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DUMP TANK CRITICALITY AND POISONS FOR SLURRY REACTORS

B. E. Prince

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REACTOR EXPERIMENTAL ENGINEERING DIVISION

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B. E. Prince

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SUMMARY

Criticality conditions in slurry dump tanks and "poisoned" reactors were investigated in a computational study. The maximum "eversafe" diameters were about 9 in. and 8 in. for infinite H_2O-reflected cylinders containing ThO_2-H_2O slurries having U^{235}-to-thorium mass ratios of 0.10 and 0.15, respectively. The corresponding maximum thicknesses of infinite slabs with infinite H_2O reflectors were very nearly one-half the cylinder diameters. For these slurries, approximately 3 in. was the maximum separation of control "planes" for eversafe conditions; these planes were assumed to absorb 100% of the incident thermal and low-energy epithermal neutrons. In order to ensure subcriticality at all thorium concentrations with an array of cylindrical control rods, the rod pitch (center-to-center) should be 2.5 in. or less for 1-in.-dia rods placed in slurry containing 0.10 g of U^{235} per g of Th; the corresponding rod pitch for 2-in.-dia rods should be 3.7 in. or less. Replacement of the H_2O by D_2O increased the permissible rod pitch; however, the increase was small for water containing less than 50% D_2O.

The amount of natural boron (added as a homogeneous poison) required to decrease the critical temperature from operating conditions to 20°C was calculated for three slurry reactors. In a 12-ft-dia core-region thorium breeder (150 g of Th per liter in D_2O) about 50 ppm boron would decrease the critical temperature from 280 to 20°C; in a $4\frac{1}{2}$-ft-dia reactor containing D_2O and 200 g of Th per liter, the corresponding boron concentration was 550 ppm; in a $2\frac{1}{2}$-ft-dia reactor containing 400 g of Th per liter and moderator of 20% H_2O - 80% D_2O, about 700 ppm boron would decrease the operating temperature from 200 to 20°C.

INTRODUCTION

Safety considerations in the design of dump tanks for urania-thoria slurries require that criticality does not occur in the tanks during reactor shutdown or operation. Also, closely related problems in startup and shutdown of slurry reactors might be simplified if it were possible to add homogeneously to the slurry fuel a neutron poison which could also be readily removed.

The design parameter which may be considered fixed in slurry fuels is the uranium-to-thorium ratio. An important criterion determining the eversafe limits is that the slurry remain subcritical at any concentration resulting from settling of the solids. Also if, under reactor operations conditions, the moderator is D_2O, the possibility of contamination by light water must be considered in the eversafe margin.

In this report three means of providing for subcritical storage were investigated:

1. Noninteracting arrays of infinite slabs and cylinders; each slab or cylinder is assumed to contain light-water-moderated, urania-thoria slurry at 20°C, and to be reflected by light water.

2. Large single containers of slurry, heterogeneously poisoned with neutron-absorbing rods and planes.

3. Addition of a homogeneous poison to slurry under conditions of reactor operation, so that the maximum critical temperature in the reactor is reduced below a specified temperature level (between 280 and 20°C).

RESULTS

The critical-size limits for H_2O-reflected, aqueous-slurry-containing cylinders and slabs were calculated for U^{235}-to-thorium mass ratios of 0.10 and 0.15. These ratios were chosen as reasonable upper limits in the design of small slurry reactors. The computations were performed on the IBM-704, using a two-group diffusion program (WANDA). Figure 1 gives a plot of the critical thicknesses and diameters as functions of thorium concentration, up to 1500 g/liter. The regions below the curves correspond to eversafe conditions for the concentrations shown.

The spacing of neutron-poison planes and rods required for eversafe conditions in large dump tanks was also calculated; in these calculations maximum permissible spacings of the planes and rods to maintain subcritical conditions at 20°C were obtained for H_2O-ThO_2-UO_3 slurries (infinite media). This computation was based on a cell diffusion model given by Greebler.[1] A derivation of the equations for a parallel array of "control planes" is given in the appendix (the corresponding equations for an array of cylindrical rods are also summarized).

The planes and rods were assumed to have the neutron absorption characteristics of natural boron, so that effectively all incident thermal and low-energy epithermal neutrons were absorbed in the "poison" region. The planes were considered as thin regions (infinite in their lateral dimensions). The material multiplication was computed in terms of the product of the effective thermal utilization (f) and the effective resonance escape probability (p) in the associated cell. The computational results are shown in Fig. 2, where the fp product is plotted vs thorium concentration for various plane spacings.

