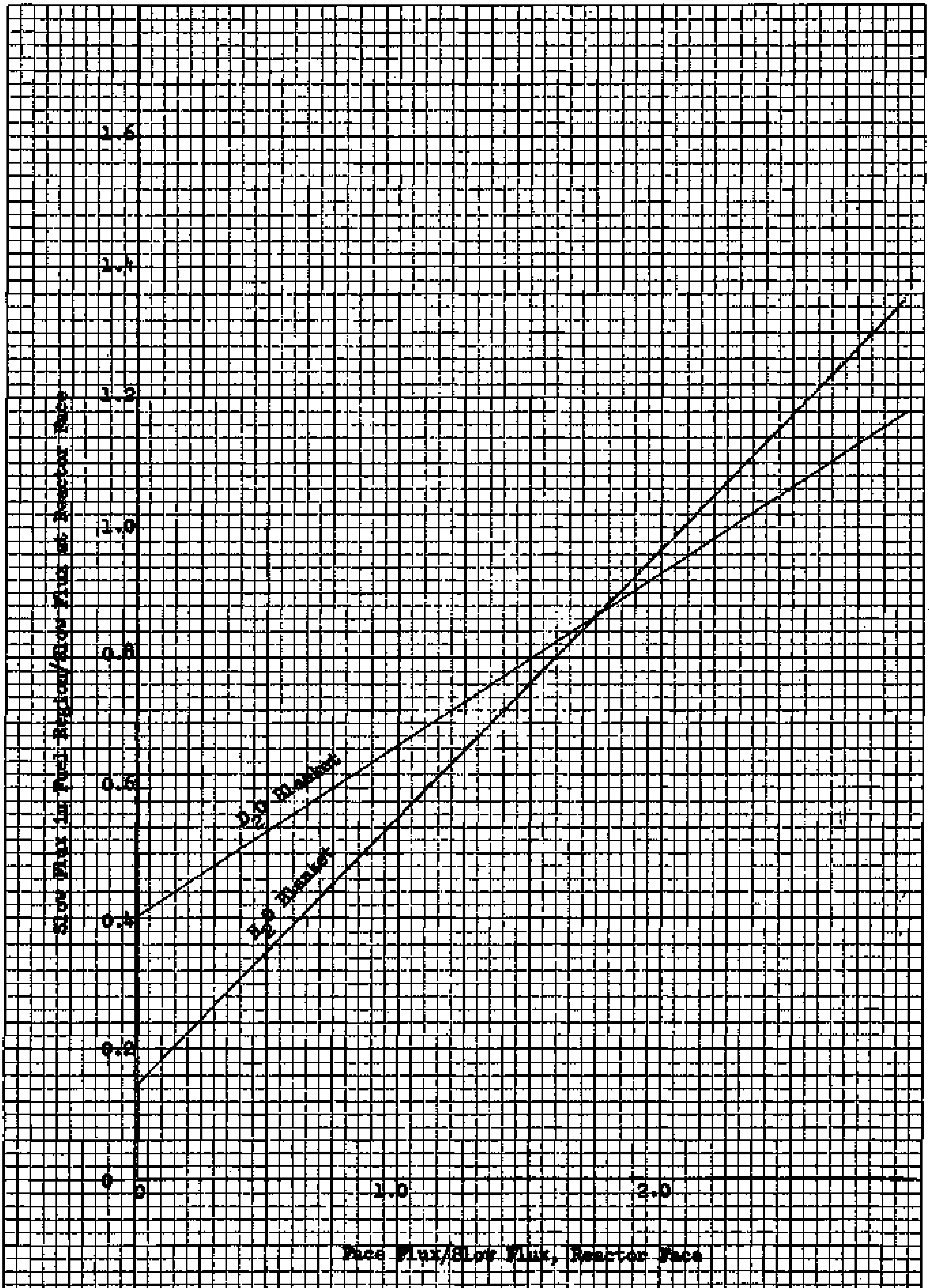

Fig. 2. Effect of Moderator Adjacent to Loop Fuel Tank on Average Thermal Flux

Appendix I. Two-Group Diffusion Theory Applied to a Cylindrical Fuel Containing Region Subject to Certain Simplifying Boundary Conditions

