PNCT831-79-02

NEACRP-L-247

Calculational Investigations on Designing Methods of Fuel Thicknesses of Annular Tanks for Plutonium Solutions *

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1. Introduction

There are some criticality handbooks for plutonium solutions on critical radii of spheres, those of infinite cylinders, and critical thicknesses of infinite slabs. It is easy to convert them to finite cylinders and finite slabs by buckling conversions using corresponding reflector savings. The critical thickness of an annulus, however, cannot be determined unless the inner or outer radius is specified. It is therefore, a complicated work to establish a handbook of critical thicknesses of annular nuclear fuels.

Annular tanks recently became key instruments, being adopted widely by the requirement for increased lot size of uniform plutonium composition. The general design processes and the criticality characteristics of the annular tanks are not well defined because of above-mentioned complexity. The purpose of this study is to understand the effects of design parameters on the criticality of annular tanks. Critical thicknesses of annular fuels are calculated by the one dimensional transport code, ANISN[1)], and the 16 group Hansen-Roach neutron cross-section set[2)]. The main design parameter is the inner radius of annular fuel region, and sub-parameters are the plutonium concentration and the thicknesses of the tank wall material, the neutron absorber, the inside filling material and the outside reflector.

2. Calculational Conditions

2.1 Fuel Composition

The chemical form of fuel solution and the composition of plutonium are specified as follows because of simplicity and conservativeness.

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* Presented at the Fall Meeting of the Atomic Energy Society of Japan (Oct., 1978).

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- Chemical form : $Pu-H_2O$ system
- Pu composition : Pu^{239} 95 w/o
  Pu^{240} 5 w/o
- Pu concentration : Parametric (see below)

2.2 Geometry of Fuel and Structures

One dimensional generalized model for calculation is shown in Fig. 1. The total calculational system is an infinite cylinder, and the fuel region is an annulus of infinite length. The design parameters (1∿7 in Fig. 1) of an annular tank are the calculational parameters in this study. The critical thickness, Tc of the fuel region is calculated on each case.

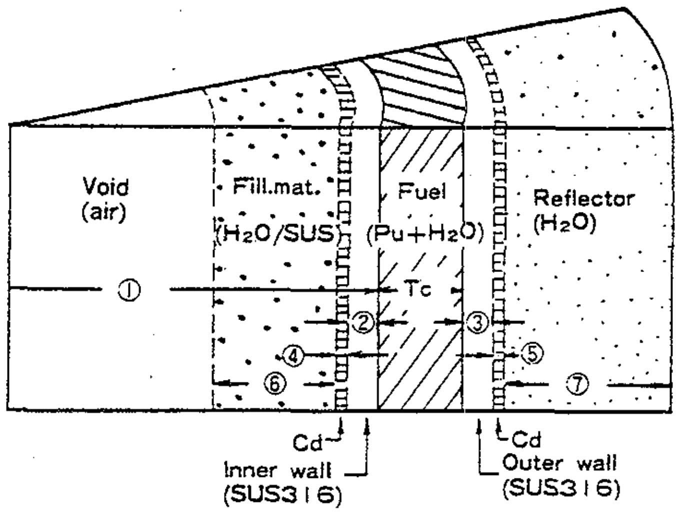

Fig. 1. One dimensional generalized model for annular tanks.

2.3 Range of Calculational Parameters

The ranges of parameters investigated in this study are shown in Table 1. The inner radius of fuel region is the main parameter, and the others are sub-parameters. The cases of complexed combination of sub-parameters are limited in the cases of fixed inner radius (=15 cm) only.

2.4 Cases of Calculations

The combination of parameters of each calculation series is shown in Table 2. Each series has a parameter which is symbolized as Ci, Ti, or Ri, and is variable in the range shown in Table 1.

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Table 1. Ranges of sub-parameters investigated.

Sub-parameter \ Inner radius, Rin	Fixed (15 cm)		Parametric (0*∼30 cm, ∞*)		I.D. No. in Fig. 1.
	Range of sub-para.	Series I.D.	Range of sub-para.	Series I.D.	
Pu concentration	0.1 ∼ 1.0 gPu/cc	CS-i	0.1 ∼ 1.0 gPu/cc	W4i ∼ W1i	
Stainless steel**) wall thickness					
Inside (only)	0.0 ∼ 3.0 mmt	WS-i	——	——	②
Outside + inside	0.0 ∼ 3.0 mmt	WSS-i	——	——	③
Existence of Cd-absorber					
Inside (only)	1.0 mmt	WCD-i	1.0 mmt	WCD-Bi	④
Outside + inside	——	——	1.0 mmt	WCD-Ci	⑤
Inside filling conditions					
Material	H_2O	——	(H_2O), SUS316, or Void	(WCD-Bi), SUS-i, VCD-i	——
Thickness	0.0(Void)∼15.0cm(full)	(WCD-i), WV-i	Full-filled	——	⑥
Outside reflector					
Material	H_2O	——	H_2O	——	——
Thickness	0.0(Bare) ∼ 20.0cm (full reflection)	WR-i	20.0 cm (full reflection)	——	⑦

*) "Rin=0.0" means a cylinder, and "Rin = ∞" means a slab.

