LA-3219-MS

LOS ALAMOS SCIENTIFIC LABORATORY
LOS ALAMOS of the NEW MEXICO
University of California

CRITICAL ASSEMBLIES OF FISSIONABLE MATERIALS

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

Printed in USA. Price $2.00. Available from the

Clearinghouse for Federal Scientific
and Technical Information,
National Bureau of Standards,
U. S. Department of Commerce,
Springfield, Virginia

LA-3219-MS
UC-46, CRITICALITY STUDIES
TID-4500 (38th Ed.)

LOS ALAMOS SCIENTIFIC LABORATORY
LOS ALAMOS of the NEW MEXICO
University of California

Report written: October 1959

Report distributed: April 7, 1965

CRITICAL ASSEMBLIES OF FISSIONABLE MATERIALS

by

Carroll B. Mills

ABSTRACT

A number of critical assemblies were studied for reactor safety and criticality evaluation reasons early in the nuclear powered rocket development period. These were all of the H_2O moderated U^{233}, U^{235}, and Pu^{239} critical experiments and the relatively few D_2O, Be, BeO, and C moderated, enriched U^{235} critical experiments available that provided simple parametrics and extremes in type. The atomic densities and dimensions directly useful for computational purposes are listed for fast to thermal flux spectrum assemblies.

This report is concerned with the tabulation of a variety of critical assemblies, using as fissionable materials the three isotopes U^{233}, U^{235}, and Pu^{239}. Other transuranium isotopes will fission, on neutron absorption, but no others presently available in substantial quantities can sustain a chain reaction alone for several reasons having to do with fission cross sections and neutron flux. For one, the average energy of the neutron flux in any multiplying system is below the fission threshold of such isotopes as U^{238} and Th^{232}. Enriched isotopes only are used for the major number of experiments to diminish the effect of resonance absorption of nonfissionable companion isotopes. Also, there are many more experiments using enriched U^{235} because it is most available and because of the greater interest during this early phase of atomic development in simpler systems most easily made to chain react.

Table 1 describes critical reactors in sufficient detail for a calculation. The atomic ratio of moderator to fissionable isotope (fuel) and the density in grams per cubic centimeter of the fissionable isotope are usually given, so that the average atomic densities of the major components are known. This, with the dimensions of the experiment, permits a calculation with small error since the impurities not listed have small effect on reactivity. The reflector is usually a pure material, so name, dimension, and density are sufficient.

Finite cylinder and rectangular parallelepiped (slab) geometries are transformed to infinite cylinder and slab in some instances by the use of the geometrical buckling B^2, including the reflector savings and the mean extrapolation distance δ in the dimension R-radius; L-length; and a, b, c-length; in the form

$$B^2 = \left(\frac{\pi}{R}\right)^2_{\text{sphere}} = \left[\left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{L}\right)^2\right]_{\text{cylinder}}$$

$$= \left[\left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2 + \left(\frac{\pi}{c}\right)^2\right]_{\text{slab}}$$

Container walls of water solutions are very thin aluminum or stainless steel but may affect solution criticality significantly. Solid materials are frequently assembled in a rectangular aluminum square element "honeycomb" lattice, with an aluminum density ($\rho \simeq 6.1\%$ of the full density of 2.7 gm/cc) such that the effect on criticality is negligible in comparison to geometrical effects. Also, neutron conservation by scattering is almost exactly cancelled by absorption by the aluminum matrix. This is one example of the many cancellations that have sometimes resulted in good results with poor analyses.

The larger number of experiments were made in connection with critical data for nuclear safety guidance. It is a curious fact that although it is available in quantity very few experiments have been made for a most important material, plutonium, except for impurity studies and some shape-factor (effect of cylinder height to diameter ratio) work.

There are many experiments for U^{235} solutions, both bare and reflected with water or paraffin, and a much smaller number for U^{233}. Experiments with the important reactor moderators D_2O, Be, BeO, and C are very few in number but are frequently reported in more detail so that flux weighted integrals (foil activation and fissioning density distribution) may be studied. The few fast reactors have been studied in great detail, but few dilute (e.g. low U^{235}/U^{238} atomic ratio) systems have been reported.

The more complex critical assemblies, with several regions or at high temperatures, are found in connection with the development of power producing reactors. The most complex systems, which require large variations in material density and temperature, and which are most interesting in connection with multidimensional calculations, are not now generally available for study. Only some early work on one of these sections is reported here.

