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Critical Experiments to Measure the Neutron Poisoning Effects of Copper and Copper-Cadmium Plates

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There has been considerable interest in the use of fixed neutron absorbers (poisons) for criticality control since their use would permit safely handling larger quantities of nuclear materials with reduced probability of criticality. The effectiveness of such absorbers as neutron poisons depends on self-shielding effects which in turn are determined by the magnitude of the absorption cross sections and their variation with energy, the thickness of material, and the neutron-energy spectrum. For the fixed poisons to be considered as either a primary or secondary means of criticality control, their use must be based on a firm knowledge of these effects. To obtain experimental data in this area, the reactivity worth of two such materials, copper and copper containing 1 wt% cadmium, was recently measured in two different energy spectrums and at different thicknesses up to ~$2\frac{1}{2}$ cm. The results of these measurements are presented in this paper and provide a set of clean, well-defined, poisoned critical assemblies that can be used to check calculational techniques and cross-section data.

In the relatively thermalizwd neutron-energy spectrum, very little additional absorption was observed in the copper plate at thicknesses greater than ~$2\frac{1}{2}$ cm or in the copper-cadmium plate at thicknesses greater than 1 cm. At thicknesses greater than these, self-shielding precluded any additional absorption, and the change in reactivity was due almost entirely to the additional void being introduced into the system by the poison plates.

In the relatively fast neutron energy spectrum, neutron absorption was observed to continually increase with plate thickness for both sets of plates. However, in this spectrum the void effects, caused by the presence of the poison plates, had a greater reactivity worth, over the thickness range covered, than the neutron absorption.

In either spectrum, the 1 wt% cadmium in the copper contributed significantly to the neutron absorption. Of course, the cadmium was found to be worth much more in the thermalized spectrum.

INTRODUCTION

Shipping casks, storage facilities, and process vessels involved in handling fissile materials contain neutron absorbing materials—either for their neutron absorbing properties or for structural reasons. These types of systems can be fully utilized safely, only if the neutron absorbers are properly accounted for in the criticality analyses. The reactivity worth of two such materials, copper and copper containing 1 wt% cadmium, was recently measured at the Battelle-Northwest operated Critical Mass Laboratory. The results of these measurements are presented in this paper

and provide a set of clean, well-defined, poisoned critical assemblies that can be used to check calculational techniques and cross-section data.

GENERAL DESCRIPTION OF EXPERIMENTS

The relative worth of copper and copper-cadmium plates was measured in two different fuels to provide data on these neutron absorbers in widely differing neutron-energy spectrums. Both sets of fuel were homogeneous mixtures of PuO_2-UO_2-polystyrene in the form of 5- × 5-cm compacts having different thicknesses. A complete description of each fuel, including cladding, composition, and size, is shown in Table I. One fuel, having an H:(Pu + U) atomic ratio of 30.6 in which the oxide mixture contained 14.62 wt% PuO_2, had a relatively soft neutron-energy spectrum. The second fuel, of which the oxide mixture contained 30.3 wt% PuO_2 and the overall composition corresponded to an H:(Pu + U) atomic ratio of 2.8, had a much harder spectrum. Calculated 18 en-