**) SUS 316

Table 2. List of calculation cases.

Series I.D.	Inside conditions			Inner radius of annular fuel (cm)	Fuel concentration (gPu/cc)	Outside conditions	
CS-i	H_2O (full)	Cd(0.1cmt)	SUS(0.5cmt)	15.0 (fixed)	Ci	SUS(0.5cmt)	H_2O(20cm)
WSS-i	"	Cd(0.1cmt)	SUS(Ti)	"	1.0	SUS(Ti)	"
WS-i	"	Cd(0.1cmt)	SUS(Ti)	"	"	H_2O (20cm)	
WR-i	"		Cd(0.1cmt)	"	"	H_2O (Ti)	
WCD-i	Void	H_2O (Ti)	Cd(0.1cmt)	"	"	H_2O (20cm)	
WV-i	Void	H_2O (Ti)		"	"	"	
W1-i	H_2O (full)			Ri(parametric)	1.0	H_2O (20cm)	
W2-i	"			"	0.5	"	
W3-i	"			"	0.3	"	
W4-1	"			"	0.1	"	
WCD-Bi	H_2O (full)		Cd(0.1cmt)	Ri(parametric)	1.0	H_2O (20cm)	
WCD-Ci	"		Cd(0.1cmt)	"	"	Cd(0.1cmt)	H_2O(20cm)
VCD-i	Void (full)		Cd(0.1cmt)	"	"	H_2O (20cm)	
SUS-i	SUS (full)			"	"	"	

2.5 Flow of a Calculation

The flow chart of each calculation is shown in Fig. 2. The just critical core dimension (k_{eff}=1.0) is obtained by automatic iteration of dimension search option of ANISN code. The critical thickness of the fuel region is the difference of inner and outer radius of the fuel region.

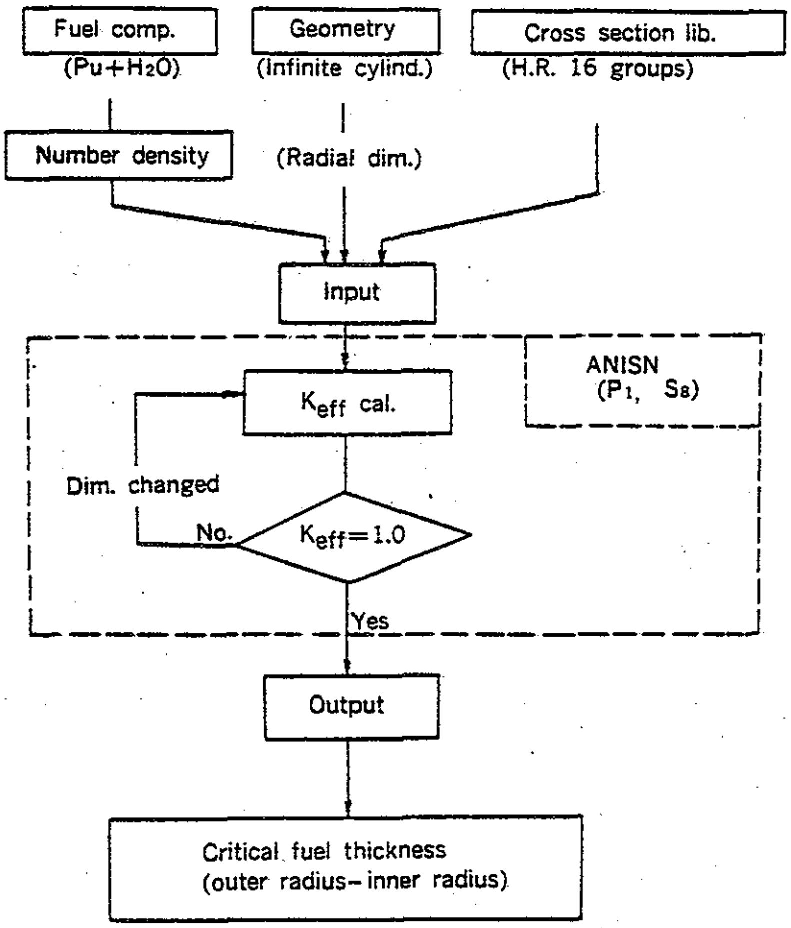

Fig. 2. Calculation flow.