Operationally the experimental development of a critical assembly is a separate and difficult discipline which will not be discussed here. It consists essentially in the accumulation of discrete increments of materials in arrays of interest, with a record kept of the multiplication of a constant neutron source N_0. The total multiplication to N of neutrons N_0 (e.g. from a Po-Be source) in successive generations follows the sequence

$$\frac{N}{N_0} = 1 + k + k^2 + \cdots + k^n + \cdots = \frac{1}{1 - k}$$

where n is the number of generations, k is the increase in population per generation, and the ratio N/N_0 is the multiplication of the neutron source N_0 as determined by counting techniques using boron (n,α) or fission (n,F) detectors. Since the measuring times are much longer than the delayed neutron lifetimes for most experimental studies, the neutron flux transients may be ignored. It should be mentioned that all measurements are made by remote control because of the effect of neutron moderation by the human body and because a subcritical system is not very different from a supercritical and hazardous one.

DETAILED CRITICAL ASSEMBLIES FOR ENRICHED FUEL

Critical experiments using high enrichment fuels are described in Tables 1 through 6. The relatively few numbers tabulated here represent an extreme simplification from sometimes difficult experimental configurations.

Reflector Moderated Reactors

1. U^{235} foil with a D_2O reflector*

A right circular cylindrical cavity 40 in. in height and diameter surrounded by an 80 in. diameter and height right circular cylindrical reflector was made critical with a thin layer of 6.415 kg U(93.5% U^{235}), 4.15 mils thick, on the inside surface of the cavity. There was a 3/16

*Communicated by G. I. Bell, W. Bernard, and C. C. Byers, LASL.

in. layer of aluminum separating cavity and reflector. H_2O impurity was 0.77% by weight. (Calculations of an equal area and equal volume sphere gave the same results—critical within approximately 1% in k_{eff}.)

2. U^{235} with Be reflector*

A right circular cylinder 31 in. in length and 15½ in. in diameter was reflected by Be of density 1.77 gm/cc and thickness: top, 18 in., bottom, 15 in., and sides, 14 in.. The cavity was fueled to criticality with 10.97 kg U^{235} on the inner surface; with 9.01 kg U^{235} as a 3-in.-thick cylindrical annulus leaving a 9½-in.-diameter axial void; with 7.64 kg U^{235} homogeneously distributed in the cavity; and with 10.04 kg U^{235} in the same homogeneous geometry but 16-in. core length. The latter three experiments supported the U^{235} in graphite with the atomic ratio C/U^{235} = 75.6. (k_{eff} for this set of experiments was computed to be 1.00 ± 0.02.)

LOW ENRICHMENT CRITICAL ASSEMBLIES

Critical experiments with small concentrations of U^{235} in U^{238} are described in Table 7. A few other low enrichment experiments exist, but they are more concerned with geometry effects on criticality and were made to establish reactor safety parameters. The largest number of these experiments was made by D. F. Cronin (Oak Ridge National Laboratory) using 4.89 wt % U^{235} enriched uranium.[1] These were reported in sufficient detail to be directly useful in neutron cross-section studies.

*Communicated by C. C. Byers and G. Jarvis, LASL.

TABLE 1

CRITICAL EXPERIMENTS

A - Criticality Data for U^{235} in H_2O

Atomic Ratio H/U^{233}	Density of U^{233} (gm/cc)	Geometry	Critical Dimensions (cm) Diameter	Height	Reflector[a]	Reduced Core Radius[b] (cm)	Reference
57.5	0.381	cylinder	15.1	27.9	Paraffin	6.77	2 p. 14
67.0	0.336	cylinder	15.1	29.0	Paraffin	6.82	2 p. 14
84.4	0.275	cylinder	15.1	30.7	Paraffin	6.88	2 p.14
120	0.198	cylinder	15.1	38.5	Paraffin	7.08	2 p. 14
151	0.160	cylinder	15.1	46.8	Paraffin	7.21	2 p. 14
154	0.165	cylinder	25.5	24.0	None	10.47	2 p. 14
193	0.127	cylinder	15.1	73.0	Paraffin	7.39	2 p. 14
213	0.117	cylinder	20.5	19.3	Paraffin	7.94	2 p. 14
247	0.101	cylinder	20.5	21.2	Paraffin	8.18	2 p. 14
356	0.070	cylinder	22.9	21.3	Paraffin	8.89	2 p. 14
379	0.067	cylinder	22.9	22.9	Paraffin	9.10	2 p. 14
381	0.067	sphere	31.9	--	None	--	2 p. 14
405	0.062	sphere	26.6	--	H_2O	--	2 p. 14
418	0.0613	sphere	26.4	--	H_2O	--	2 p. 14
426	0.060	sphere	26.6	--	H_2O	--	3 p. 8
582	0.044	cylinder	30.5	21.1	Paraffin	10.70	2 p. 14
630	0.040	cylinder	30.5	23.8	Paraffin	11.25	2 p. 14
663	0.0368	sphere	30.2	--	H_2O	--	3 p. 8
757	0.0330	cylinder	30.5	30.4	Paraffin	12.27	2 p. 14
1532	0.01686	sphere	69.2	--	None	--	4 p. 30
2106	0.01221	cylinder	154.7	13.99	None	62.5	5 p. 77