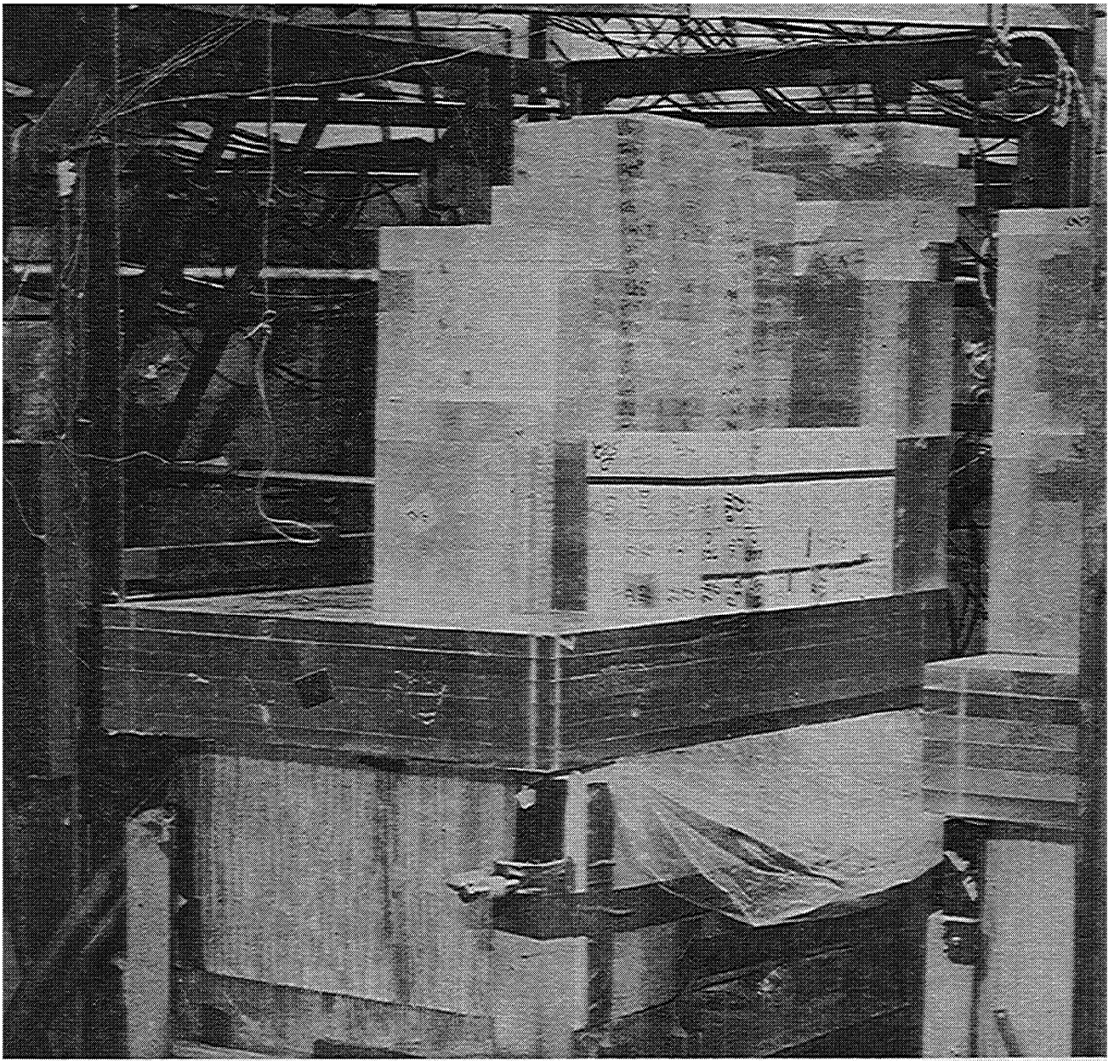

Fig. 1. Experimental assembly with part of the reflector removed.

TABLE I

Description of Experimental Fuel and Reflector Material

	2.8 H:(Pu + U) Fueled Experiments			30.6 H:(Pu + U) Fueled Experiments		
Cladding material per compact, g	2.432			3.175		
Cladding density, g/cm^3	1.12			1.12		
Composition of cladding, at./b cm						
H	4.489×10^{-2}			4.489×10^{-2}		
C	3.110×10^{-2}			3.110×10^{-2}		
Cl	0.724×10^{-2}			0.724×10^{-2}		
Composition of reflector, at./b cm						
H	5.712×10^{-2}			5.712×10^{-2}		
C	3.570×10^{-2}			3.570×10^{-2}		
O	1.428×10^{-2}			1.428×10^{-2}		
Composition of fuel compacts, at./b cm						
^{241}Am	1.017×10^{-5} [a]			4.036×10^{-7} [b]		
^{239}Pu	2.186×10^{-3}			1.954×10^{-4}		
^{238}Pu	2.288×10^{-6}			0.0		
^{240}Pu	2.927×10^{-4}			1.702×10^{-5}		
^{241}Pu	5.875×10^{-5}			1.211×10^{-6}		
^{242}Pu	6.751×10^{-6}			0.0		
O	1.864×10^{-2}			3.023×10^{-3}		
^{238}U	6.162×10^{-3}			1.252×10^{-3}		
^{235}U	9.269×10^{-6}			1.904×10^{-6}		
H	2.432×10^{-2}			4.489×10^{-2}		
C	2.660×10^{-2}			4.412×10^{-2}		
PuO_2 particle size, μm						
95%	<20			<20		
50%	<8			<5		
5%	<2			<0.5		
UO_2 particle size, μm						
95%	<40			<40		
50%	<9			<9		
5%	<2			<3		
Polystyrene particle size, μm						
95%	<225			<225		
50%	<150			<150		
5%	<50			<50		
Uranium density, g/cm^3	2.438 ± 0.023			0.495 ± 0.005		
Plutonium density, g/cm^3	1.012 ± 0.010			0.085 ± 0.001		
Fuel compact density, g/cm^3	4.520 ± 0.043			1.615 ± 0.017		
Dimensions of fuel compacts, cm	Length	Width	Thicknesses	Length	Width	Thicknesses
unclad compacts	5.090 ± 0.005	5.083 ± 0.026	5.090 ± 0.005; 1.339 ± 0.026	5.090 ± 0.005	5.090 ± 0.025 [c]	5.090 ± 0.005; 3.400 ± 0.044; 1.384 ± 0.039
clad compacts	5.114 ± 0.009	5.170 ± 0.026	5.114 ± 0.006; 1.363 ± 0.026	5.121 ± 0.005	5.137 ± 0.005 [d]	5.121 ± 0.005; 3.431 ± 0.044; 1.415 ± 0.039
clad compacts + voids	5.118 ± 0.015	5.174 ± 0.030	5.118 ± 0.015; 1.367 ± 0.026	5.130 ± 0.010	5.190 ± 0.025	5.130 ± 0.010; 3.440 ± 0.048; 1.424 ± 0.043

[a] Isotopic analysis made on Dec. 2, 1971. Experiments performed June 1973.
[b] Isotopic analysis made on May 28, 1970. Experiments performed May 1973.
[c] 5.095 ± 0.021 cm for the 5.09-cm-thick compacts.
[d] 5.142 ± 0.021 cm for the 5.12-cm-thick clad compacts.

ergy group spectra, using the GAMTEC-II (Ref. 1) code and ENDF/B-III cross-section data, are shown in Table II for each of the fuels.