3. Calculational Results and Discussions

3.1 Effects of the Plutonium Concentration

The relations of the inner radius and the calculated critical thickness of the fuel region (infinite annulus) are shown in Fig. 3 at four concentrations of plutonium. Each curve has a minimum point at the inner radius of about 5∿6 cm, and the minimum thickness is thinner than the thickness of infinite slab shown by the horizontal dotted line. This characteristic makes the designing process of an annular tank complicated.

The dependence of critical fuel thickness on the plutonium concentration is shown in Fig. 4 at the inner radius of 15 cm. The point A in Fig. 4 corresponds to the point A in Fig. 3. The marks A∿F in Figs. 3∿9 are given for the convenience of the comparison, and the same marks mean the same calculational conditions. The critical fuel thickness decreases simply with the increase in plutonium concentration, and the model of "1.0 gPu/cc" is sufficiently conservative for the plutonium solution.

This trend is same in the cases where the tank walls (5 mmt SUS304) and the Cd-absorber (1 mmt) are considered. It is apparent from the upper line in Fig. 4.

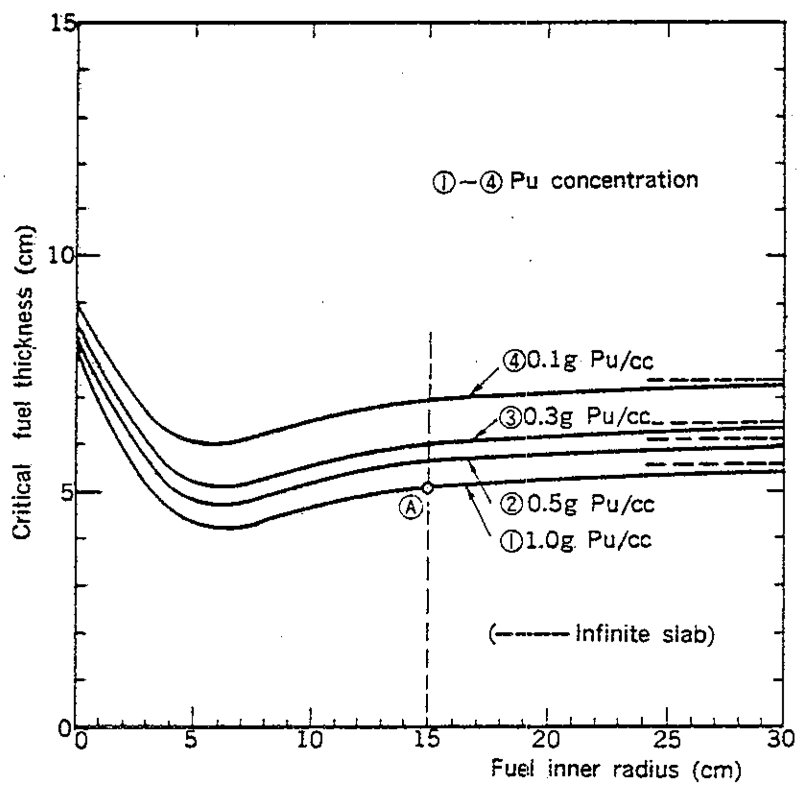

Fig. 3. Effects of inner radius and Pu concentration.

Tank materials : None
Inside : Flood (water)
Outside : Full water reflection

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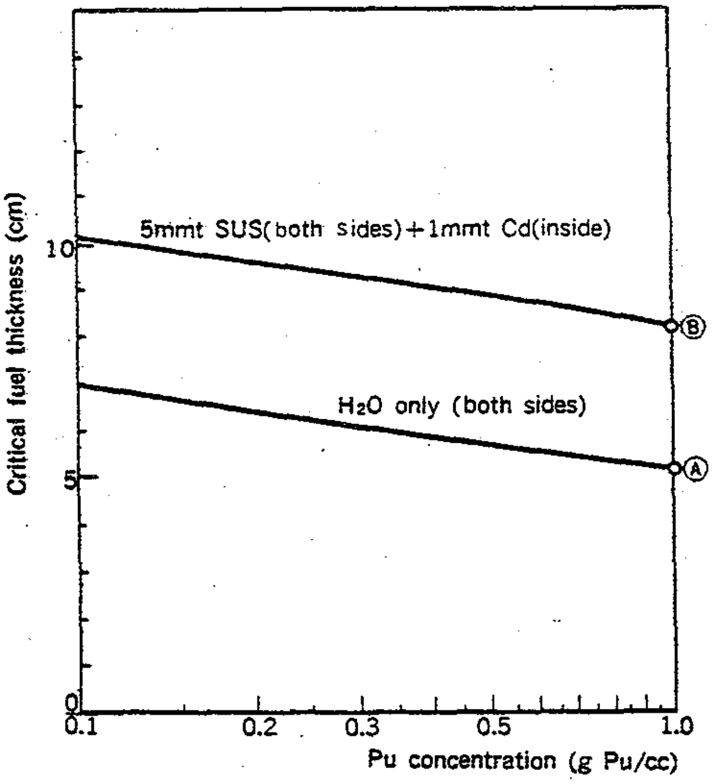