Note: Analysis showed the Composition to be 97,65% U^{233}, 1.63% U^{234}, 0.06% U^{235}, and 0.66% U^{236} (Ref. 6).

B - Criticality Data for U^{235} in H_2O

Atomic Ratio H/U^{235}	Density of U^{235} (gm/cc)	Geometry	Critical Dimensions (cm) Diameter	Height	Reflector	Reduced Core Radius (cm)	Reference
26.2	0.827	cylinder	20.32	21.5	H_2O	6.16	7 p. 69
27.1	0.829	cylinder	15.24	69.3	H_2O	7.50	8 p. 24
27.1	0.829	cylinder	25.4	36.9	None	11.28	8 p. 24
29.9	0.759	cylinder	20.32	20.7	H_2O	6.07	7 p. 69
35.8	0.649	sphere	23.04	--	H_2O	--	3 p. 6
44.3	0.577	cylinder	16.51	38.7	H_2O	7.69	8 p. 24
44.3	0.538	cylinder	22.25	219.0	None	11.20	8 p. 24
44.3	0.538	cylinder	25.4	35.1	None	11.46	8 p. 24
49.9	0.463	sphere	23.04	--	H_2O	--	3 p. 6
47.3	0.483	sphere	22.66	--	None	--	8 p. 24
52.9	0.459	cylinder	20.32	19.5	H_2O	7.91	7 p. 69
52.9	0.459	cylinder	25.4	34.0	None	11.4	7 p. 69
58.8	0.415	cylinder	20.32	20.5	H_2O	6.04	7 p. 69
73.4	0.337	cylinder	25.4	33.7	None	11.39	8 p. 24
76.1	0.325	sphere	23.0	--	H_2O	--	6 p. 42
99.5	0.254	cylinder	20.32	22.4	H_2O	6.26	7 p. 24
126.5	0.1997	sphere	23.6	--	H_2O	--	4 p. 30
169.0	0.151	cylinder	25.4	41.2	None	11.6	7 p. 69
192.0	0.134	cylinder	20.32	26.1	H_2O	6.75	7 p. 69
203.5	0.1252	sphere	32.0	--	None	--	3 p. 18

TABLE 1 (continued)

B - Criticality Data for U^{235} in H_2O

Atomic Ratio H/U^{235}	Density of U^{235} (gm/cc)	Geometry	Critical Dimensions (cm)			Reduced Core Radius (cm)	Reference
			Diameter	Height	Reflector		
268.8	0.0951	sphere	26.4	--	H_2O	--	3 p. 8
290.0	0.0881	cylinder	20.32	40.1	H_2O	9.33	7 p. 69
328.7	0.0787	cylinder	38.1	21.7	None	12.5	7 p. 69
499.0	0.0522	cylinder	38.1	16.90	H_2O	10.7	7 p. 69
499.0	0.0522	cylinder	38.1	27.4	None	14.1	7 p. 69
755	0.0343	cylinder	38.1	43.6	None	16.5	7 p. 69
755	0.0343	cylinder	38.1	27.10	H_2O	13.6	7 p. 69
1000	0.0260	cylinder	38.1	44.30	H_2O	16.1	7 p. 69
1000	0.0260	cylinder	50.8	38.3	H_2O	19.1	5 p. 77
1112	0.0234	sphere	55.8	--	None	--	4 p. 30
1270	0.0204	sphere	55.8	--	H_2O	--	6 p. 42
1387	0.0188	sphere	69.2	--	None	--	4 p. 30
1981	0.01307	cylinder	154.7	203.3	None	66.5	5 p. 77

Note: Analysis showed the composition to be 1.04% U^{234}, 93.18% U^{235}, and 5.51% U^{236} (Ref. 6). This adds up to 99.73%.