Consider a two-region cylinder as in Fig. 3. If one assumes that the cylinder is insulated radially, the diffusion equations reduce to those of slab geometry. The average power density in region 1 will be found in terms of R, the ratio of fast-to-thermal flux, and the thermal flux itself at the reactor face. The fluxes at the reflector end will be considered zero. Let x be the axial distance from the reactor face. Then, neglecting fast group absorptions and fissions

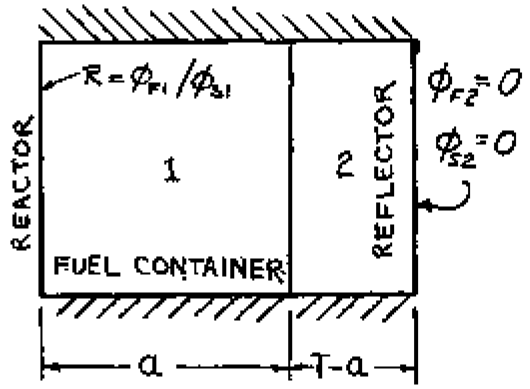

Fig. 3. Schematic Diagram of Fuel Loop

$$D_{F1} \frac{d^2 \phi_{F1}}{d\, x^2} - \Sigma_{F1} \phi_{F1} + \nu\Sigma_f \phi_{S1} = 0$$

$$D_{S1} \frac{d^2 \phi_{S1}}{d\, x^2} + \Sigma_{F1} \phi_{F1} - \Sigma_{S1} \phi_{S1} = 0$$

Assuming that $\frac{d^2 \phi}{d\, x^2} = B^2 \phi$ and that $\nu\Sigma_f \cong \Sigma_{S1}$ (approximately true under the conditions of this problem) the solutions for the case of no reflector are:

$$\phi_{F1} = A\,(a-x) + C \sinh \nu\,(a-x)$$

$$\phi_{S1} = S_1 A\,(a-x) + S_2\, C \sinh \nu\,(a-x)$$

where $$\nu = \sqrt{\frac{\Sigma_{F1}}{D_{F1}} + \frac{\Sigma_{S1}}{D_{S1}}}$$

$$S_1 = \frac{\Sigma_{F1}}{\Sigma_{S1}}$$

$$S_2 = \frac{\Sigma_{F1}}{\Sigma_{S1} - D_{S1}\,\nu^2} = - \frac{D_{F1}}{D_{S1}}$$

If one is given R, the ratio of the fast-to-thermal flux, at x = 0, and the thermal flux at zero then

$$A = \frac{S_2 R - 1}{(S_2 - S_1)\, a}\ \phi_{S1}(0)$$

$$C = \frac{S_1 R - 1}{(S_1 - S_2) \sinh \nu a}\ \phi_{S1}(0)$$

The average power density in the cylinder per unit thermal flux at x = 0 may be expressed as follows:

$$\frac{P.D.}{\phi_{S1}(0)} \quad \left[\frac{S_1 Aa}{2} + \frac{S_2 C}{\nu a} \left(\cosh \nu a - 1 \right) \right] \frac{\Sigma_{S1}}{\phi_{S1}(0)}$$

Since A and C contain $\phi_{S1}(0)$ as a factor, this ratio is independent of the thermal flux level at the reactor face.

For the case of a reflector at the cylinder face opposite the reactor, the flux equations are

$$\phi_{F1} = D + Ex + F \sinh \nu x + G \cosh \nu x$$

$$\phi_{S1} = S_1 \left[D + Ex \right] + S_2 \left[F \sinh \nu x + G \cosh \nu x \right]$$

$$\phi_{F2} = H \sinh \sqrt{\frac{\Sigma_{1R}}{D_{1R}}}\,(T - x)$$

$$\phi_{S2} = S_3 H \sinh \sqrt{\frac{\Sigma_{1R}}{D_{1R}}}\,(T - x) + J \sinh \sqrt{\frac{\Sigma_{2R}}{D_{2R}}}\,(T - x)$$

