Critical Three-Dimensional Arrays of U(93.2)-Metal Cylinders

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Criticality studies were made of three-dimensional arrays of uranium-metal cylinders enriched to 93.2 wt% in ^{235}U. Four weight groups of units, ranging from 10.4 to 26.2 kg of uranium in five geometries, were employed to determine the critical surface separation between units as a function of the number in an array. The influence on criticality of hydrogenous neutron reflecting and moderating materials, unit shape, array shape, and of other controlled perturbations to some assemblies was examined. Monte Carlo calculations were performed of the experimental assemblies to confirm the neutron multiplication factors and to interpret the behavior of several subcritical assemblies. The Hansen-Roach neutron cross-section sets reproduce the results of the experiments, in a majority of cases, to an accuracy of ~1% in k_{eff}.

INTRODUCTION

A series of experiments performed during 1962-63 in support of nuclear criticality safety in the handling of accumulations of individually subcritical units of fissile materials was part of a continuing program in criticality safety at the Oak Ridge Critical Experiments Facility (CEF). Portions of these results have been previously reported.[1-3] In the experiments, the critical surface separation of cylindrical units of ^{235}U-enriched uranium metal, usually equal in three directions, was measured as a function of the number of units in an array and of the thickness of paraffin surrounding the array. Units of five sizes were employed, permitting an examination of the effect

of varying the mass of the units and their dimensions. A few definitive experiments indicate the effect of adding hydrogenous neutron moderating material between the units of arrays, of changing the geometric shape of the array, and of partially reflecting the array.

The experimental data have contributed to the development and evaluation of calculational techniques,[4] most effectively to the Monte Carlo codes where the understanding and handling of neutronics in hydrogenous reflectors have been advanced.[5-6]

MATERIALS AND ASSEMBLY DEVICE

Uranium-metal cylinders, enriched to 93.2 wt% in ^{235}U, were available, which could be combined to provide cylindrical units of several masses. The uranium contained 1.0 wt% ^{234}U, 0.2 wt% ^{236}U, and 5.6 wt% ^{238}U in addition to the ^{235}U isotope.

[1]L. W. GILLEY and J. T. THOMAS, *Trans. Am. Nucl. Soc.*, **4**, 54 (1961).

[2]J. T. THOMAS, *Trans. Am. Nucl. Soc.*, **6**, 169 (1963).

[3]J. T. THOMAS, "A Method for Estimating Critical Conditions of Large Arrays of Uranium," *Proc. Nuclear Criticality Safety*, SC-DC-67-1305, p. 189, Sandia Corporation (1966); also, J. T. THOMAS, "Critical Three-Dimensional Arrays of Neutron-Interacting Units. Part II—U(93.2) Metal," ORNL-TM-868, Oak Ridge National Laboratory (1964).

[4]G. E. WHITESIDES and N. F. CROSS, *Trans. Am. Nucl Soc.*, **10**, 239 (1967).

[5]G. E. WHITESIDES and J. T. THOMAS, *Trans. Am. Nucl. Soc.*, **12**, 889 (1969).

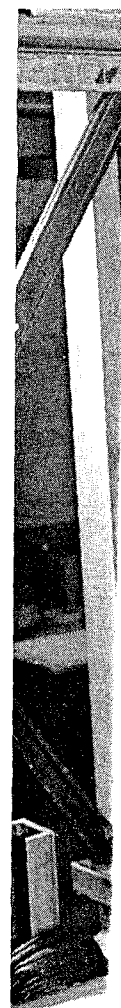[6]G. E. WHITESIDES and N. F. CROSS, "KENO—A Multigroup Monte Carlo Criticality Program," CTC-5, Oak Ridge Computing Technology Center (1969).

The uranium density was 18.76 g/cm³. The cylindrical pieces available are described in Table I. The cylinders were arranged into units varying in mass from 10.4 to 26.2 kg and in height-to-diameter ratio from 0.47 to 1.90. The units in a particular array were made as similar as possible by careful selection of the individual cylinders.