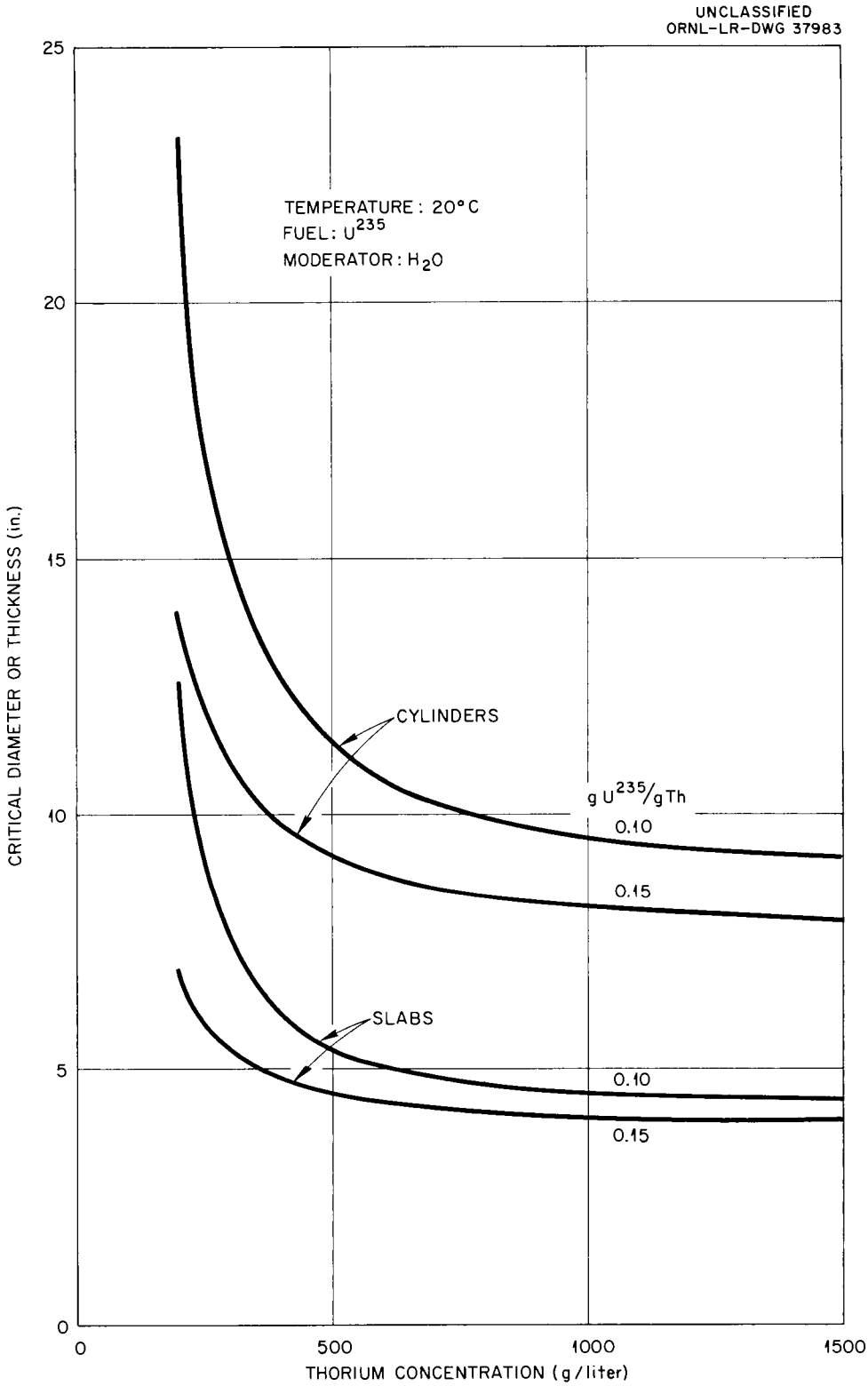

Fig. 1. Critical Dimensions of H_2O-Reflected, Infinite Aqueous-Slurry-Containing Cylinders and Slabs.

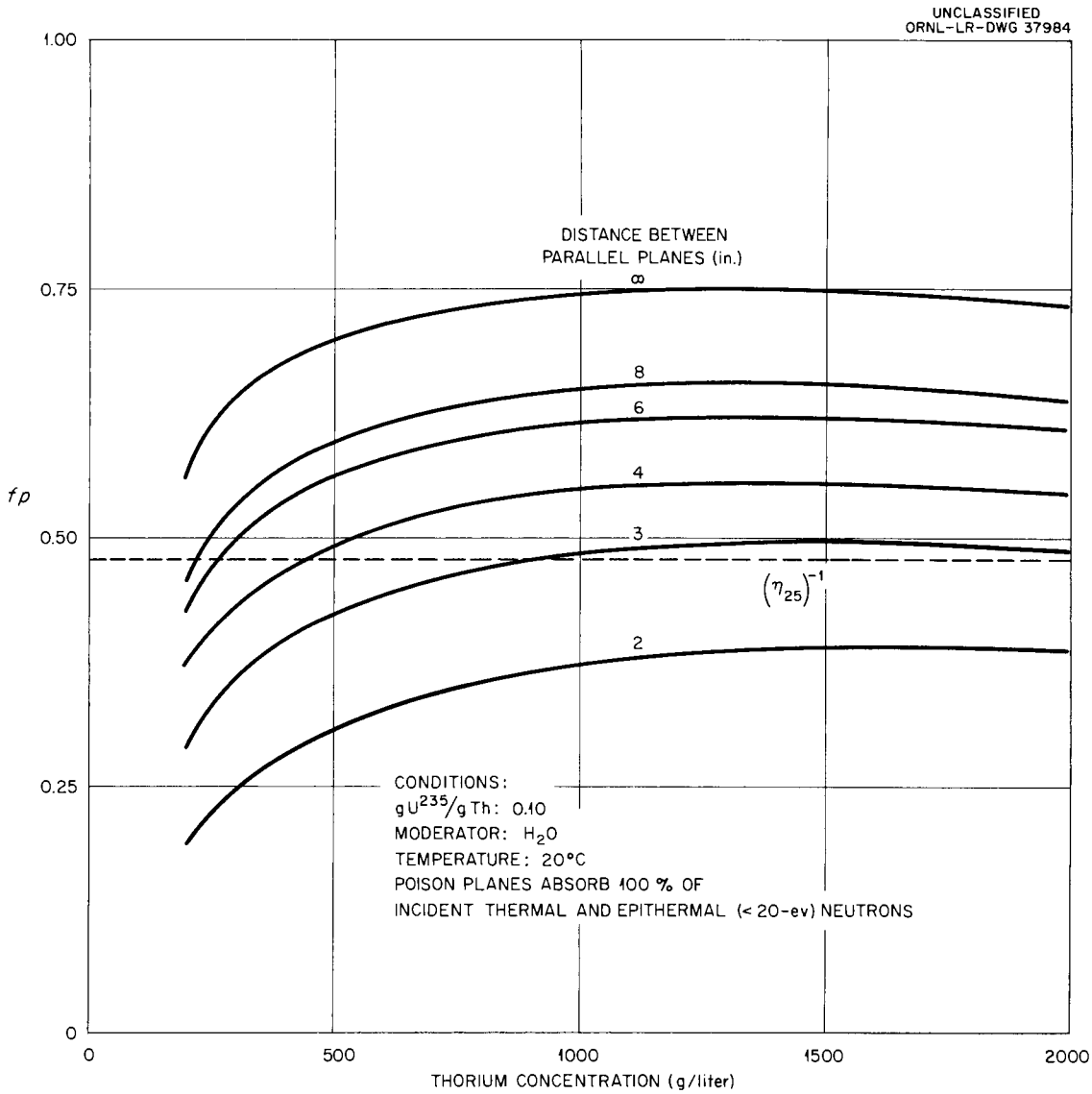

Fig. 2. Product of Thermal Utilization and Resonance Escape Probability for an Infinite Array of Poison Planes in Slurry.

The horizontal line $(\eta_{25})^{-1}$, shown dotted, is the permissible upper limit for noncritical conditions if net contributions due to resonance fissions are negligible.