The critical assemblies consisted of rectangular parallelepipeds of fuel fully reflected with 15 cm of a methacrylate plastic (Plexiglas). All assemblies had a base of 9 fuel compacts on a side. The plates, having thicknesses up to $\sim 2\frac{1}{2}$ cm and the same cross-section dimensions as the assemblies, were positioned horizontally in the assemblies. Except for one series of experiments to measure the worth of a plate as a function of position in the assembly, the position of the plates, relative to the bottom of the assembly, was constant for each fuel. This distance from the bottom was such that the plates were approximately centered in the fuel for all the experiments. A portion of the experimental assembly is shown in Fig. 1 with the remote-operated split-table, used in the experiments, fully open and part of the reflector material removed.

In addition to the measurements with copper or copper-cadmium plates, measurements were similarly made without any plates and with aluminum plates to provide a measure of the void effects relative to the poison effects caused by the plates being present in the assemblies. The compositions for each type of plate are given in Table III.

TABLE II

Calculated 18 Energy Group Neutron Flux for PuO_2-UO_2-Polystyrene Fuels

Relative Flux 30.6 H:(Pu + U) Fuel	Lower Energy of Group	Relative Flux 2.8 H:(Pu + U) Fuel
0.0024	7.79 MeV	0.0023
0.0069	6.07 MeV	0.0071
0.0155	4.72 MeV	0.0164
0.0253	3.68 MeV	0.0267
0.0337	2.87 MeV	0.0375
0.0958	1.74 MeV	0.1074
0.0475	1.35 MeV	0.0538
0.2419	183.00 keV	0.3212
0.0987	24.80 keV	0.1404
0.0688	3.36 keV	0.0912
0.0628	454.00 eV	0.0750
0.0447	101.00 eV	0.0443
0.0284	37.30 eV	0.0222
0.0264	13.70 eV	0.0169
0.0245	5.04 eV	0.0116
0.0250	1.86 eV	0.0130
0.0220	0.683 eV	0.0058
0.1297	0	0.0072

DISCUSSION OF EXPERIMENTAL DATA

Critical heights were determined for the 30.6 H:(Pu + U) fueled assemblies both with and without poison regions in the fuel. The poisoned assemblies had either a single region of aluminum, copper, or copper-cadmium plates or two regions separated by 5.09 cm of fuel. Except for one series of experiments, which will be discussed later, the bottom plate, in either type of assembly, was always located 10.32 cm from the bottom of the fuel. The geometries of these poisoned assemblies are shown graphically in Figs. 2 and 3. The measurements with the aluminum and copper plates were made with different thicknesses of plates up to $\sim 2\frac{1}{2}$ cm. The measurements with the copper-cadmium plates were limited to a maximum thickness of $\sim 2\frac{1}{4}$ cm for the single region experiments and to a single thickness of about $\frac{1}{3}$ cm for the two-region experiments. The results of these experiments are shown graphically in Figs. 4 and 5. Critical heights as a function of plate position in the 30.6 H:(Pu + U) fuel were also obtained for a single region of aluminum, copper, or copper-cadmium about $\frac{1}{3}$ cm thick. The results of these experiments are shown graphically in Fig. 6.

Critical heights, both with and without plates of aluminum, copper, or copper-cadmium, were similarly determined for the 2.8 H:(Pu + U) fueled

TABLE III

Composition of Neutron Poison Plates

Element	Copper (8.913 g/cm³) (wt%)	Copper Cadmium[a] (8.910 g/cm³) (wt%)	Aluminum (2.692 g/cm³) (wt%)
Cu	99.960	98.685	0.14[b]
Cd	---	0.989	---
Al	---	---	97.98
Zn	0.001	0.007	0.25
Sn	---	0.250	---
Ni	---	0.010	---
Fe	0.003	0.020	0.70
Cr	---	---	0.15
Mn	---	0.009	0.15
Mg	0.001	---	0.08
Ti	---	---	0.15
Si	0.001	0.004	0.40
O	0.030	0.019	---
C	0.004	0.002	---
B	---	0.005	---

[a]The standard deviation in the cadmium composition is 0.003 wt%.

[b]Impurity elements could be in error by a factor of 3.

[1]L. L. CARTER, C. R. RICHEY, and C. E. HUGHEY, "GAMTEC-II: A Code for Generating Consistent Multigroup Constants Utilized in Diffusion and Transport Theory Calculations," BNWL-35, Battelle-Pacific Northwest Laboratories (1965).

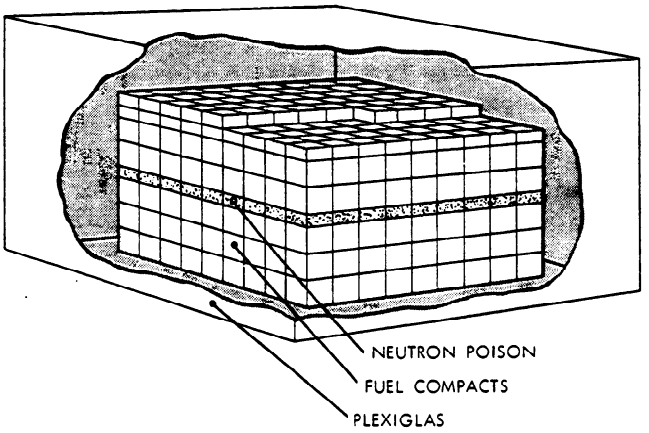

Fig. 2. Physical model of the PuO_2-UO_2-polystyrene assemblies—single neutron poison plate.