The units were supported in an assembly, with their axes vertical, on stainless-steel rods passing through two 0.508-cm-diam holes in each cylinder parallel to the axis and located 8.547 cm apart on a diameter. Vertical separation of the cylinders was established by spacers of appropriate length cut from Inconel tubing closely fitting

the support rods. The rods were mounted in sections of aluminum Unistrut attached to the two parts of the "split table" critical experiment equipment described by Rohrer et al.[7] The horizontal position of the rods was adjustable. A photograph of an unreflected assembly of forty-five 10.4-kg U(93.2) cylinders, shown in Fig. 1, illustrates the means of effecting the spacing and method of adjustment.

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[7]E. R. ROHRER et al., "New Critical Experiment Machines," *Neutron Phys Div Ann. Prog. Report for Period Ending Sept. 1, 1961*, ORNL-3193, p. 168, Oak Ridge National Laboratory (1961).
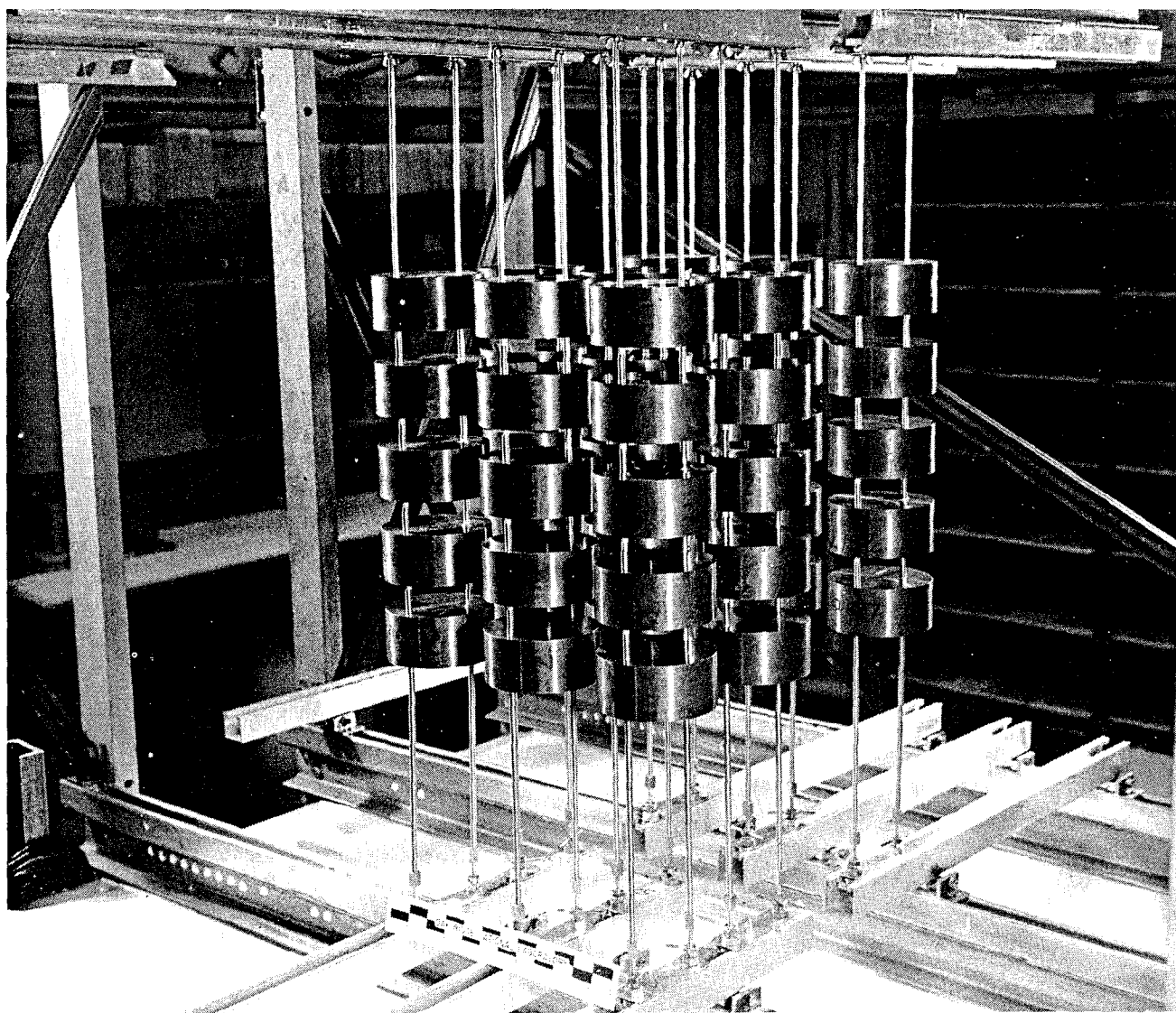