Fig. 4. Effects of Pu concentration.

Fuel inner radius : 15.0 cm
Inside : Flood (water)
Outside : Full water reflection

3.2 Effects of the Stainless Steel Wall Thickness

The effect of the stainless steel walls and the Cd-absorber is negative (i.e. they increase the critical fuel thickness) as shown in Fig.4. The net effect of stainless steel wall, however, is not apparent. The effects of the inside and the outside walls are shown in Fig. 5. The effect of the inside wall is positive (i.e. it decreases the critical fuel thickness), because the wall removes the inside filling water which is the good neutron insulator. The effects of detailed inside filling conditions are discussed below. The effect of the both side walls is negative up to the wall thickness of about 2.5 cm. The net effect of outside wall, which is shown as the difference of the upper and the lower curves, is estimated to be negative and satulated at the thickness of about 1 cm.

The annular tank model without stainless steel walls is conservative for criticality calculation, because the effect of both side walls is negative in the practical range of the wall thickness.

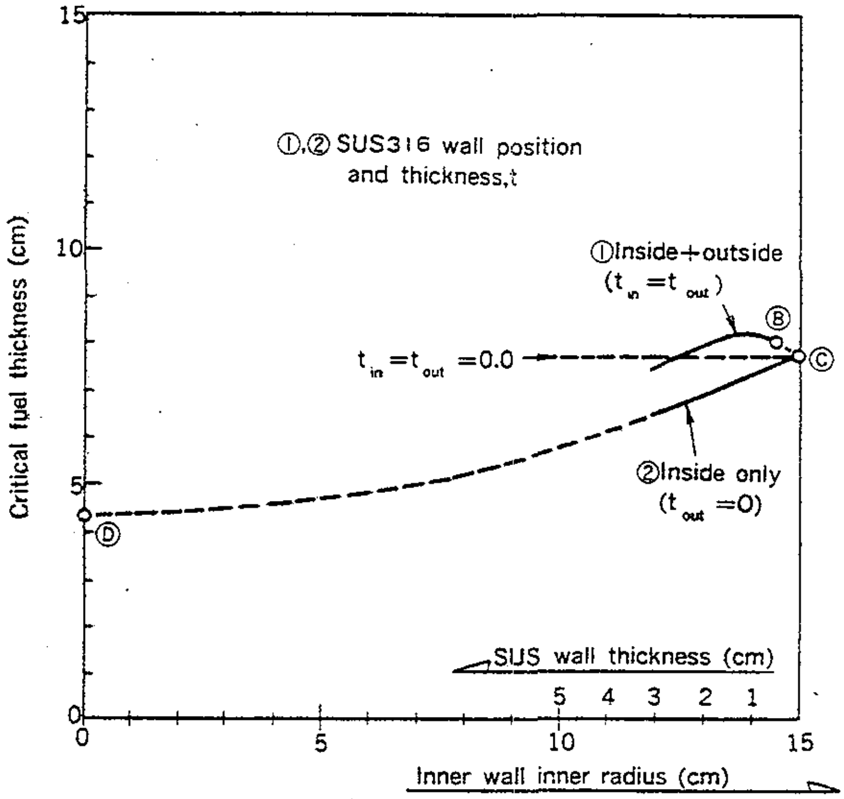

Fig. 5. Effects of stainless steel wall thickness.

Pu concentration : 1.0 gPu/cc
Fuel inner radius : 15.0 cm
Inside : Flood (water) + 1mmtCd
Outside : Full water reflection

3.3 Effects of the Existence of Cd-absorber

The net effects of Cd-absorber at some positions on the critical fuel thickness are shown in Fig. 6 as a function of the inner radius of the fuel region. The dotted line shows the critical infinite slab thickness, which is same as the thickness of 'the annulus with the infinite inner radius and infinite axial length.