Figures 3-6 were obtained in the same manner, and are plots of the fp product vs thorium concentration for arrays of cylindrical control rods in slurry media. In these figures, the rod pitch assigned is that of a square array; equivalence of other configurations may be obtained by equating the ratios of slurry volume to control-rod surface area, for the same rod diameter. Figure 3 gives results for an array of 1-in.-dia rods placed in a slurry containing a uranium-to-thorium ratio of 0.10, while Fig. 4 gives corresponding results for a uranium-to-thorium ratio of 0.15. Figure 5 shows results for an array of 2-in.-dia rods placed in slurry containing 0.10 g of U^{235} per g of Th. Results for 1-in.-dia rods in a slurry containing 0.10 g of U^{235} per g of Th and a moderator mixture of 50% D_2O - 50% H_2O are given in Fig. 6.

Under adverse temperature conditions during startup and shutdown of slurry reactors, large reactivity additions could result from changes in slurry concentration. These problems might be simplified if it were possible to add to the slurry fuel a homogeneous poison, which also could be readily removed. The amount of poison to be added would be that amount required to reduce the maximum critical temperature in the reactor from the operating level to some specified temperature. An estimate was made of the homogeneous thermal-poison levels required for: (1) a large single-region breeder, (2) a bare reactor equivalent in size to the core of a large two-region breeder, and (3) a small single-region slurry reactor. The large one-region reactor had a 12-ft diameter and heavy water was the moderator; at 280°C it had a thorium concentration of about 150 g/liter and a critical-mass ratio of about 0.02 g of U^{235} per g of Th. The equivalent

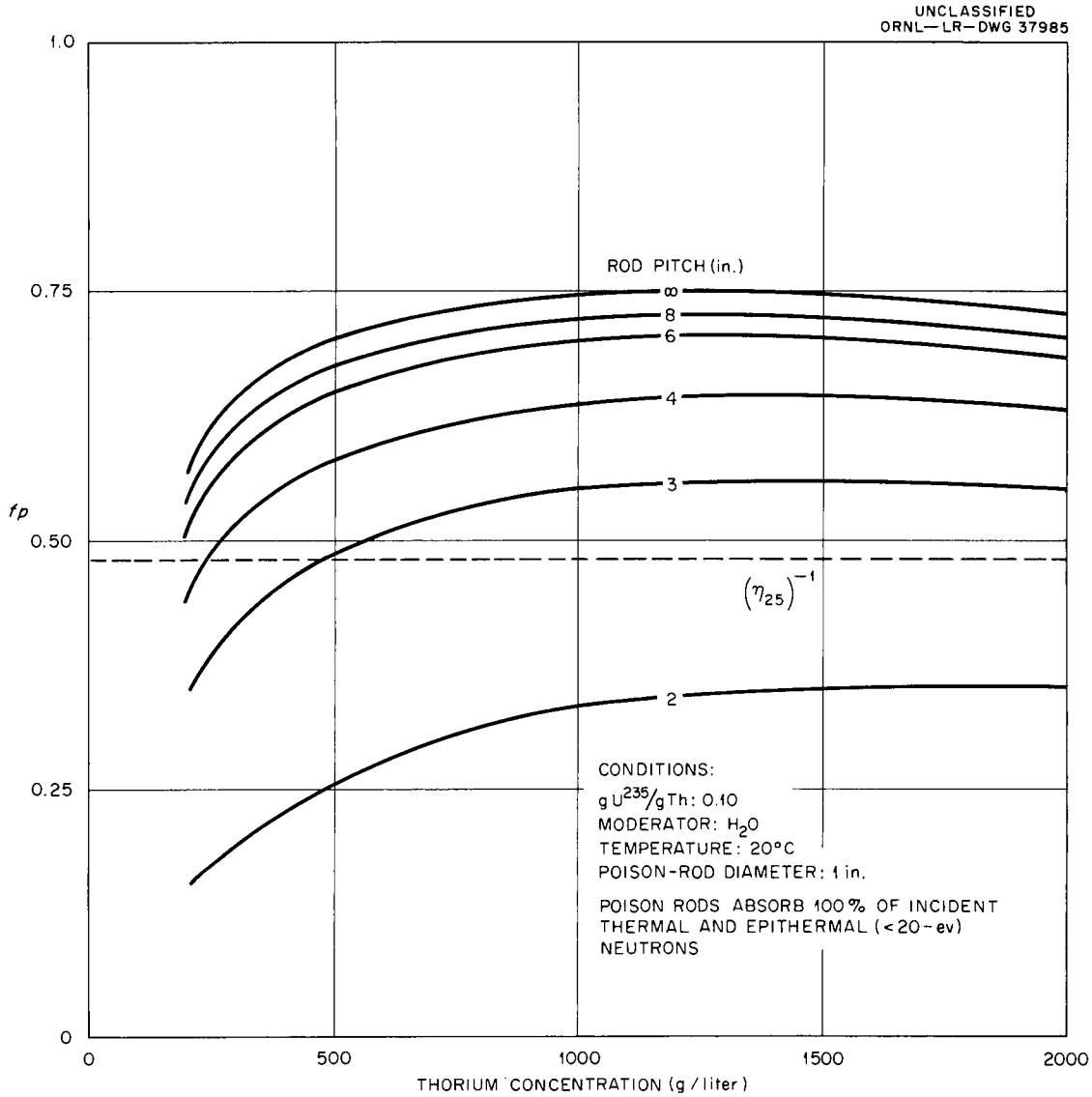

Fig. 3. Product of Thermal Utilization and Resonance Escape Probability for an Infinite Array of Poison Rods in Slurry.