Fig. 1. An unreflected assembly of 10.4-kg U(93.2)-metal cylinders containing 45 units at equal surface separation in the three principal axes of the array. Reactivity control is effected by the horizontal movement of one third of the assembly, the plane of units in the background.

TABLE I

Description of U(93.2)-Metal Cylinders Available
for the Experiments

| Number of Cylinders | Average Mass kg U | Average Dimensions of Cylinders (cm) | |
		Radius	Height
54	10.439 ± 0.059	5.737 ± 0.016	5.382 ± 0.003
27	5.236 ± 0.017	5.746 ± 0.009	2.691 ± 0.003
54	5.247 ± 0.035	4.539 ± 0.015	4.321 ± 0.003

All arrays were constructed with the centers of the units at the corners of rectangular parallelepipeds, thus associating with each unit a cuboidal volume. In a few cases this pattern was cubic.

The reflector material was paraffin ($C_{25}H_{52}$) and could be varied in thickness from 1.3 to 15.2 cm. The density of the paraffin in the 1.3-cm-thick reflector was 0.88 g/cm^3; in all other reflectors, it was 0.93 g/cm^3. Various thicknesses of Plexiglas, a methacrylate plastic having a density of 1.18 g/cm^3 and containing 60.5 wt% C, 8.3 wt% H, and 31.2 wt% O, was the moderator material in one series of experiments.

EXPERIMENTAL RESULTS

Critical assemblies of the various U(93.2)-metal units are reported in Table II, where each experiment is indexed by a pair of numbers (i,j), i denoting the average unit and j the reflector condition. Reference to an experiment in the table will be made by the notation Expr. (i,j). Although the measured parameters in each experiment were the number of units and their surface separation at criticality, the center separation of the units is reported to facilitate the computation of the cuboidal cell volume. The tabulated description of a unit in an assembly includes a correction of ~0.2% reduction in the radius to compensate for the support rod holes. The location of the reflector in all reflected assemblies was at the outer boundary of the peripheral cuboidal cells. The data contain much of relevance concerning the influence of the unit mass and shape and of the array shape and reflector thickness on the critical spacing and number of units. For example, arrays of units with different masses but of the same shape are displayed by units i = 6, 7, 10, 11, and 12; the effect of unit shape change is recorded by units i = 1, 2, 6, and 7.

Essentially all of the arrays were constructed with the surface spacing of the units equal in three directions. Some operational convenience derived from the selection of this pattern, and more im-

portantly, it was possible to construct more critical arrays in a greater variety of shapes than would have been possible had only cubic arrays, i.e., equal center spacing of units, been built. Four arrays were constructed, however, with units at equal center spacing. These results are presented in Table III. The data may be compared to those of corresponding arrays in Table II for equal surface separation. If the average uranium density of an array at criticality is taken as the mass of the unit divided by the volume of the cell occupied by the unit, it is evident that the maximum achievable density is greater in the cubic pattern than in the cuboidal pattern whenever the height-to-diameter ratio (h/d) of a unit is ≥ 1. The opposite is true when the $h/d < 1$.