The inside Cd-absorber makes the critical fuel thickness larger than the original by about 2.5 cm (about 50 percent). The inside and the outside Cd-absorbers make it larger than the original by about 5 cm (nearly 100 percent). The net effect of the outside Cd-absorber is almost constant at any inner radius and it makes the critical fuel thickness larger than that of the inside Cd case (without outside Cd-absorber) by about 2.5 cm.

The inner radius, where the critical thickness is minimum, decreases by the existence of a Cd-absorber, and the difference between the minimum critical thickness and the critical thickness of infinite slab is about 1.3 cm in each case. The following guidelines for the designing of annular tanks are derived from the above-mentioned criticality characteristics of the annular fuels. But they are limited in the case where the inside hole is filled with water or its equivalents.

(1) It is sufficiently conservative at any inner radius of the annular tank to use directly the critical thickness of infinite slab fully reflected by water as the design fuel-thickness, provided that the Cd-absorber is positioned inside of the inner wall.

(2) It is sufficiently conservative at any inner radius of the annular tank to use directly the critical thickness of infinite slab semi-reflected (i.e. one side is bare) by water as the design fuel-thickness, provided that the Cd-absorbers are positioned inside of the inner wall and outside of the outer wall.

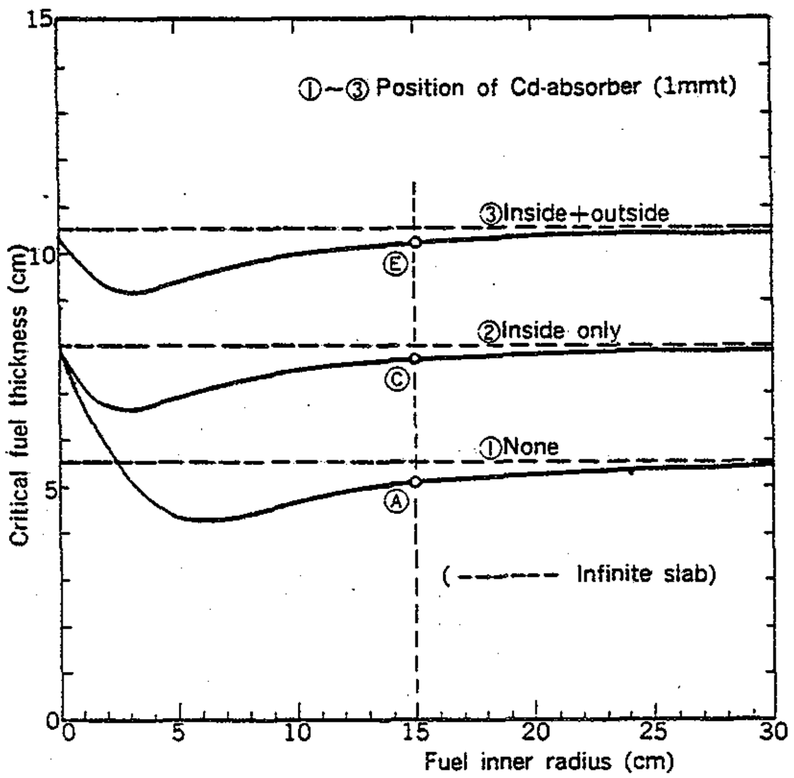

Fig. 6. Effects of inner radius and Cd-absorbers.

- Pu concentration : 1.0 gPu/cc
  Tank materials : None
  Inside : Flood (water)
  Outside : Full water reflection

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3.4 Effects of Inside Filling Conditions

The importance of inside filling materials and its conditions can be seen from the effect of the inside wall thickness shown in Fig. 5. The effects of stainless steel (SUS 316) and void (with Cd), and the combined effects of Cd, H_2O, and central void on the critical fuel thickness are calculated and discussed here.

The effects of stainless steel and void (with Cd) as well as H_2O full-filled as a function of the fuel inner radius are shown in Fig. 7. The neutron interaction of annular fuel itself through the inside non-fuel region is shielded more effectively by water than stainless steel and void (with Cd) at fuel inner radii of more than about 10 cm. But the water is less effective than the others at fuel inner radii less than about 10 cm. The net shielding effect of water inside of annular fuel of infinite length is shown by the difference of line ① and line ④ in Fig. 7.