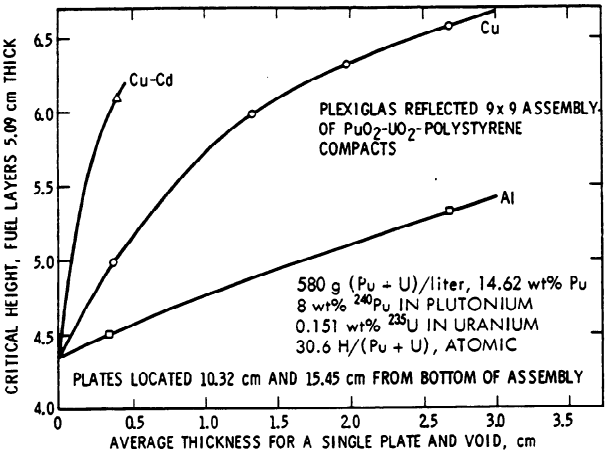

Fig. 5. Effect of aluminum, copper, and copper-cadmium plates on critical height.

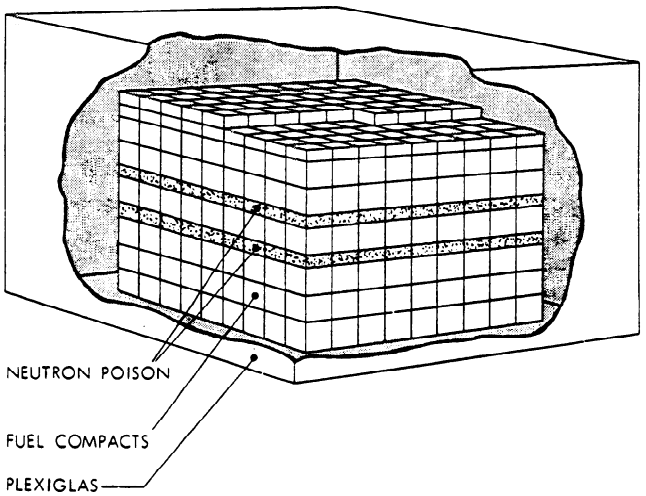

Fig. 3. Physical model of PuO_2-UO_2-polystyrene assemblies—two neutron poison plates.

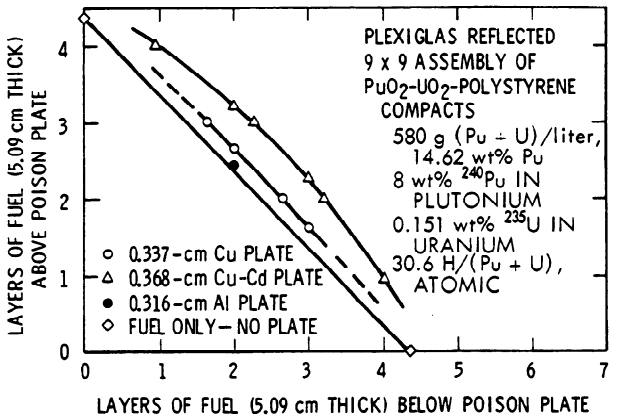

Fig. 6. Effect of plate position on critical height.

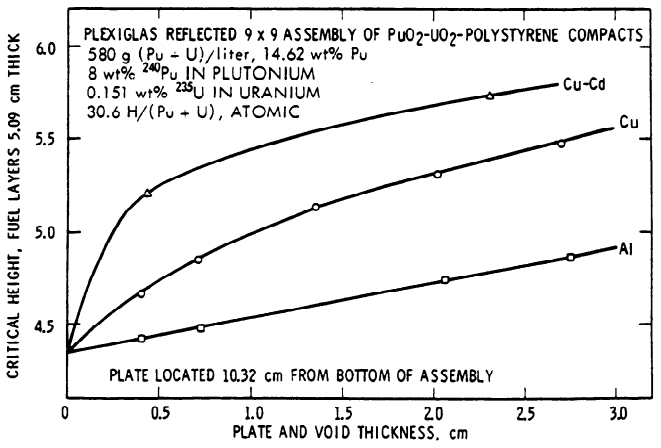

Fig. 4. Effect of aluminum, copper, and copper-cadmium plates on critical height.

assemblies. However, the measurements were limited to a single region of plates located 15.35 cm from the bottom of the fuel. The results of these experiments are shown in Fig. 7.

Since the plates could not be located at exactly the same position in all the assemblies, the neutron importance in the vicinity of the plates is not the same in all of the assemblies. Consequently, the data as shown in Figs. 4 through 7 are intended to show only approximately the relative effectiveness of the copper and copper-cadmium plates as neutron absorbers in the two different fuels. From the data shown in these figures, however, the void and absorption effects that the copper and copper-cadmium plates have on the reactivity of each system, can be distinguished between and the relative effectiveness of each as an absorber can be obtained.