Six unreflected assemblies having an unequal number of units along the three axes of an array were also constructed. The average mass of the units in these experiments was 20.89 kg U(93.2). The data are reported in Table IV. These arrays are compared in Fig. 2 to arrays of units of similar mass having an equal number of units along the three axes, from Table II, Exprs. (11,1) and (12,1). The number of units in an array is shown as a function of the average uranium density in the array. The rearrangement of units from equal to unequal numbers in the three directions of an array maintaining the uranium density reduces the array reactivity.
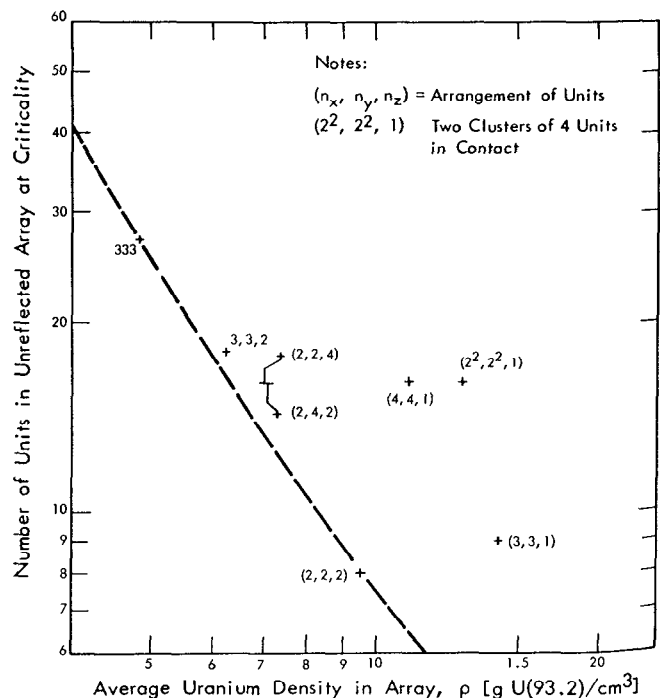

Fig. 2. Influence of array shape on the number of 20.9 kg U(93.2) and on the averaged uranium density in unreflected assemblies.

TABLE II

Experimentally Determined Spacing for U(93.2)-Metal Cylinders Assembled to Criticality in Cuboidal Arrangements for Various Reflector Conditions

Reflector Index, j					1		2		3		4		5	
Paraffin Reflector Thickness[a] (cm)					0.0		1.3[a]		3.8		7.6		15.2	
Expr. (i,j)		Unit Description			Center Spacing		Center Spacing		Center Spacing		Center Spacing		Center Spacing	
Cylinder Index, i	Array n_x, n_y, n_z	Radius (cm)	Height (cm)	Mass kg U(93.2)	Horizontal (cm)	Vertical (cm)	Horizontal (cm)	Vertical (cm)	Horizontal (cm)	Vertical (cm)	Horizontal (cm)	Vertical (cm)	Horizontal (cm)	Vertical (cm)
1	2 2 2	5.748	5.382	10.482 ± 0.005	11.50[b]	5.38[b]	11.73	5.61	13.48	7.36	14.91	8.80	15.19	9.08
2	2 2 4	5.748	5.382	10.481 ± 0.018	12.85	6.73	--	--	--	--	--	--	--	--
3	3 3 5	5.742	5.382	10.457 ± 0.044	14.93	8.82	--	--	--	--	--	--	--	--
4	4 4 4	5.740	5.382	10.451 ± 0.048	15.43	9.33	--	--	--	--	--	--	23.84	17.74
5	3 3 3	5.748	5.382	10.481 ± 0.026	13.50	7.39	14.49	8.37	17.37	11.25	19.75	13.64	20.19	14.07
6	2 2 2	4.542	8.641	10.507 ± 0.001	9.08[b]	8.64[b]	9.69	9.24	11.45	11.00	13.05	12.61	13.39	12.95
7	3 3 3	4.540	8.641	10.495 ± 0.025	11.52	11.08	12.51	12.07	15.66	15.22	18.10	17.66	18.51	18.08
8	2 2 2	5.742	8.077	15.694 ± 0.003	12.39	8.98	13.39	9.98	16.45	13.04	18.88	15.47	19.31	15.90
9	3 3 3	5.741	8.077	15.690 ± 0.020	15.69	12.28	17.16	13.75	21.67	18.27	25.18	21.77	25.68	22.27
10	2 2 2	5.726	10.765	20.803 ± 0.004	13.67	12.98	--	--	--	--	--	--	--	--
11	2 2 2	5.748	10.765	20.962 ± 0.004	13.74	13.01	15.17	14.44	19.70	18.97	23.01	22.27	23.48	22.75
12	3 3 3	5.736	10.765	20.877 ± 0.026	17.84	17.13	20.05	19.34	26.24	25.53	30.19	29.49	30.62	29.91
13	2 2 2	5.749	13.459	26.218 ± 0.005	15.04	17.00	16.92	18.88	23.03	24.99	27.20	29.16	27.88	29.84
14	3 3 3	5.738	13.459	26.113 ± 0.022	19.97	21.95	22.80	24.78	31.08	33.07	35.97	37.96	36.47	38.45
15	2 2 2	4.542	17.282	21.008 ± 0.001	10.55	18.75	--	--	--	--	--	--	19.41	27.61