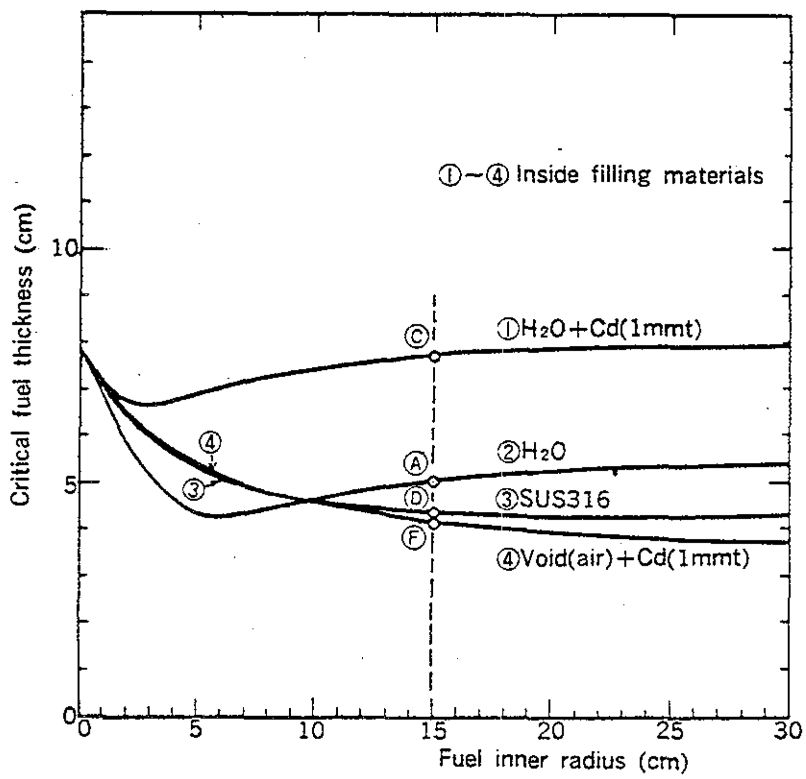

Fig. 7. Effects of inside filling materials.

Pu concentration : 1.0 gPu/cc
Tank materials : None
Outside : Full water reflection

The combined effects of Cd, H_2O, and central void on the critical thickness of the annular fuel at inner radius of 15 cm are shown in Fig. 8. The critical thickness curve of annular fuel without Cd-absorber has a minimum point at the inside water thickness of about 2.2 cm, which seems to correspond to the optimum moderation of the interacting neutron by the water positioned inside the fuel annulus. But the minimum critical fuel thickness is obtained at no inside water, i.e. complete void is the severest when Cd-absorber is positioned inside of the fuel annulus. The existence of Cd-absorber makes the consideration of optimum moderation by inside water or water equivalent unnecessary.

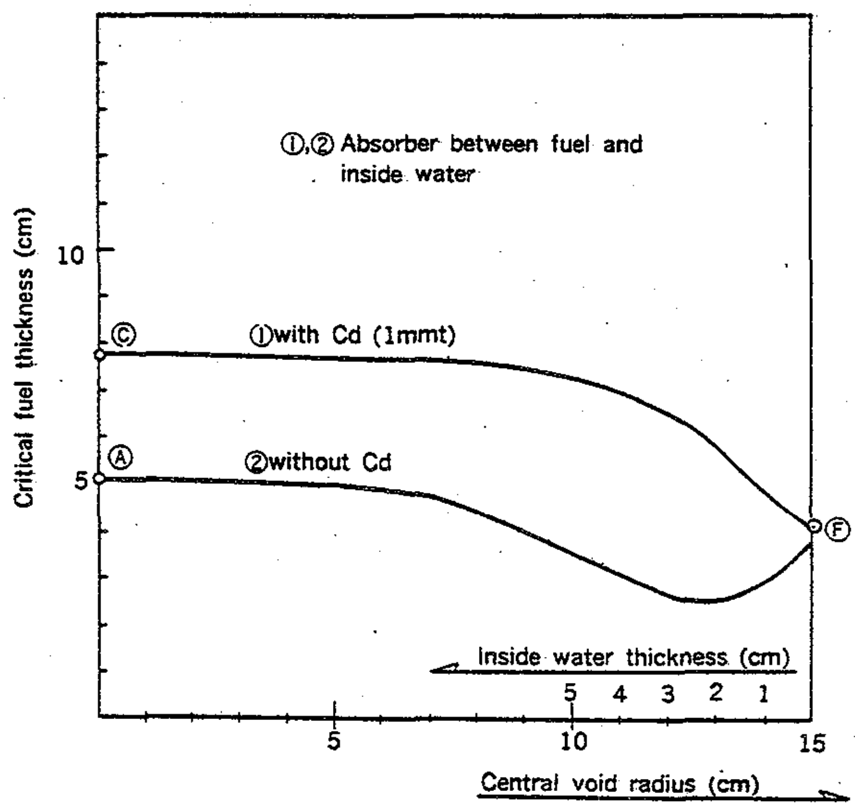

Fig. 8. Effects of inside filling conditions.