C - Criticality Data for Pu^{239} in H_2O

Atomic Ratio H/Pu^{239c}	Density of Pu^{239} (gm/cc)	Geometry	Critical Dimensions (cm)			Reduced Core Radius (cm)	Reference
			Diameter	Height	Reflector		
397	62.86	cylinder	15.24	37.06	--	13.36	9
655	38.63	cylinder	15.24	78.04	--	14.74	9
397	62.86	cylinder	15.24	25.77	H_2O	10.52	9
655	38.63	cylinder	15.24	32.64	H_2O	11.83	9
892	28.55	cylinder	15.24	45.30	H_2O	13.19	9

a. Reflector effectively infinite; paraffin density 0.859 gm/cc at 27°C and hydrogen content 14.39 wt. %; cylinder walls typically 0.16 cm Al, spheres 0.13 cm Al (all for Ref. 2 experiments).

b. Reduced radius is the critical radius for an equivalent one-dimensional geometry; from equal geometrical buckling (extrapolation distance dependent on flux spectrum).

c. Pu nitrate dissolved in nitric acid (1.7 N); tank walls 0.159 cm thick; reflector 6 in. H_2O; no end reflectors.

TABLE 2

CRITICAL EXPERIMENTS FOR INTERMEDIATE SPECTRUM SYSTEMS (93.4% U^{235})

A - One Region Geometry

Moderator	Atomic Ratio (moderator) (U^{235})	Atomic density U^{235} (atom/cc x 10^{19})	Fuel Foil Thickness (in. x 10^3; mils)	Dimensions (cm)			Equivalent Sphere Radius (cm)	Reference
				Length	Width	Height		
D_2O	230	28.0	Solution	Sphere, 1/8" Stainless steel			36.15	10
	419	15.62	Solution				36.97	10
	856	7.71	Solution				38.94	10
	2081	3.18	Solution				43.31	10
Be	364	30.8	10	53.34	53.34	59.18	30.9	11
	1360	8.99	8				32.24	12
	1455	7.25	10	60.96	61.21	72.14	35.4	11
BeO	247	27.91	8	60.96	60.96	51.31	33.34	13
	493	13.96	4	60.96	60.96	55.88	34.45	13
	986	6.97	2	60.96	60.96	63.50	35.97	13
	1920	3.58	1	76.20	76.20	53.59	38.56	13
	3826	1.798	1	91.44	91.44	57.56	43.72	13
	7660	0.899	1	91.44	91.44	91.95	53.06	13
C	301	27.34	None	(Note: 6 ppm boron for these carbon moderated reactors)			63.48	14
	603	13.68	None				64.56	14
	1206	6.84	None				66.62	14
	2355	3.50	None				69.36	14
	9550	0.864	None				83.72	14

TABLE 2 (continued)

B - Two Region Geometries

Moderator		Atomic Ratio	Atomic Densities (atom/cc × 10^{24})			Dimensions (cm)				
						Core		Reflector		
Core	Reflector	(Moderator/U^{235})	U^{235}	Core Moderator	Reflector	Radius	Length	Radius	Length	Reference
D_2O^a	D_2O	34.2	0.00174	0.0297	0.0335	17.14	--	44.45	--	10
D_2O^a	D_2O	135.3	0.000495	0.0335	0.0335	20.96	--	44.45	--	10
D_2O^a	D_2O	431	0.0001544	0.0335	0.0335	23.37	--	44.45	--	10
C^b	Be	116	0.000614	0.07126	0.1109	31.30	77.7	43.7	77.7	15
C^b	Be	369	0.000193	0.07126	0.1113	40.56	78.7	53.6	78.7	15
C^b	Be	962	0.000077	0.07407	0.1112	48.83	76.2	60.8	76.2	15
C^c	C	1206	0.0000684	0.0825	0.0825	51.45	104.9	68.59	104.9	14
C^c	Be	2355	0.0000350	0.0825	0.1229	52.95	87.63	69.69	87.63	14
C^d	Be	411	0.000183	0.0752	0.1108	40.56	81.28	70.46	81.28	15
C	C	7114	0.00001057	0.0752	0.0777	a cube: core 121.9 cm; cube				16
C	C	4377	0.00001535	0.0672	0.0777	core 114.3 × 114.3 × 121.9; reflector 30.48 cm for both				16
BeO^e	BeO	1702	0.00003372	0.05742	0.06106	39.35	60.32	90.49	90.49	17
BeO^e	BeO	1300	0.00004418	0.05742	0.06106	32.46	60.32	90.49	90.49	17

a. SS-347 shell 0.047 in., around core; 1% H_2O in D_2O molecular density; U^{235} in solution.