The changes in critical heights due to neutron absorption in different thicknesses of copper and

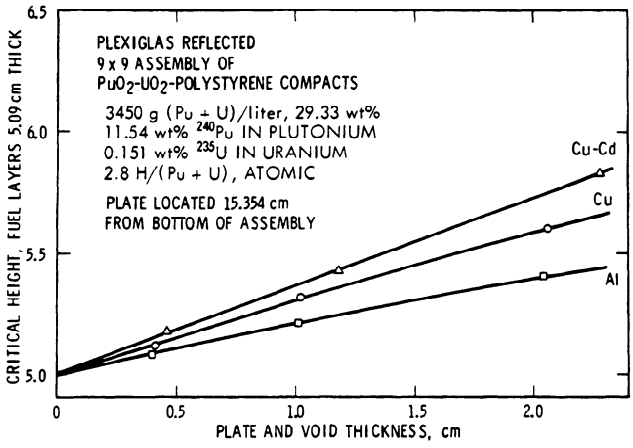

Fig. 7. Effect of aluminum, copper, and copper-cadmium plates on critical height.

copper-cadmium plates in the 30.6 and the 2.8 H:(Pu + U) fuels are shown in Fig. 8 along with the changes in critical heights due to the void these plates cause by their presence in each fuel. (The data, shown in Fig. 8, were obtained from Figs. 4 and 7.) As can be seen in Fig. 8, the void (as represented by the aluminum plus void data) introduced into the 2.8 H:(Pu + U) fueled assemblies by the copper and copper-cadmium plates is worth more than neutron absorption in either of these plates over the thickness range covered in these experiments. In the more thermalized 30.6 H:(Pu + U) fuel, the void effects are worth less than the neutron absorption in these plates.

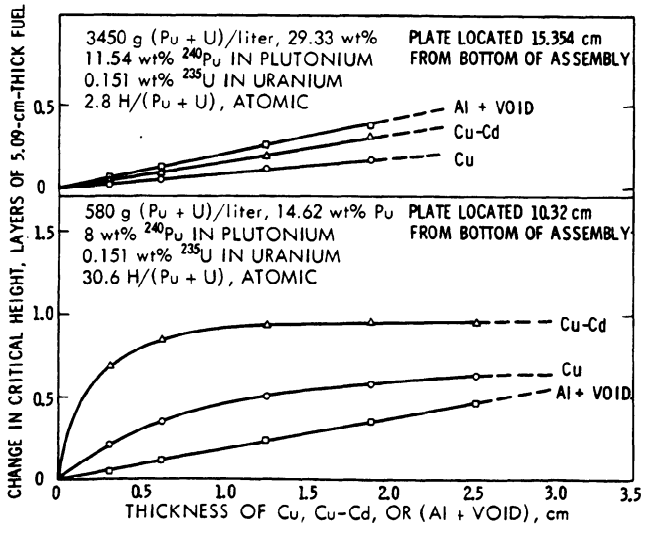

Fig. 8. Changes in critical height due to reduction of core density and to increased neutron absorption—Plexiglas reflected 9×9 assemblies of PuO_2-UO_2-polystyrene compacts.

However, even in the 30.6 H:(Pu + U) fuel the continual increase in critical height, observed in the data shown in Fig. 4, with increased thicknesses of copper and copper-cadmium plates is due almost entirely to void effects above a given plate thickness. As can be seen in Fig. 8, little, if any, additional neutron absorption occurs in the copper plate at thicknesses greater than $\sim 2\frac{1}{2}$ cm or in the copper-cadmium plate at thicknesses greater than ~1 cm. At thicknesses greater than these, self-shielding has precluded any additional absorption and the change in reactivity is due almost entirely to the additional void being introduced into the assemblies.

The experimental data in Fig. 8 also show that significantly increased neutron absorption is obtained, even in the relatively fast neutron spectrum of the 2.8 H:(Pu + U) fuel, with 1 wt% Cd in the copper-cadmium plates. Of course, as shown in Fig. 8, the cadmium was found to be worth much more in the thermalized spectrum of the 30.6 H:(Pu + U) fuel.

DETAILED DESCRIPTION OF EXPERIMENTAL ASSEMBLIES

A detailed description is given in Table IV for each critical assembly fueled with the 30.6 H:(Pu + U) compacts. Each critical assembly of 2.8 H:(Pu + U) compacts is described in Table V. In both tables the layers of fuel above, below, and between (when applicable) the poison plates are given. The dimensions associated with each type of fuel layer are given in Table I along with the associated cladding thicknesses and stacking voids. The total number of fuel layers in terms of 5.09-cm-thick compacts is also given for each assembly in Tables IV and V, and can be used to obtain a more simplified geometry description of each assembly.

The approach-to-critical for each of the assemblies shown in Tables IV and V was made by incrementally loading fuel compacts to the top face of each assembly in a symmetrical manner with respect to the neutron flux. Since the neutron flux in these finite assemblies has a spatial dependency, the reactivity worth of a single fuel compact is dependent on its location in each assembly. However, since the top face of each assembly is rectangular and since the fuel compacts are of uniform composition, the neutron flux is symmetrical over this top face. By restricting the incremental loadings to fuel compacts ~1.27 cm in thickness and fully loading either half of the top face, a spatially independent loading, smaller than one full layer, can be obtained. Consequently, the fractional layers given in Tables IV