Pu concentration : 1.0 gPu/cc
Fuel inner radius : 15.0 cm
Outside : Full water reflection

3.5 Effects of Outside Water Reflector Thickness

The condition of "full water reflection" is assumed almost always when the criticality safety design bases or administrative limits are determined. The effects of outside water reflector thickness and the Cd-absorber inserted between the fuel and the reflector on the critical fuel thickness are shown in Fig. 9. The critical fuel thickness decreases rapidly up to about 5 cm in the reflector thickness, and the effect of water reflector is almost satulated at about 15 cm. The water thickness as much as 20 cm seems to correspond to the condition of full water reflection.

It is not necessary to assume the full water reflection when the Cd-absorber is inserted between the fuel region and the reflector region. Under that condition "1 inch water reflection" is a conservative assumption for the determination of the design basis and others. The change in the thermal neutron fluxes (Group 16 of the Hansen-Roach cross-section set) by the reflector thickness and the Cd-absorber is shown in Fig. 10.

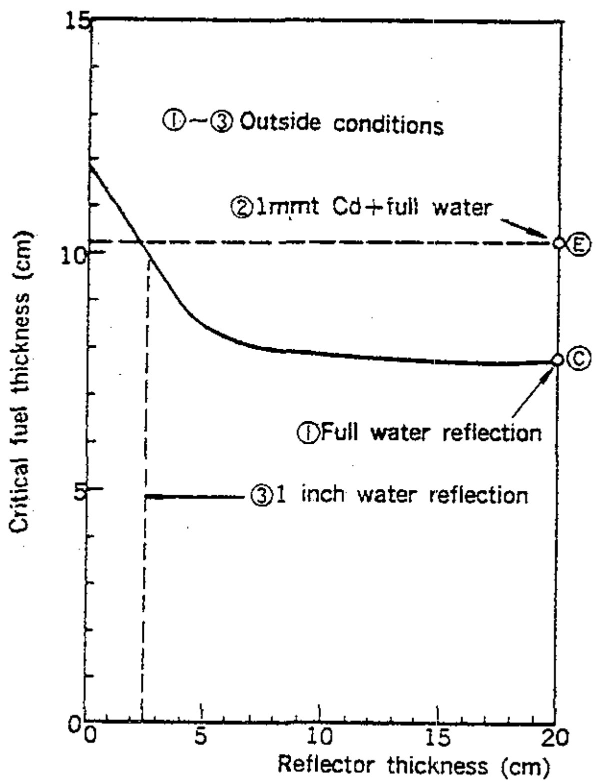

Fig. 9. Effects of outer reflector thickness.

Pu concentration : 1.0 gPu/cc
Fuel inner radius : 15.0 cm
Inside : Flood (water) + 1mmtCd