b. Al lattice support ρ = 0.165 gm/cc; ρ(C) = 1.42; ρ(Be) = 1.66; axial ends have C + Be thickness 2.54 + 10.1, 11, 47, and 9.76 cm each on one end and 1.0 + 20.2, 0 + 8.12, and 2.54 + 9.76 on the other, respectively; 5 mil Dy foils except for C/U 962 which used 2 mil Dy foils.

c. Reduced from an approximate cube reflected on sides and bare on ends; 1 mil Dy foils.

d. ρ(C) = 1.50 gm/cc; ρ(Be) = 1.66 gm/cc; bare ends; Al lattice support ρ = 0.165 gm/cc; 5 mil Dy foils.

e. Volume fraction stainless steel in core 0.01546; inconel in reflector 0.023; core made of hexagonal BeO blocks, 3-3/4 in. across flats with fuel tubes 1-1/4 in. O.D., 0.060 in. walls filled with NaF, U_2O_3 mixture. Impurity in BeO corresponds to 7.5 ppm boron by weight. Critical radius corresponds to central BeO block area with fuel tubes. $B^2(BeO/U^{235} = 1702) = 0.002765$; $B^2(BeO/U^{235} = 1300) = 0.003132$.

TABLE 3

CRITICAL EXPERIMENTS FOR FAST SPECTRUM SYSTEMS

A - Spherical Systems

	Atomic densities, Region 1 (atom/cc x 10^{24})					Core	Atomic densities, Region 2 (atoms/cc x 10^{24})					Reflector	
Name	U^{233}	U^{234}	U^{235}	U^{238}	Pu^{239}	Radius	U^{233}	U^{234}	U^{235}	U^{238}	Pu^{239}	Thickness (cm)	Reference
Godiva	--	0.00045	0.04511	0.00245	--	8.71	--	--	--	--	--	--	18
16-1/4% Jemina	--	0.00007	0.00777	0.03971	--	7.62	--	--	0.00034	0.04721	--	7.62	18
37-1/2% Jemina	--	0.00018	0.01814	0.02934	--	14.57							
Oy refl. U^{233} [a]	0.04716	--	--	0.00048	--	3.147	--	0.00045	0.04517	0.00251	--	4.79	18
0.695 in. Tu refl. Oy	--	0.00045	0.04511	0.00245	--	7.725	--	--	0.000346	0.04769	--	1.765	18
1.76 in. Tu refl. Oy	--	0.00045	0.04511	0.00245	--	6.962	--	--	0.000346	0.04769	--	4.47	18
3.525 in. Tu refl. Oy	--	0.00045	0.04511	0.00245	--	6.391	--	--	0.000346	0.04769	--	8.95	18
3.925 in. Tu refl. Oy	--	0.00045	0.04511	0.00245	--	6.312	--	--	0.000346	0.04769	--	9.97	18
Topsy	--	0.00045	0.04511	0.00245	--	6.045	--	--	0.000346	0.04769	--	22.86	18

B. Cylindrical Systems

α-Phase Pu [b]	--	--	--	--	0.04836	4.3	(length 11.65 cm)	19

a. W - 0.00033, void $0 < r < 0.533$ cm.

b. α-Phase Pu density 19.6 gm/cc; assumed 96.0% Pu^{239}.

TABLE 4

CRITICAL EXPERIMENTS FOR MIXED FAST SPECTRUM SYSTEMS

A - Atomic Densities of Some Simple Spherical Systems (Reference 18)

Core	Reflector (density in gm/cc)	Atomic Density Regions 1 and 2 (Atoms/cc × 10^{-24}) U^{235}	U^{238}	Moderator	Core Radius (cm)	Reflector Thickness (cm)
U^{235}	C (ρ = 1.632)	0.0450	0.0031	0.0838	7.756	2.54
U^{235}	C (ρ = 1.632)	0.0450	0.0031	0.0838	8.111	1.27
U^{235}	Polythene	0.0450	0.0031	0.0790(H)		
				0.0395(C)	7.477	2.54
U^{235}	Polythene	0.0450	0.0031	same	8.016	1.27

TABLE 4 (continued)

B - Critical Masses of Spherical Oralloy with Various Reflector (kg Oy)(Reference 16)