TABLE

Plexiglas Reflected 9 × 9 Assemblies of 30.6

Layers of Fuel[a] (3.4 cm)	Neutron Poison Plate					Layers of Fuel[c]	
	Type	Plate Mass (kg)	Plate Thickness (cm)	Plate + Void Thickness (cm)	Reduced Density[b] (%)	(5.09 cm)	(1.384 cm)
3	None	0	0	0	-	2	1.276
3	$\frac{1}{8}$ in. Cu	6.440 ± 0.013	0.337 ± 0.008	0.40 ± 0.06	83.8	2	2.415
3	$\frac{1}{4}$ in. Cu	11.985 ± 0.024	0.637 ± 0.003	0.71 ± 0.07	87.8	2	3.110
3	$\frac{1}{2}$ in. Cu	24.425 ± 0.049	1.290 ± 0.004	1.35 ± 0.06	94.1	3	0.463
3	$\frac{3}{4}$ in. Cu	36.410 ± 0.072	1.927 ± 0.005	2.02 ± 0.09	93.8	3	1.136
3	1 in. Cu	48.785 ± 0.096	2.580 ± 0.006	2.70 ± 0.10	94.0	3	1.746
3	$\frac{1}{8}$ in. Cu-Cd	6.905 ± 0.014	0.368 ± 0.005	0.43 ± 0.06	83.6	3	0.757
3	$\frac{3}{4}$ in. Cu-Cd	40.635 ± 0.081	2.160 ± 0.006	2.30 ± 0.10	91.9	3	2.698
3	$\frac{1}{8}$ in. Al	1.790 ± 0.025	0.316 ± 0.001	0.40 ± 0.08	77.1	2	1.548
3	$\frac{1}{4}$ in. Al	3.665 ± 0.012	0.645 ± 0.002	0.73 ± 0.08	86.5	2	1.739
3	$\frac{3}{4}$ in. Al	11.270 ± 0.049	1.983 ± 0.004	2.06 ± 0.07	94.2	2	2.713
3	1 in. Al	15.250 ± 0.034	2.676 ± 0.002	2.75 ± 0.07	95.5	2	3.158
g	$\frac{1}{8}$ in. Cu	6.440 ± 0.013	0.337 ± 0.008	0.40 ± 0.06	83.8	1	2.349
g	$\frac{1}{8}$ in. Cu-Cd	6.905 ± 0.014	0.368 ± 0.005	0.43 ± 0.06	83.6	2	0.952
h	$\frac{1}{8}$ in. Cu-Cd	6.905 ± 0.014	0.368 ± 0.005	0.43 ± 0.06	86.6	0	3.463
3	$\frac{1}{8}$ in. Cu	6.440 ± 0.013	0.337 ± 0.008	0.37 ± 0.03	90.6	1	0
3	$\frac{1}{2}$ in. Cu	24.425 ± 0.049	1.290 ± 0.004	1.33 ± 0.04	95.5	1	0
3	$\frac{3}{4}$ in. Cu	36.410 ± 0.073	1.927 ± 0.005	1.98 ± 0.05	95.7	1	0
3	1 in. Cu	48.470 ± 0.096	2.565 ± 0.006	2.68 ± 0.06	94.1	1	0
3	$\frac{1}{8}$ in. Cu-Cd	6.905 ± 0.014	0.368 ± 0.005	0.41 ± 0.04	87.6	1	0
3	$\frac{1}{8}$ in. Al	1.790 ± 0.025	0.316 ± 0.001	0.34 ± 0.02	90.7	1	0
3	1 in. Al	14.940 ± 0.056	2.628 ± 0.004	2.68 ± 0.05	96.0	1	0

[a]Layers of 3.4-cm-thick fuel compacts below bottom poison plate unless noted otherwise.
[b]Plate mass per plate and void volume relative to 8.913 g Cu/cm^3, 8.910 g Cu-Cd/cm^3, or 2.692 g Al/cm^3.
[c]Layers of 5.09- and 1.384-cm-thick fuel compacts above or between poison plates. Fractional layers should be treated as full layers having the indicated fractional thickness.
[d]Layers of 5.09- and 1.384-cm-thick fuel compacts above top poison plate.

and V should be treated as full layers of thinner fuel compacts having a thickness equal to the fractional layer times the full-sized compact.

The effect of the cladding and stacking voids was experimentally determined[2,3] for each of these fuels. The fuel regions in each 30.6 H:(Pu + U) assembly can be expressed as homogeneous regions of PuO_2-UO_2-polystyrene fuel only, by reducing the amount of fuel in each assembly 3.92%. For the 2.8 H:(Pu + U), corrections are not needed. The negative reactivity effects, caused by the stacking voids and the reduced fuel density because of the cladding being present, were compensated for by the positive worth of the additional hydrogen and carbon introduced into each assembly by the cladding material.

The total mass and thickness of copper, copper-cadmium, or aluminum present in each poison region are also given in Tables IV and V for each critical assembly. In some of these assemblies the poison region actually is made up of several thinner plates stacked on top of one another to achieve the plate thickness that is indicated. The combined poison plate thickness and additional void space, caused by the neutron poison material being present, are shown for each poison region.

COMPARISON BETWEEN CALCULATIONS AND EXPERIMENTS

Effective neutron multiplication factors were calculated for some of the experimental assem-

[2]S. R. BIERMAN, E. D. CLAYTON, and L. E. HANSEN, *Nucl. Sci. Eng.*, **50**, 115 (1973).
[3]S. R. BIERMAN and E. D. CLAYTON, *Trans. Am. Nucl. Soc.*, **15**, 307 (1972).