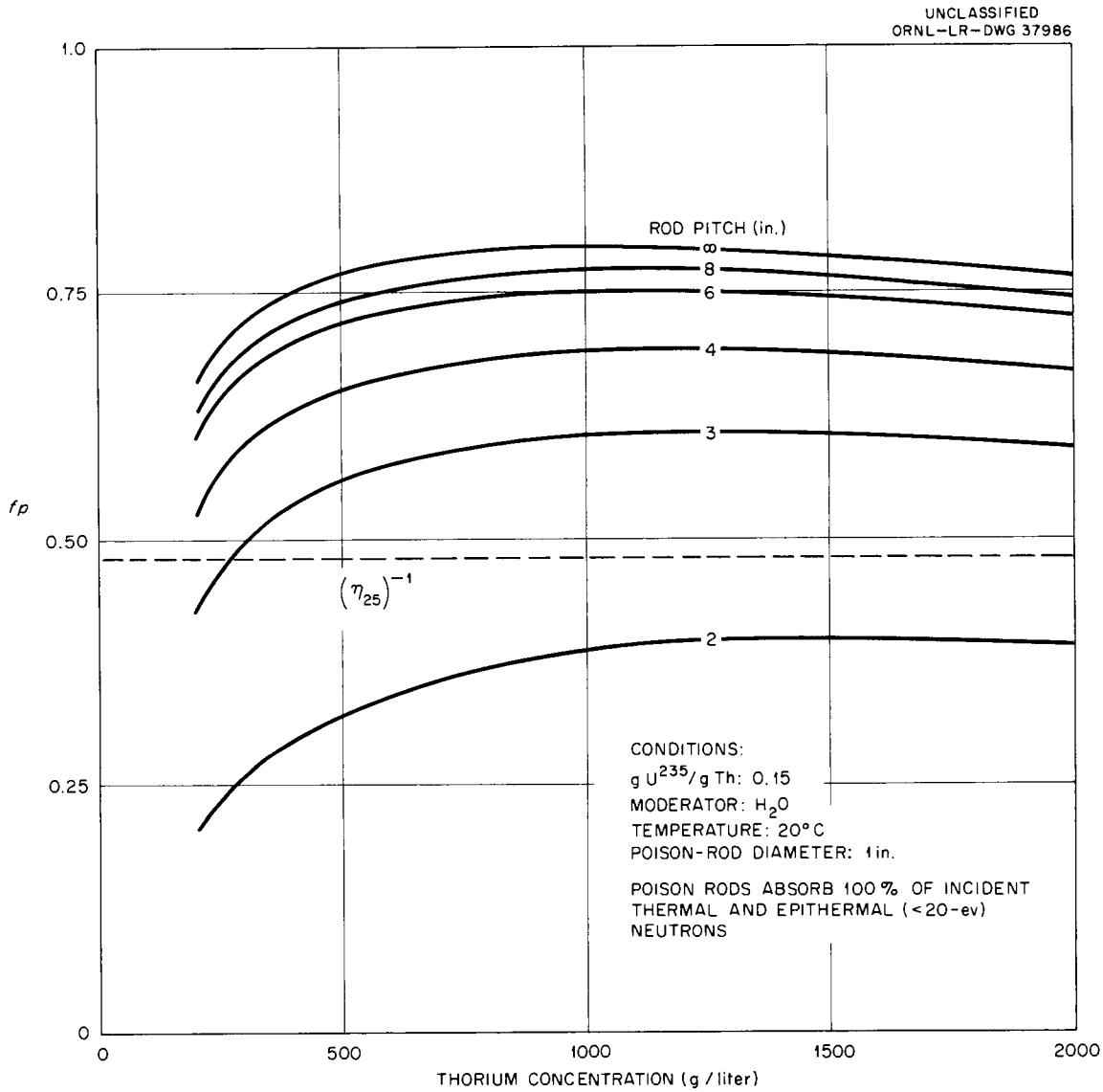

Fig. 4. Product of Thermal Utilization and Resonance Escape Probability for an Infinite Array of Poison Rods in Slurry. Conditions Same as in Fig. 3, Except for U^{235}/Th Ratio.

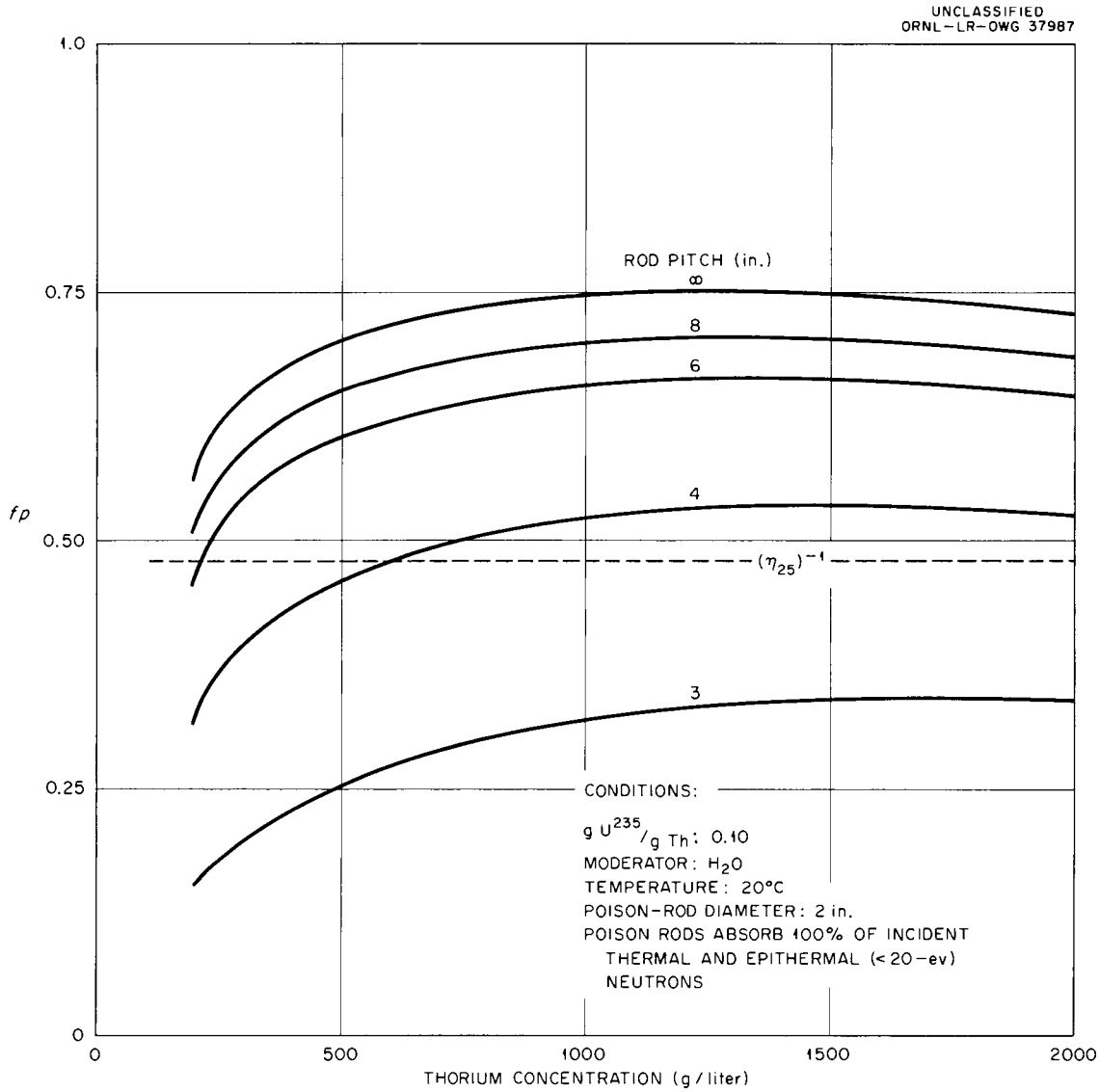

Fig. 5. Product of Thermal Utilization and Resonance Escape Probability for an Infinite Array of Poison Rods in Slurry. Conditions Same as in Fig. 3., Except for Poison-Rod Diameter.