Reflector thickness (in.)	1	2	4	infinite
Be (ρ = 1.84)	31.2	22.3	15.1	--
BeO (ρ = 2.69)	--	22.8	16.6	~ 9.5
WC (ρ = 14.7)	--	22.8	17.7	~17.1
U (ρ = 19.0)	33.0	25.2	19.7	17.2
W Alloy (92% W, ρ = 17.4)	33.4	25.8	20.8	--
Paraffin	--	--	--	23.3
H_2O	--	~ 25.7	24.5	24.4
D_2O	--	~ 29.0	22.5	14.6
Cu (ρ = 8.88)	34.77	27.2	22.2	--
Ni (ρ = 8.35)	--	28.7	~ 23.5	~ 21
Al_2O_3 (ρ = 2.76)	37.6	--	--	--
C (CS-312, ρ = 1.69)	38.0	31.5	25.9	~ 17.9
Fe (ρ = 7.87)	38.5	31.3	27.1	24.8
Zn (ρ = 7.04)	--	31.9	26.7	--
Th (ρ = 11.48)	--	35.6	--	--
Al (2S, ρ = 2.70)	42.0	~ 38.0	~ 34.0	< 32.1
Ti (ρ = 4.50)	42.5	--	--	--
Mg (ρ = 1.77)	43.9	--	--	--

Note: Density of Oralloy = 18.8 gm/cc; 93.5% U^{235} for this set.

TABLE 4 (continued)

C - Critical Dimensions of Simple Spherical Pu Systems (Reference 20)

Pu Critical Mass (kg)	Reflector (density gm/cc)	Reflector Thickness (cm)
10.79	Uranium (ρ = 18.8)	1.93
10.79	Be (ρ = 1.86)	1.77
10.79	C (ρ = 1.632)	3.83
10.79	Ti (ρ = 4.46)	8
10.79	Li (ρ = 0.5)	∞
7.366	Uranium (ρ = 18.8)	6.74
7.366	Be (ρ = 1.86)	5.25

Note: ρ(δ phase Pu) = 15.8 gm/cc.

D - Critical Dimensions of Simple Cylindrical Pu Systems (Reference 19)

Pu Diameter (cm)	Pu Critical Mass (kg)	Reflector	Reflector Thickness (cm)
4.1	6.2	CH_2	10
4.1	6.9	Fe	10

Note: ρ(α phase Pu) = 19.6 gm/cc; CH_2 Polythene.

TABLE 5

TEMPERATURE DEPENDENT CRITICAL ASSEMBLIES

A - BeO Moderated Reactors

Temperature (°F)	Critical Mass (kg)	Atomic Ratio Moderator $\times (U^{235})^{-1}$	Atomic Densities (atoms/cc $\times 10^{24}$) U^{235} (4 mil foils)	Moderator	Fe	Reactor Dimensions (cm) Length	Width	Height	Equivalent Sphere Radius (cm)	Reference
90[a]	15.20	373	0.0001787	0.0677	0.00122	86.52	60.84	60.23	38.75	21
950[a]	16.18	373	0.0001776	0.0673	0.00121	91.60	60.96	60.35	39.18	21
90[b]	--	565	0.0001155	0.0653	0.0081	85.52	66.55	63.75	40.8	21
950[b]	--	565	0.0001148	0.0649	0.0080	91.92	66.62	64.01	41.5	21

B - C Moderated Reactors

Temperature (°F)	Critical Mass (kg)	Atomic Ratio Moderator $\times (U^{235})^{-1}$	Atomic Densities (atoms/cc $\times 10^{24}$) U^{235} (4 mil foils)	Moderator	Fe	Reactor Dimensions (cm) Length	Width	Height	Equivalent Sphere Radius (cm)	Reference
68[c]	20.40		0.0000234	0.0735	0.000136	See b below			82.72	21
355[c]	22.60		0.0000259	0.0734	0.000206				82.82	21
755[c]	25.41		0.0000291	0.0732	0.000232				82.88	21
1180[c]	27.81		0.0000319	0.0730	0.000255				82.95	21

a. Experimental neutron temperature coefficients average 39¢ 100°F; stainless-steel/oralloy (93.2% U^{235}) weight ratio 210.6/245.2 gm/gm (SS-347); foils doubled, 2 mil Oy and 2 mil SS-347 on each side; oralloy foils 22.92 × 8.72 in.; dimensions reduced from inhomogeneous reactors by diffusion theory equivalent thickness means; iron absorption equal to SS-347 absorption; Hot Box Note, in Ref. 21, p. 3.