IV

H:(Pu + U) PuO_2-UO_2-Polystyrene Compacts

Type	Neutron Poison Plate				Layers of Fuel[d]		Total Layers of Fuel[e]	KENO-II k_{eff}[f]
	Plate Mass (kg)	Plate Thickness (cm)	Plate + Void Thickness (cm)	Reduced Density[b] (%)	(5.09 cm)	(1.384 cm)		
-	-	-	-	-	-	-	4.351 ± 0.004	1.018 ± 0.005
-	-	-	-	-	-	-	4.661 ± 0.005	
-	-	-	-	-	-	-	4.850 ± 0.004	
-	-	-	-	-	-	-	5.13 ± 0.01	
-	-	-	-	-	-	-	5.313 ± 0.005	0.998 ± 0.006
-	-	-	-	-	-	-	5.479 ± 0.001	
-	-	-	-	-	-	-	5.210 ± 0.003	
-	-	-	-	-	-	-	5.738 ± 0.006	
-	-	-	-	-	-	-	4.425 ± 0.003	1.013 ± 0.006
-	-	-	-	-	-	-	4.477 ± 0.007	
-	-	-	-	-	-	-	4.742 ± 0.004	1.020 ± 0.007
-	-	-	-	-	-	-	4.863 ± 0.003	
-	-	-	-	-	-	-	4.643 ± 0.005	
-	-	-	-	-	-	-	5.263 ± 0.003	
-	-	-	-	-	-	-	4.946 ± 0.002	
$\frac{1}{8}$ in. Cu	6.415 ± 0.013	0.337 ± 0.008	0.37 ± 0.03	90.2	1	3.603	4.984 ± 0.005	
$\frac{1}{4}$ in. Cu	24.360 ± 0.049	1.290 ± 0.004	1.33 ± 0.03	95.3	2	3.584	5.979 ± 0.005	
$\frac{3}{4}$ in. Cu	36.450 ± 0.072	1.927 ± 0.005	1.98 ± 0.05	95.8	3	1.129	6.311 ± 0.003	1.020 ± 0.005
1 in. Cu	48.450 ± 0.096	2.565 ± 0.006	2.68 ± 0.06	94.1	3	2.092	6.573 ± 0.003	
$\frac{1}{8}$ in. Cu-Cd	6.685 ± 0.013	0.354 ± 0.005	0.39 ± 0.03	89.2	3	0.331	6.094 ± 0.022	
$\frac{1}{8}$ in. Al	1.790 ± 0.025	0.317 ± 0.002	0.34 ± 0.02	90.7	1	1.812	4.497 ± 0.002	
1 in. Al	14.965 ± 0.031	2.629 ± 0.013	2.69 ± 0.05	95.8	2	1.151	5.317 ± 0.003	

[c]Total layers of full compacts expressed as equivalent 5.09-cm-thick compacts. Multiply by 0.9608 to correct for stacking voids and cladding.

[f]18-group GAMTEC-II averaged cross sections using FLANGE-ETOG processed ENDF/B-III data. Unless noted otherwise, 15 000 histories at 200 per batch.

[g]Three layers of 3.4 cm plus one layer of 5.09-cm-thick fuel compacts below poison plate.

[h]Three layers of 3.4 cm plus two layers of 5.09-cm-thick fuel compacts below poison plate.

blies as indicated in Tables IV and V. The calculations were made with the Monte Carlo code KENO (Ref. 4) using 18-group GAMTEC-II (Ref. 1) averaged cross sections that had been processed from the ENDF/B-III with FLANGE-II (Ref. 5) and ETOG-I (Ref. 6) codes. The geometries for each assembly were input to KENO as described in Tables IV and V and as shown in the applicable Figs. 2 or 3. Stacking voids and cladding materials, as specified in Table I, were included in the calculational models. The mass of the aluminum, copper, or copper-cadmium plates was homogenized, at the reduced densities indicated in Tables IV and V, over the plate-plus-void space of the respective poison region. The KENO calculations were performed using 200 neutrons per generation and running for at least 75 generations. Additional generations were run if, after 15 000 histories, k_{eff} had not attained a constant level as illustrated in Fig. 9 for one of the critical assemblies.

As has been reported previously[2,3] for these two fuels, the calculated k_{eff} values are about 2% high for the 30.6 H:(Pu + U) fuel and 1 to 2% low for the 2.8 H:(Pu + U) fuel. However, as can be seen by comparing the poisoned with the un-

[4]G. E. WHITESIDES, "KENO—A Multigroup Monte Carlo Criticality Program," CTC-5, Computing Technology Center (1969).

[5]H. C. HONECK and D. R. FINCH, "FLANGE-II (Version 71-1): A Code to Process Thermal Neutron Data from an ENDF/B Tape," DP-1278 (ENDF-152), Savannah River Laboratory (1971).

[6]D. E. KUSNER, R. A. DANNELS, and S. KELLMAN, "ETOG-I: A FORTRAN-IV Program to Process Data from the ENDF/B File to the MUFT, GAM, and ANISN Formats," WCAP-3845-1 (ENDF-114), Westinghouse Electric Corporation (1969).