NOTE: 1. Spacings have an error of ±0.01 cm in experiments with no reflector and ±0.03 for all others.
2. The isotopic content of U(93.2) metal is 1.0 wt% ^{234}U, 93.2 wt% ^{235}U, 0.2 wt% ^{236}U, and 5.6 wt% ^{238}U, and the density is 18.76 g/cm^3.
3. Spacing corresponds to equal surface separation of unit in the direction of the three principal axes.
4. The reflector was located at boundaries of peripheral cells of an array.

[a] Paraffin density = 0.88 g/cm^3; all other paraffin reflectors have a density of 0.93 g/cm^3.
[b] Assembly is subcritical.

TABLE III

Unreflected Critical Arrays of U(93.2)-Metal Cylinders
at Equal Center Spacing and with Equal Number
of Units Along the Direction of
the Three Array Axes

| Array | | | Expr. (i,1) | Unit Description | | | Unit Center Spacing (cm) |
| | | | | Radius (cm) | Height (cm) | Mass kg U(93.2) | |
n_x	n_y	n_z					
3	3	3	(5,1)	5.748	5.382	10.481 ± 0.026	11.51[a]
2	2	2	(8,1)	5.742	8.077	15.694 ± 0.003	11.48[a]
2	2	2	(11,1)	5.748	10.765	20.962 ± 0.004	13.50
3	3	3	(12,1)	5.736	10.765	20.877 ± 0.026	17.60
2	2	2	(13,1)	5.749	13.459	26.218 ± 0.005	15.78

NOTE: 1. Spacings have an error of ±0.01 cm.
2. The isotopic content of U(93.2) metal is 1.0 wt% ^{234}U, 93.2 wt% ^{235}U, 0.2 wt% ^{236}U, and 5.6 wt% ^{238}U, and the density is 18.76 g/cm^3.
3. Expr. (i,1) refers to corresponding units and reflector condition described in Table II.

[a]Array subcritical, k_{eff} ~0.98.

TABLE IV

Unreflected Critical Arrays of U(93.2)-Metal
Cylinders with Unequal Numbers of Units Along
the Direction of the Three Array Axes

Unit Description: radius = 5.738 cm; height = 10.765 cm mass = 20.890-kg U(93.2) metal				
Array			Unit Center Spacing	
			Horizontal (cm)	Vertical (cm)
n_x	n_y	n_z		
(2,2)	(2,2)	1	24.01[a]	--
4	4	1	12.99	--
3	3	1	12.13	--
2	2	4	15.38	14.67
2	4	2	15.37	14.66
3	3	2	16.12	15.41

NOTE: 1. Spacings have an error of ±0.01 cm.
2. The isotopic content of U(93.2) is 1.0 wt% ^{234}U, 93.2 wt% ^{235}U, 0.2 wt% ^{236}U, and 5.6 wt% ^{238}U, and the density is 18.76 g/cm^3.

[a]Two clusters of four cylinders each with lateral surfaces in contact. The center separation between two clusters of four units is given.