b. A repeat of the same experiments but with the BeO and U^{235} simply homogenized in the entire core volume rather than corrected for the large BeO slabs in the core which contain no U^{235}, as was done with the first set. These data are more nearly equivalent to the experiment in terms of mean thermal neutron flux. The cruciform shape is best represented for temperature coefficient studies by a symmetric slab geometry: center, 4.744, 26.84, 32.43 (outer boundary) cm, with the 5 to 26 cm distance containing N(BeO) = 0.0667, N(Fe) = 0.001031, $N(U^{235}) = 0.0001787 \times 10^{24}$ atoms per cc, and the two adjacent slabs containing only BeO at the same density. The temperature effect was compensated by a length variation in another dimension with the geometrical buckling $B^2(90°F) = 0.05392$ and $B^2(950°F) = 0.05205$.

c. Core 4 × 3 × 6.125 ft^3; 1 ft C reflector on 3 ft axis; ρ(C) = 1.46 gm/cc; 6 ppm boron assumed; 1.71 kg SS-347/1 kg Oy(93.2%) in 2 mil foils; Hot Box Note, in Ref. 21, p. 6.

TABLE 6

$Pu/Oy/Be$ CRITICALITY DATA[a]

Concentric Shells

kg Pu[b]	kg Oy	t_{Be}(cm)	
0	10.6	20.27	± 0.41
	15.4[c]	10.16	
	16.19	9.27	± 0.18
	21.7	5.44	± 0.07
	22.8[c]	5.08	
	27.911	3.264	± 0.033
	31.9[c]	2.54	
	32.574	2.22	± 0.066
	52.4[c]	0	
2.472	0	32	± 4
	2.14	20	± 1
	2.857	16.20	± 0.05
	5.586	8.67	± 0.09
	8.340	5.60	± 0.04
	13.842	2.74	± 0.03
	19.355	1.36	± 0.02
3.217	0	21.0	± 1.0
	0.715	17.26	± 0.1
	1.426	13.17	± 0.07
	2.143	10.78	± 0.02
	4.872	6.10	± 0.05
	7.63	3.68	± 0.04
	13.13	1.77	± 0.01
	18.64	0.67	± 0.01
3.933	0	13.0	± 0.1
	0.712	10.20	± 0.01
	1.428	8.37	± 0.07
	4.157	4.62	± 0.02
	6.912	2.90	± 0.02
	12.414	1.23	± 0.01
4.664	0	8.17	± 0.03
	3.445	3.57	± 0.04
	6.20	2.09	± 0.02
	11.702	0.657	± 0.006
5.426	0	5.22	± 0.02
	2.729	2.66	± 0.01
	5.484	1.47	± 0.01

a. Tabulated by J. E. Carothers, Lawrence Radiation Laboratory, Livermore, and R. Canada and G. E. Hansen of Los Alamos Scientific Laboratory.

b. $\rho(Pu) = 19.25$, $\rho(Oy, 93.17\%) = 18.6$, $\rho(Be) = 1.84$.

c. LASL data.

TABLE 7

CRITICAL EXPERIMENTS

Uranium enrichment (weight %)	H/U^{235} atomic ratio	Density of U^{235} (gm/cc)	Hydrogen atomic density ($\times 10^{22}$ atoms/cc)	Bare sphere critical volume (liters)	Core radius (cm)	Water reflector savings (cm)	Reference
1.42[a]	417.5	0.03553	3.80	647	53.64	3.8	22
2.0[a]	195.3	0.06299	3.15	380	44.93	5.5[b]	23
2.0[a]	293.7	0.05291	3.98	237	38.39	4.8[b]	23
2.0[a]	403.9	0.04448	4.60	203	36.46	4.2[b]	23
2.0[a]	500.5	0.03940	5.05	202	36.40	4.2[b]	23
3.0[a]	133.5	0.09333	3.19	200	36.28	--	23
4.89[c]	524	0.04254	5.71	67.2	24.77[d]	3.2[e]	1
4.89[c]	643	0.03562	5.86	81.4	26.02	2.9[e]	1
4.89[c]	735	0.03179	5.98	95.4	27.49	2.7[e]	1
4.89[c]	1025	0.02354	6.18	150.6	33.84	1.8	1

a. UF_4 in paraffin.

b. Paraffin reflector.

c. UO_2F_2 in water reduced by equivalent buckling from a cylindrical experiment.

d. $\Delta k/\Delta$ radius = 0.021/cm.

e. Stainless steel container.