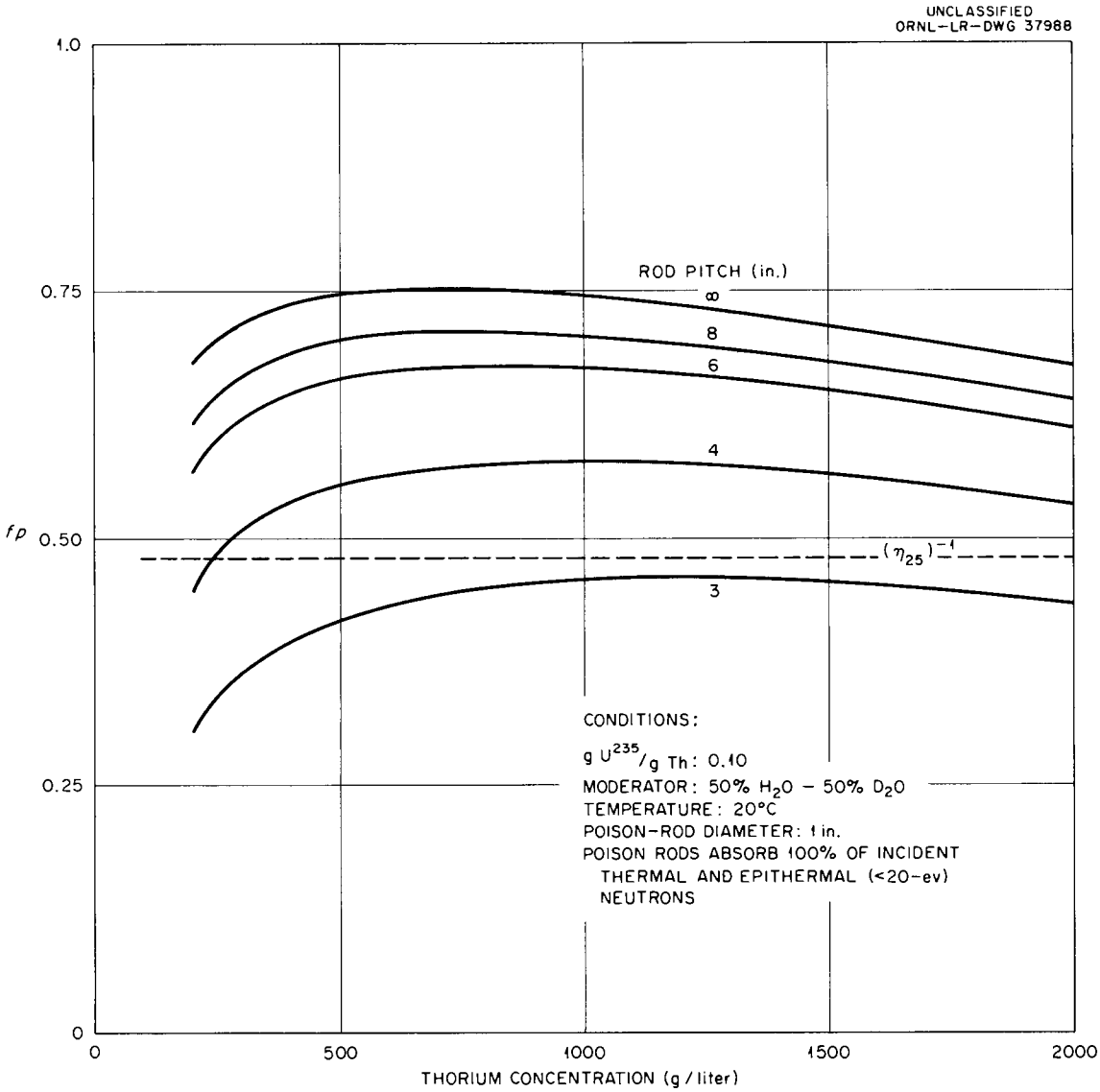

Fig. 6. Product of Thermal Utilization and Resonance Escape Probability for an Infinite Array of Poison Rods in Slurry. Conditions Same as in Fig. 3., Except for Moderator Composition.

two-region breeder core reactor* had a $4\frac{1}{2}$-ft-dia core and was moderated with heavy water; at 280°C it had a thorium concentration of 200 g/liter and a critical-mass ratio of about 0.08 g of U^{235} per g of Th. The small slurry reactor had a $2\frac{1}{2}$-ft-dia core and the moderator was composed of 20% H_2O - 80% D_2O; the maximum critical temperature was 200°C; at this temperature it had a thorium concentration of about 400 g/liter and a critical-mass ratio of about 0.10 g of U^{235} per g of Th.

The initial poison level in the above reactors was assumed to be zero, and the critical temperature was calculated as a function of neutron poison level. Figure 7 summarizes the results of the computations (the poison fraction is the ratio of thermal neutrons absorbed in poison to thermal neutrons absorbed in U^{235}). The basis for the calculations is discussed in reference 2.

To illustrate the use of Fig. 7, consider that the maximum critical temperature in the 12-ft-dia reactor is to be reduced from 280 to 20°C. The poison will be assumed to be a soluble form of natural boron which remains homogeneously distributed with the thoria. From Fig. 7, the poison fraction required is about 0.20. Since the thermal-absorption cross section of natural boron is about the same as that for U^{235}, about 50 ppm of natural boron is required to keep the reactor subcritical at temperatures above 20°C. The corresponding boron concentrations for the $4\frac{1}{2}$- and $2\frac{1}{2}$-ft-dia reactors would be about 550 and 700 ppm, respectively. In terms of grams of boron per kilogram of water, the above values correspond to 0.03 g/kg in the large reactor and to about 0.43 g/kg in the small slurry reactor.

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* The single-region reactor will be a sufficient approximation to the core of the two-region slurry system, provided the blanket of the latter contains a high thorium concentration.