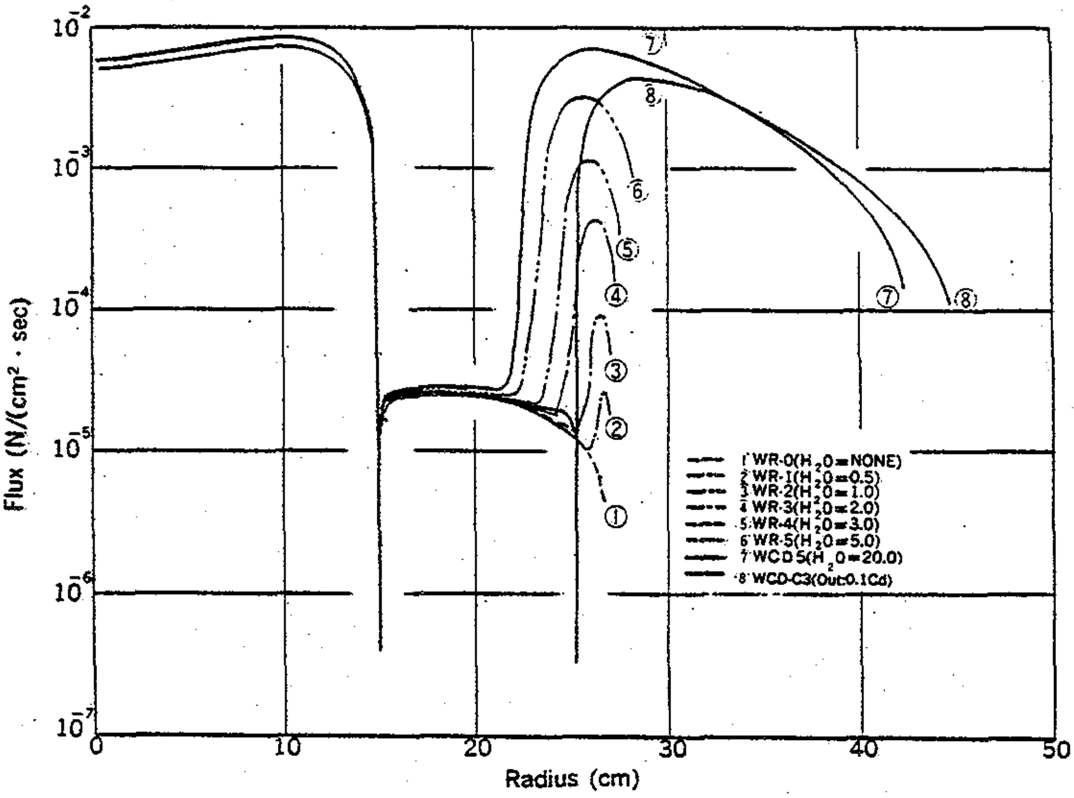

Fig. 10. Thermal neutron fluxes (Group 16) with several reflection conditions.

3.6 Relations of k_{eff} vs. Critical Fuel Thickness

The proper margin is required in the k_{eff} or the fuel dimension whenever the calculated criticality datum is adopted as a criticality safety basis. The margin in the k_{eff} is discussed directly by the comparison of k_{eff} calculated and measured. The margin in the fuel dimension is derived from the relation between the k_{eff} and the fuel dimension. The typical relations calculated in this work are shown in Fig. 11. The relations are almost linear but have various slopes by the calculational conditions. It is sufficient for the criticality safety margin in our work to reduce the critical thickness by 15 percent provided that the subcriticality is assured by the k_{eff} below 0.95.

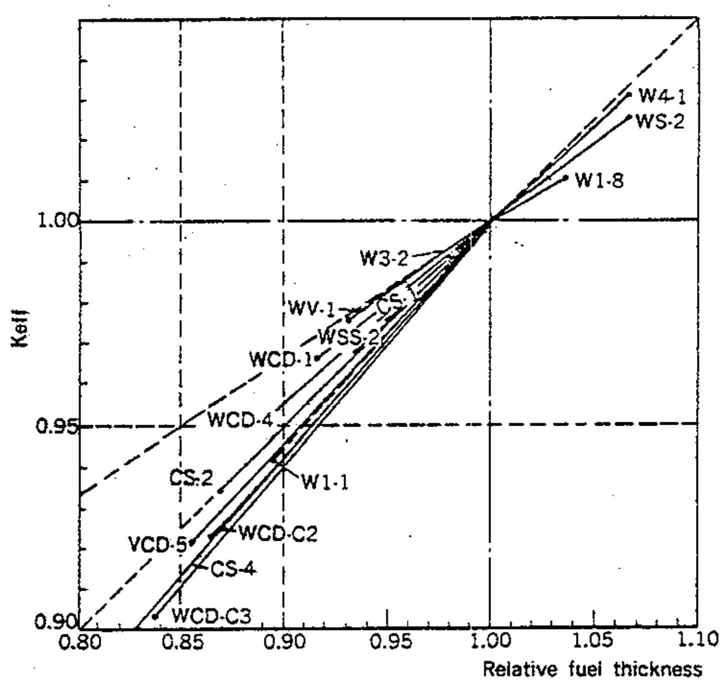

Fig. 11. Typical relations of k_{eff} vs. relative fuel thickness.

4. Conclusions

Some of the fundamental characteristics of the annular fuel are made clear by this calculational investigation. Especially the existence of Cd-absorber and the filling condition inside of fuel annulus are shown to be important design subparameters.

The critical thickness of infinite slab is a good design basis of the annular fuel, provided that the inside of the fuel is filled with water or water equivalent material and the Cd-absorber is inserted between the fuel and the filling material.

The calculational assumptions on the chemical form and the concentration of the plutonium fuel are extremely conservative in this work. The critical thickness will be increased by more realistic assumptions.

References

1) R.G. Soltesz, R.K. Disney; "ANISN-W, Nuclear Rocket Shielding Methods, Modification, Updating, and Input Data Preparation Volume 4", WANL-PR-(LL)-034.

2) G.E. Hansen, W.H. Roach; "Six and Sixteen Group Cross Sections for Fast and Intermediate Critical Assemblies", LAMS-2543.