Table V records critical reflected and unreflected eight-unit assemblies of units comprised of coaxial cylinders of different diameters. Three of the arrays required a larger average uranium density than did corresponding arrays of similar masses reported in Table II. The remaining array of reflected 20.89-kg U(93.2) units resulted in a slight reduction in the average uranium density. The effect of a 15.3-cm-thick reflector on

three sides of an array, simulating the location of fissile units above a floor adjacent to two intersecting walls, was investigated in two assemblies of units having mass ~20.9 kg U(93.2) and an h/d ratio of 0.94. The results are given in Table VI and are plotted in Fig. 3 for comparison with arrays completely enclosed by paraffin, Exprs. (11,j) and (12,j) of Table II. An additional array of eight units of unit index 11 from Table II is reported in Fig. 3 for a 2.5-cm-thick reflector completely enclosing the array. The measured surface separation of units in this array was 5.710 cm. Reflection on three sides of an array by 15.2 cm of paraffin would not appear to be as effective as complete reflection by a 2.5-cm-thick reflector.

Substitutions in Arrays

The effect on array reactivity of replacing a unit in a critical array by one of different mass or dimensions was examined in two 27-unit assemblies. In one experiment, the central unit in assembly Expr. (12,1) was replaced by a unit from the assembly Expr. (13,1). The substitution of a 26.2-kg U(93.2) unit for one of 20.9 kg U(93.2) maintaining the center spacing resulted in a reactivity increase in excess of 1.5 dollars. Criticality of this perturbed array was achieved by increasing
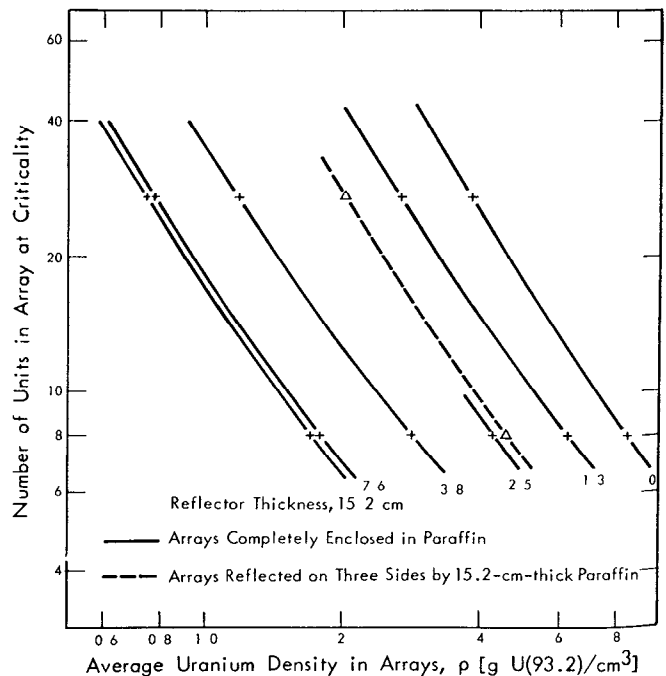

Fig. 3. Influence of uniform reflector thickness and partial, three-corner reflection on the average uranium density required for criticality of 20.9-kg U(93.2)-metal units.

TABLE V

Critical Arrays of Eight Irregular Units of U(93.2) Metal in
Unreflected and Paraffin-Reflected Geometries

Description of Coaxial Cylindrical Components of Unit			Average Unit Total Mass kg U(93.2)	Paraffin Reflector Thickness (cm)	Unit Center Spacing	
Radius (cm)	Height (cm)	Mass kg U(93.2)			Horizontal (cm)	Vertical (cm)
5.743	2.691	5.233 ± 0.009		0.0	11.71	9.93
4.538	4.321	5.245 ± 0.004	15.696 ± 0.002	15.2	18.38	16.61
5.734	2.691	5.217 ± 0.007				
4.544	4.321	5.258 ± 0.027		0.0	12.45	15.04
5.720	5.385	10.384 ± 0.011	20.893 ± 0.012	15.2	22.39	24.97
4.545	4.321	5.259 ± 0.010				

NOTE: 1. Spacings have error of ±0.01 cm for unreflected assemblies and ±0.03 for reflected assemblies.
2. Cuboidal cells defined by center spacing of units result in equal surface separation of units along the three principal axes of the array.
3. The reflector is located at the boundaries of peripheral cells of the array.
4. The isotopic content of U(93.2) metal is 1.0 wt% ^{234}U, 93.2 wt% ^{235}U, 0.2 wt% ^{236}U, and 5.6 wt% ^{238}U, and the density is 18.76 g/cm^3.