REFERENCES

1. Cronin, D. F., "Critical Mass Studies, Part X, Uranium of Intermediate Enrichment," ORNL-2968, p. 46, 1960.
2. Fox, J. K., Gilley, L. W., and Rohrer, E. R., "Critical Mass Studies, Part VIII, Aqueous Solutions of U-235," ORNL-2143, 1959.
3. Thomas, J. T., Fox, J. K., and Callihan, D., "A Direct Comparison of some Nuclear Properties of U-233 and U-235," ORNL-1992, 1955; Thomas, J. T., "Applied Nuclear Physics Division annual report for Period Ending Sept. 10, 1956," ORNL-2081.
4. Magnuson, D. W., "Determination of η of U^{233} by Comparison of Critical Experiments in a 69.2 cm-dia. Sphere," ORNL-2609, p. 29, 30, 1958.
5. Fox, J. K., Gilley, L. W., Givin, R., and Magnuson, D. W., "Neutron Physics Division Annual Progress Report," ORNL-2842, p. 77, 1959.
6. Fox, J. K., Gilley, L. W., Givin, R., and Thomas, J. T., "Critical Parameters of Uranium Solutions in Simple Geometries," ORNL-2609, p. 42, 1958.
7. Beck, C. K., Callihan, A. D., Morfitt, J. W., and Murray, R. L., "Critical Mass Studies, Part III," K-343, 1949.
8. Fox, J. K., Gilley, L. W., and Callihan, D., "Critical Mass Studies, Part IX, Aqueous U-235 Solutions," ORNL-2367, 1958.
9. Horton, C. C. and McCullen, J. D., "Plutonium-Water Critical Assemblies," Proc. Int. Conf. on Peaceful Uses of Atomic Energy, 5, 156, 1956.

10. Olcott, R. N., "Homogeneous Heavy Water Moderated Critical Assemblies," Part I, Experimental, N.S.E., 1, 327 (1956).

11. Zimmerman, E. L., "Two Beryllium-Moderated Critical Assemblies," ORNL-2201. 1958.

12. Kloverstrom, F. A., University of California at Livermore, communication.

13. Kloverstrom, F. A., Dick, R. M. R., and Reyenaga, A. J., "Critical Measurements on Near-Homogeneous BeO-Moderated, Oralloy-Fueled Systems," UCRL-5369, pt. 1, 1959. Lingenfelter, R. E., "Criticality Calculations of BeO-Moderated Oralloy Systems," UCRL-5740, 1959.

14. Reynolds, H. L. and Kloverstrom, F. A., "Critical Measurements and Calculations for Enriched Uranium Graphite-Moderated Systems," UCRL-5175, 1958.

15. Hansen, G. E., Hoogterp, J. C., Orndoff, J. D., and Paxton, H. C., "Beryllium-Reflected, Graphite-Moderated Critical Assemblies," LA-2141, 1957.

16. Paxton, H. C., "Critical Masses of Fissionable Metals as Basic Nuclear Safety Data," LA-1958, 1955.

17. Callihan, A. D. and Scott, D., "Preliminary Critical Assembly for the Aircraft Reactor Experiment," ORNL-1634, 1953.

18. Hansen, G. E., Los Alamos Scientific Laboratory, communication.

19. Kloverstrom, F. A. and Carothers, J., UCRL-4457, 1955 (classified).

20. Kloverstrom, F. A., "Spherical and Cylindrical Plutonium Critical Masses," UCRL-4957, September, 1957.

21. Finke, R. and Grammens, G., University of California at Livermore California, communications on Hot Box experimental series.

22. Walford, J. G., Dounreay Experimental Criticality Laboratory, communication, 1960.

23. Mihalczo, John, ORNL, communication, 1960. See also Mihalczo, John and Mills, C. B., "Criticality of Low Enrichment U^{235} in Hydrogen," Nuc. Sci. and Eng. 11, 95 (1961).

SUPPLEMENTARY REFERENCES

1. Kruesi, F. E., Erkman, J. O., and Lanning, D. D., "Critical Mass Studies of Plutonium Solutions," HW -24514, May 1952 (classified).

2. Fox, J. K. and Gilley, L. W., "Critical Parameters of a Proton Moderated and Proton Reflected Slab of U-235," CF 56-2-63, February 7, 1956.

3. Fox, J. K., Gilley, L. W., Callihan, A. D., "Critical Mass Studies, Part IX, Aqueous U-235 Solutions," ORNL-2367, p. 25, 1958.

4. Hart, F. F. "Safety Tests for Melting and Casting Oralloy," LA-1623, December, 1953.

5. Masterson, R. H., Neeley, V. I., and Powell, T. J., "Physics Research Quarterly Report, " USAEC Report HW-73116, Hanford Works, Richland, April 1962.