TABLE V

Plexiglas Reflected 9 × 9 Assemblies of 2.8 H:(Pu + U) PuO_2-UO_2-Polystyrene Compacts

Layers of Fuel[a] (5.09 cm)	Neutron Poison Plate				Reduced Density[b] (%)	Layers of Fuel[c]		Total Layers of Fuel[d]	KENO-II k_{eff}[e]
	Type	Plate Mass (kg)	Plate Thickness (cm)	Plate + Void Thickness (cm)		(5.09 cm)	(1.339 cm)		
-	None	0	0	0	-	4	4.207	4.997 ± 0.013	0.989 ± 0.006
3	$\frac{1}{8}$ in. Cu	6.440 ± 0.013	0.337 ± 0.008	0.41 ± 0.07	82.2	2	0.502	5.119 ± 0.010	0.988 ± 0.006
3	$\frac{3}{8}$ in. Cu	18.425 ± 0.037	0.974 ± 0.008	1.02 ± 0.07	94.5	2	1.321	5.313 ± 0.004	
3	$\frac{3}{4}$ in. Cu	37.280 ± 0.075	1.964 ± 0.012	2.06 ± 0.08	95.0	2	2.536	5.601 ± 0.013	0.976 ± 0.006
3	$\frac{1}{8}$ in. Cu-Cd	6.905 ± 0.014	0.386 ± 0.005	0.46 ± 0.07	78.5	2	0.738	5.175 ± 0.010	
3	$\frac{3}{8}$ in. Cu-Cd	20.419 ± 0.040	1.085 ± 0.005	1.18 ± 0.09	90.5	2	1.827	5.433 ± 0.003	
3	$\frac{3}{4}$ in. Cu-Cd	40.635 ± 0.081	2.160 ± 0.006	2.28 ± 0.09	93.2	2	3.468	5.822 ± 0.007	0.976 ± 0.006
3	$\frac{1}{8}$ in. Al	1.790 ± 0.025	0.316 ± 0.001	0.39 ± 0.07	79.5	2	0.342	5.081 ± 0.012	
3	$\frac{3}{8}$ in. Al	5.455 ± 0.044	0.961 ± 0.002	1.01 ± 0.05	93.5	2	0.873	5.207 ± 0.016	
3	$\frac{3}{4}$ in. Al	11.185 ± 0.083	1.971 ± 0.005	2.04 ± 0.08	95.0	2	1.688	5.400 ± 0.004	

[a] Layers of 5.09-cm-thick fuel compacts below poison plate.
[b] Plate mass per plate and void volume relative to 8.913 g Cu/cm^3, 8.910 g Cu-Cd/cm^3, or 2.692 g Al/cm^3.
[c] Layers of 5.09- and 1.339-cm-thick fuel compacts above poison plate. Fractional layers should be treated as full layers having the indicated fractional thickness.
[d] Total layers of fuel compacts expressed as equivalent 5.09-cm-thick compacts.
[e] 18 Group GAMTEC-II averaged cross sections using FLANGE-ETOG processed ENDF/B-III data. Unless noted otherwise, 15 000 histories at 200 per batch.

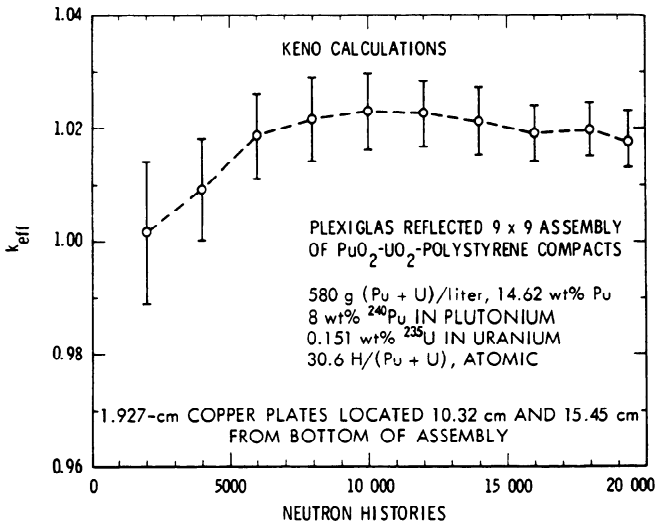

Fig. 9. Variation in k_{eff} average with neutron histories.

TABLE VI

Comparison Between k_{eff}'s Calculated Using Experimental Geometries and Simplified Geometries

Critical Assembly	KENO-II k_{eff}
30.6 H:(Pu + U) fuel as in experiment, including stacking voids and cladding material	1.018 ± 0.005
30.6 H:(Pu + U) fuel as uniform 5.09-cm-thick compacts with stacking voids and cladding material	1.020 ± 0.006
30.6 H:(Pu + U) fuel as homogenized fuel corrected for stacking voids and cladding material	1.016 ± 0.009
2.8 H:(Pu + U) fuel as in experiment, including stacking voids and cladding material	0.989 ± 0.006
2.8 H:(Pu + U) fuel as homogenized fuel corrected for stacking voids and cladding material	0.989 ± 0.005

poisoned k_{eff} values shown in Tables IV and V, the calculations reproduce the effects of the aluminum, copper, and copper-cadmium plates with a reasonable degree of accuracy.

As indicated previously, the geometry of these assemblies can be simplified by describing the compacts in terms of a uniform set of compacts 5.09 cm thick. A further simplification can be accurately attained by applying the experimentally determined corrections previously discussed for the stacking voids and cladding materials. A calculational comparison was made between these simplified assemblies and the actual experimental assembly and is shown in Table VI.

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