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SPECIFICATIONS:

REACTOR	(a)	(b)	(c)
VESSEL DIAMETER (ft)	12	4½	2½
THORIUM CONCENTRATION AT MAXIMUM CRITICAL TEMPERATURE (g/liter)	150	200	400
U^{235}/Th RATIO	0.02	0.08	0.10
MODERATOR	D_2O	D_2O	20% H_2O 80% D_2O

(a) LARGE SINGLE-REGION REACTOR
(b) SINGLE-REGION APPROXIMATION TO CORE OF TWO-REGION SLURRY REACTOR
(c) SMALL SLURRY REACTOR EXPERIMENT

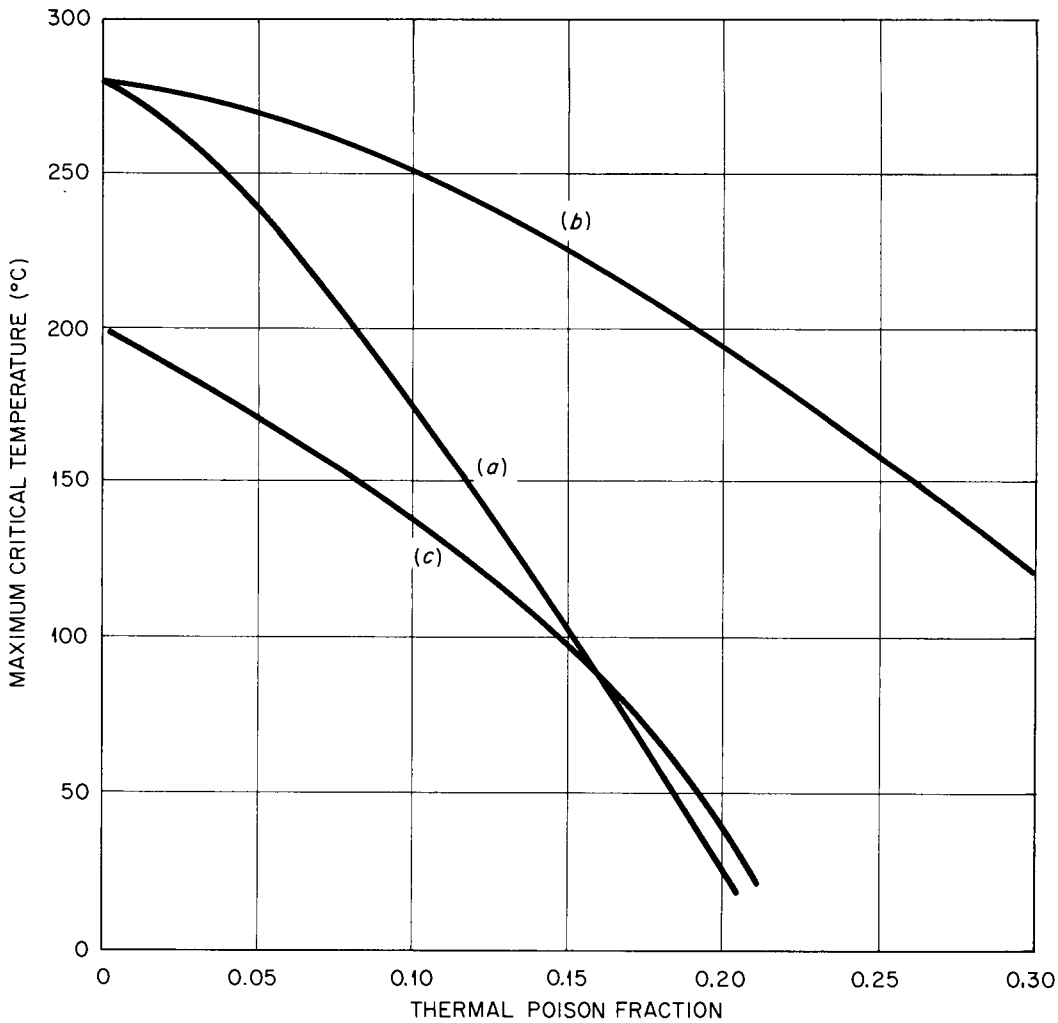

Fig. 7. Maximum Critical Temperature in Slurry Reactors vs Fraction of Homogeneous Poisons.

DISCUSSION

Subcritical storage of urania-thoria slurry can be maintained, provided that one or more of the following types of neutron losses are sufficiently high:

(a) leakage losses from the tanks,

(b) losses due to resonance absorption of neutrons in the thorium or in the "resonance poisons" present,

(c) losses by thermal absorption in neutron poisons.

The type (a) losses will be smallest if the moderator is H_2O, and this condition must be considered if there is a possibility of entrance of H_2O to the system. Losses of type (b) will also be smallest with H_2O, since the H_2O tends to moderate a larger percentage of neutrons across the thorium resonances. Although there is some thermal poisoning due to the H_2O at slurry concentrations of interest, this effect is generally of lesser importance than the moderation effects (a) and (b).

In a slurry with a fixed uranium-thorium ratio, resonance absorption by the thorium increases with slurry concentration; however, the ratio of thermal-neutron capture in thorium to that in fuel remains approximately constant. Thus the effectiveness of the thorium as a thermal poison is independent of the slurry concentration. This will also be true of any poison <u>adsorbed</u> on the surface of the slurry particles. Conversely, if the concentration of thermal poisons is fixed, such as with poison rods or with a soluble poison, then as the slurry concentration is increased the relative thermal absorption effectiveness of the poison tends to <u>decrease</u>. The potential infinite multiplication factor will rise with slurry concentration until the increase in

resonance poisoning balances this effect. As shown in the figures, if the moderator is H_2O, the critical parameters are nearly independent of concentration above 1000 g of Th per liter. At these concentrations, the thermal diffusion length becomes very small, and most of any neutron leakage occurs as fast neutrons. Also, if large containers are used, the total leakage becomes small. Thus the losses of type (b) and (c) must be kept high by internal poisoning.

The above general considerations apply whether the neutron poison is added in a homogeneous form or in the form of rods. In the latter case, if the rods absorb only thermal neutrons, the smallness of the diffusion length in the slurry requires that a small distance exist between absorbing surfaces of the rods in order to maintain subcriticality. Because of self-shielding effects, poison rods are generally much less effective than poison uniformly distributed in the slurry. Another factor which will increase the effectiveness of neutron poisons is any additional absorption poisoning in the low-energy range (epithermal or resonance energies). Natural-grade boron closely approximates a poison which absorbs both thermal and low-energy epithermal* neutrons.

Inaccuracies in the calculations result from incomplete account of the effects of resonance fissions in fuel. Also, the two-group model used for calculating neutron leakage from slabs and cylinders during slowing down becomes inadequate as the dimensions of the container become small; thus, criticality limits calculated in this study should be used only as preliminary estimates in the design of slurry reactor systems.