Knowing ϕ_{S1} and ϕ_{F1} at $x = 0$, D and G are easily determined. The remaining constants may be found from the four equations:

$$\phi_{F1}(a) = \phi_{F2}(a)$$

$$D_{F1}\,\phi'_{F1}(a) = D_{F2}\,\phi'_{F2}(a)$$

$$\phi_{S1}(a) = \phi_{S2}(a)$$

$$D_{S1}\,\phi'_{S1}(a) = D_{S2}\,\phi'_{S2}(a)$$

Calculations were performed for a concentration of 10 gm U^{235} per liter in H_2O at 280°C. The following basic constants were used for the fuel containing region

a, cylinder length = 8 inches = 20.3 cm

$\Sigma_{S1} = 0.0211$, $\Sigma_{F1} = 0.0285$

$\nu\Sigma_f = 0.0212$

$D_{F1} = 1.54$

$D_{S1} = 0.276$

For the graphite and beryllium reflectors, the constants were:

	Graphite	Beryllium
D_F, cm	0.83	0.49
D_S, cm	0.9	0.7
Σ_F, cm^{-1}	2.57×10^{-3}	5×10^{-3}
Σ_S, cm^{-1}	1.92×10^{-4}	1.17×10^{-3}
T-a	15.3 cm (6 inches)	

The fuel region constants were modified in two ways to show the effect of a surrounding void region. The first method was a simple density reduction. The second followed the prescription given by Behrens by which the diffusion length is corrected by the formula:

$$\frac{L^2}{L_o^{\,2}} = 1 + 2\alpha + \frac{\alpha^2(2r/\alpha\lambda)}{e^{2r/\alpha\lambda} - 1} + \frac{Qr\alpha}{\lambda}$$

where

r = 2α V/S

α = ratio of void volume to material volume

S = surface area of void

λ = mean free path

Q = geometry factor, taken as 1.726 based on information in Behrens' paper.

Both the fast and slow group diffusion lengths were corrected by this formula.

Appendix II. Consideration of Effect of Using Heavy Water in Place of Light Water as a Moderator Surrounding the Experiment

As this problem was burdensome to solve by direct analysis, it was treated numerically. The fuel and moderator regions were described by a 9-point mesh in slab geometry as in Fig. 4. Region A is the fuel region and B is the reflector. The fluxes are given at points 1, 7, and 2, and they are zero at 5, 9, and 10. There is an axis of symmetry to the left of points 1, 3, and 5, and to the right of 2, 4, and 10. Using two groups of neutrons and writing six difference equation balances around each point, one may solve for the six fluxes at points 3, 8, and 4 in terms of the given data. The equation for the thermal flux at point 3 would be

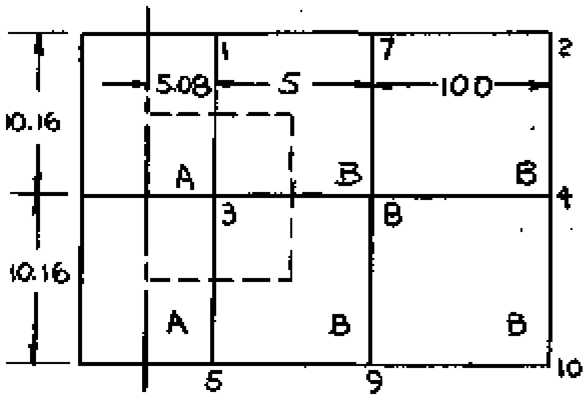

Fig. 4. Diagram of Mesh. All dimensions in cm.

$$D_{SA}\ \frac{\phi_{S1} - \phi_{S3}}{10.16}\,(5.08) + D_{SB}\ \frac{\phi_{S1} - \phi_{S3}}{10.16}\ \frac{5}{2} + D_{SB}\ \frac{\phi_{S8} - \phi_{S3}}{5}\ 10.16$$

$$- D_{SB}\ \frac{\phi_{S3}\ 5}{2\ (10.16)} - D_{SA}\ \frac{\phi_{S3}\ (5.08)}{10.16}$$

$$+ \Sigma_{FA}\ \phi_{F3}\ (5.08)(10.16) + \Sigma_{FB}\ \phi_{F3}\ \frac{5}{2}\ (10.16)$$

$$- \Sigma_{SA}\ \phi_{S3}\ (10.16)(5.08) - \Sigma_{SB}\ \phi_{S3}\ \frac{5}{2}\ (10.16) = 0$$

The balance is based on the volume enclosed by the dotted line which is half way between mesh points.

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