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* The upper and lower energy limits for the epithermal group were taken as 20 ev and 5 kT, respectively.

ACKNOWLEDGMENT

The author is indebted to M. P. Lietzke and T. B. Fowler for carrying out the IBM-704 computations for this study.

APPENDIX A

Equations for Systems With Heterogeneous Neutron Poisons

Greebler[1] has presented an approximate method for control rod analysis which is easily adaptable to simple control rod shapes and arrays. The method consists basically of a cell calculation in which the equivalent amount of uniformly distributed poison associated with each cell is obtained. In the calculational model, as many neutron energy groups as required may be used to represent the absorption in the poison. Also, the blackness of the rod may vary from group to group. In the present analysis two energy groups, thermal and epithermal, were used, and the added restriction of 100% blackness in both groups was made. A derivation is given below of the equivalent poisoning of a parallel array of control planes, which illustrates most of the assumptions in the model. A description of the more general case is given in reference 1.

Poisoning of a Parallel Array of Control Planes

For this array, a unit cell consists of the absorbing plane and half the associated slabs of fuel-moderator material between each plane (Fig. A1). The diffusion equations in the fuel bearing region for the epithermal and thermal groups are, respectively:*

$$\nabla^2 \phi_e - \frac{\phi_e}{L_e^2} + \frac{1}{D_e} = 0 \qquad (1)$$

$$\nabla^2 \phi_t - \frac{\phi_t}{L_t^2} + \frac{D_e \phi_e}{D_t \tau_e} = 0 \qquad (2)$$

---

* A table of nomenclature is given at the end of this section. The notation used here is the same as that used in reference 1.

The source term for the epithermal group, which results from slowing down of the fast neutrons, has been assumed flat and normalized to one neutron per unit volume per unit time. If epithermal absorption in the fuel bearing region is neglected, L_e^2 is equal to the neutron age (τ_e) from the upper to lower energy cutoffs of the epithermal group.

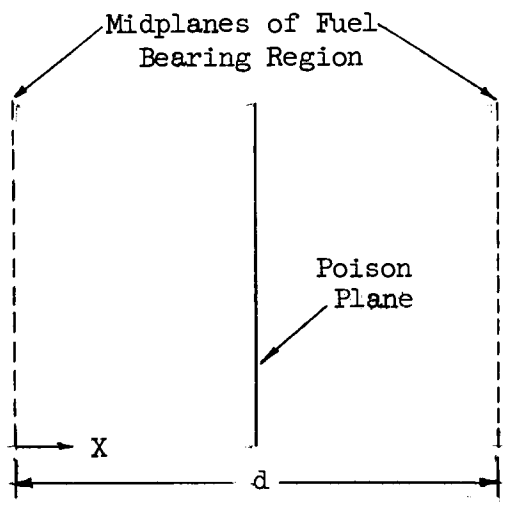

Figure A1. Coordinate Diagram for Unit Cell of Fuel Region and Poison Plane

The boundary conditions imposed on equations 1 and 2 are: (a) the net neutron current is zero at the outer surfaces of the cell, (b) the flux goes to zero at some specified distance within the "poison" plane (this distance depends on the blackness of the poison). These conditions give:

$$\frac{d\,\phi_i}{dx} = 0 \quad \text{at surface of cell; } i = e,\ t \tag{3}$$

$$\frac{d\,\phi_i}{dx} = -\frac{\phi_i}{\delta_i} \quad \text{at surface of "poison" plane; } i = e,\ t \tag{4}$$

where δ_i is the extrapolation distance for the epithermal or thermal group.

If the control plane is black, the extrapolation distances are given by:

$$\delta_i \cong 2\, D_i \qquad i = e,\ t \tag{5}$$

Using the coordinate system specified in Fig. A1, the solutions of the two-group equations, using boundary conditions (3) and (4) are:

$$\phi_e = \frac{L_e^{\,2}}{D_e}\left[1 - \frac{\cosh \frac{x}{L_e}}{\frac{\delta_e}{L_e}\sinh \frac{d}{2\,L_e} + \cosh \frac{d}{2\,L_e}}\right] \tag{6}$$

$$\phi_t = \frac{L_e^{\,2}\,L_t^{\,2}}{\tau_e\,D_t}\left[1 - \frac{L_e^{\,2}\cosh \frac{x}{L_e}}{(L_e^{\,2} - L_t^{\,2})\left(\frac{\delta_e}{L_e}\sinh \frac{d}{2\,L_e} + \cosh \frac{d}{2\,L_e}\right)} - \frac{\gamma_{te}\cosh \frac{x}{L_t}}{\left(\frac{\delta_t}{L_t}\sinh \frac{d}{2\,L_t} + \cosh \frac{d}{2\,L_t}\right)}\right] \tag{7}$$

where:

$$\gamma_{te} = 1 - \frac{L_e^{\,2}\left(\frac{\delta_t}{L_e} + \coth \frac{d}{2\,L_e}\right)}{\left(L_e^{\,2} - L_t^{\,2}\right)\left(\frac{\delta_e}{L_e} + \coth \frac{d}{2\,L_e}\right)}$$

For each group, the net number of neutrons (C_i) absorbed per unit surface area of the control plane is equal to twice the neutron current at the boundary:

$$C_e = -\,2\,D_e\left(\frac{d\,\phi_e}{dx}\right)_{x = \frac{d}{2}} = \frac{2\,L_e}{\frac{\delta_e}{L_e} + \coth \frac{d}{2\,L_e}} \tag{8}$$

$$C_t = -2D_t \left(\frac{d\,\phi_t}{dx}\right)_{x = \frac{d}{2}}$$

$$= \frac{2\,L_e^{\,2}\,L_t}{\tau_e}\left[\frac{\frac{L_t}{L_e}}{\left(1 - \frac{L_t^{\,2}}{L_e^{\,2}}\right)\left(\frac{\delta_e}{L_e} + \coth\frac{d}{2\,L_e}\right)} + \frac{\gamma_{te}}{\frac{\delta_t}{L_t} + \coth\frac{d}{2\,L_t}}\right] \tag{9}$$

Since the epithermal source is normalized to one neutron per unit volume per unit time, the total epithermal source in the cell per unit plane area is equal to the plane spacing (d). Then $d - C_e$ is the total number in the cell slowing into the thermal group per unit time and

$$a_e \equiv \frac{C_e}{d - C_e} = \frac{\text{Epithermal neutrons captured in poison plane}}{\text{neutron slowing down to thermal energies}} \tag{10}$$

If resonance absorption in fertile material is assumed to occur in the fuel bearing region, and if most of the absorption occurs above the energy region defined for the epithermal group,* the equivalent homogeneous poisoning for this group may be expressed as follows. Let p_o be the resonance escape probability in the fuel bearing region. Then the number of neutrons slowing down to thermal energies in the cell per fission neutron produced, or the effective resonance escape probability (p) is:

$$p = \frac{p_o}{1 + a_e} \tag{11}$$

Similar considerations lead to the following expressions for the poisoning in the thermal group. Let f_o be the thermal utilization in the fuel bearing region and f be the effective thermal utilization in the cell; then

---

* These conditions are approximated if the fertile material is thorium and the poison is boron.

$$a_t = \frac{C_t}{d - C_e - C_t} = \frac{\text{thermal neutrons absorbed in poison plane}}{\text{thermal neutron absorbed in fuel region}} \tag{12}$$

$$f = \frac{f_o}{1 + a_t} \tag{13}$$

Poisoning of an Array of Cylindrical Control Rods

The corresponding equations for the rod array are summarized below. These equations are derived in reference 1. Let poison rods of radius r_o be placed in a square array, each surrounded by the fuel bearing region. If the center-to-center distance of the rods is s, the area of the fuel bearing region per unit cell is:

$$A = s^2 - \pi r_o^2 \tag{14}$$

In the solution of equations 1 and 2, the unit cell is assumed to consist of the rod, surrounded by an equivalent cylindrical fuel bearing region of radius R, where:

$$s^2 = \pi R^2 \tag{15}$$

The result is:

$$C_e = 2\pi r_o L_e \alpha_e \tag{16}$$

$$C_t = \frac{L_e^2}{\tau_e} 2\pi r_o L_t \left[\frac{L_e L_t \alpha_e - L_t^2 \alpha_t + L_e (\delta_e - \delta_t) \alpha_e \alpha_t}{L_e^2 - L_t^2} \right] \tag{17}$$

where:

$$\alpha_i = \left[\frac{\delta_i}{L_i} + \frac{K_o (r_o/L_i) I_1(R/L_i) + I_o(r_o/L_i) K_1 (R/L_i)}{K_1 (r_o/L_i) I_1(R/L_i) - I_1(r_o/L_i) K_1 (R/L_i)} \right]^{-1}$$

$$i = e, t$$

where K_o, I_o, K_1, and I_1 are the modified Bessel functions.

Equations 10 through 13 will apply to the above case, if d is replaced by A.

Nomenclature for Appendix A

a_i Neutrons in group i absorbed in poison plane or rod, per neutron removed from group i in the fuel bearing region. Subscripts i = e (epithermal), t (thermal)

A Area of fuel bearing region, per unit cell

C_i Neutron absorption rate in group i per unit area of poison plane or per unit length of control rod; i = e, t

d Distance between poison planes

D_i Diffusion coefficient in fuel bearing region, for group i; i = e, t

f Thermal utilization; subscript o refers to fuel bearing region.

L_i Diffusion length in fuel bearing region, for group i; i = e, t

p Resonance escape probability; subscript o refers to fuel bearing region

r_o Radius of poison rod

R Equivalent cell radius

s Center-to-center distance of poison rods in a square array

δ_i Extrapolation distance into poison plane or rod; i = e, t

τ_e Neutron age from upper to lower energy cutoffs of epithermal group.

ϕ_i Neutron flux in group i

APPENDIX B

Nuclear Constants

The nuclear constants utilized in the calculations are summarized in Tables B1 - B5.

Table B1. Nuclear Parameters for U^{235}-Fueled, ThO_2-H_2O Slurry at 20°C

Thorium Conc. (g/ℓ)	Fuel Ratio (g U^{235}/g Th)	D_t (cm)	L_t (cm)	f_o	p_o
200	0.10	0.156	1.715	0.575	0.976
	0.15	0.156	1.510	0.670	0.976
500	0.10	0.160	1.245	0.738	0.952
	0.15	0.160	1.065	0.809	0.952
1000	0.10	0.168	0.947	0.816	0.916
	0.15	0.168	0.798	0.869	0.916
1500	0.10	0.176	0.806	0.845	0.882
	0.15	0.176	0.676	0.891	0.882
2000	0.10	0.185	0.722	0.861	0.848
	0.15	0.185	0.604	0.903	0.848

Table B2. Nuclear Parameters for ThO_2-H_2O Slurry at 20°C

Thorium Conc. (g/ℓ)	D_t (cm)	D_e (cm)	p_o	τ_e (cm^2)
200	0.156	0.582	0.976	2.23
500	0.160	0.586	0.952	2.32
1000	0.168	0.593	0.916	2.50
1500	0.176	0.600	0.882	2.71
2000	0.185	0.607	0.848	2.95

Table B3. Nuclear Parameters for ThO_2-50% H_2O-50% D_2O Slurry at 20°C

Thorium Conc. (g/ℓ)	D_t (cm)	D_e (cm)	p_o	τ_e (cm^2)
200	0.262	0.785	0.963	5.30
500	0.267	0.782	0.925	5.48
1000	0.276	0.778	0.871	5.79
1500	0.286	0.773	0.821	6.16
2000	0.296	0.769	0.770	6.58

Table B4. Thermal Utilization and Thermal Diffusion Length in U^{235}-Fueled, ThO_2-H_2O Slurry at 20°C

Thorium Conc. (g/ℓ)	Fuel Ratio (g U^{235}/g Th)	f_o	L_t (cm)
200	0.10	0.575	1.71
	0.15	0.670	1.51
500	0.10	0.738	1.25
	0.15	0.809	1.06
1000	0.10	0.816	0.947
	0.15	0.869	0.798
1500	0.10	0.845	0.806
	0.15	0.891	0.676
2000	0.10	0.861	0.722
	0.15	0.903	0.604

Table B5. Thermal Utilization and Thermal Diffusion Length in U^{235}-Fueled, ThO_2 - 50% H_2O - 50% D_2O Slurry at 20°C

Thorium Conc. (g/ℓ)	Fuel Ratio (g U^{235}/g Th)	f_o	L_t (cm)
200	0.10	0.701	2.45
	0.15	0.779	2.11
500	0.10	0.811	1.69
	0.15	0.865	1.42
1000	0.10	0.855	1.25
	0.15	0.899	1.03
1500	0.10	0.871	1.04
	0.15	0.910	0.86
2000	0.10	0.880	0.92
	0.15	0.916	0.77

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