TABLE VI

Conditions for Criticality of Arrays Reflected on Three Sides by 15.2-cm-Thick Paraffin

Array			Unit Description			Paraffin Reflector	Unit Center Spacing	
n_x	n_y	n_z	Radius r (cm)	Height h (cm)	Mass kg U(93.2)		Horizontal (cm)	Vertical (cm)
2	2	2	5.748	10.765	20.962	a	16.89	16.16
3	3	3	5.736	10.765	20.877	b	22.01	21.31

NOTE: 1. Spacings have an error of ±0.03 cm.
2. The isotopic content of U(93.2) metal is 1.0 wt% ^{234}U, 93.2 wt% ^{235}U, 0.2 wt% ^{236}U, and 5.6 wt% ^{238}U, and the density is 18.76 g/cm^3.

[a]The dimensions of the base reflector were 76.2 × 76.2 × 15.2 cm, and the dimensions of the two sides were 76.2 × 45.7 × 15.2 cm.

[b]The dimensions of the base reflector were 106.7 × 106.7 × 15.2 cm, and the dimensions of the two sides were 106.7 × 76.2 × 15.2 cm.

the separation of one vertical plane of the units by 1.98 cm. In the second experiment, the central unit of assembly Expr. (9,1) was replaced by a unit having a 4.558-cm radius, a 12.962-cm height, and a mass of 15.807 kg U(93.2). This replacement resulted in a measured loss in reactivity of 0.05 dollars.

Additional experiments utilizing parts of unreflected critical eight-unit arrays were performed to illustrate the effect of multiple component replacement. In this series, one-half of each of two different critical arrays were brought together along a common array centerline until their cell boundaries coincided. Each of the three assemblies composed of composite arrays

was subcritical. In one experiment, one-half of Expr. (11,1) and one-half of Expr. (13,1) were utilized. The remaining two experiments used units of fissile material as aqueous solution. Each unit had 2.066 kg of U(92.6) as aqueous uranyl nitrate solution at 415 g U/liter at a specific gravity of 1.55, corresponding to an atomic ratio of H:^{235}U of 59. The isotopic content of the uranium was 0.01 wt% ^{234}U, 0.005 wt% ^{236}U, and 5.9 wt% ^{238}U. The nitrogen content resulted in an atomic ratio of N:U of 2.006. The solution was contained in 0.64-cm-thick Plexiglas cylinders having an outside radius and height of 10.16 and 19.05 cm, respectively. Criticality of a (2,2,2) unreflected array occurred at a horizontal center spacing of

21.75 ± 0.01 cm and a vertical center spacing of
20.48 ± 0.01 cm. The volume of solution per unit
was 5 liter ± 0.3 cm³, determined by weight. One
half of this array was assembled with one half of
Expr. (15,1). In the third experiment, half of the
solution array was assembled with one half of
Expr. (11,1). Criticality of the latter assembly
was achieved by reducing the center spacing of the
metal units by 0.56 cm.

The data of these composite arrays indirectly
substantiate results by Thomas and Scriven,[8]
which imply, for criticality, that assemblies of
different fissile materials in air must be separated
by less than the geometric mean of the separations
for the individual assemblies.

Interspersed Materials

The effect of hydrogenous material, placed
between adjacent units, on the criticality of arrays
was examined in assemblies of ~20.9-kg U(93.2)
units. Plexiglas boxes of several sizes and wall
thicknesses were mounted on the supporting rods
and enclosed the uranium units. Some of the
arrays were enclosed in a paraffin reflector. In
another array, the units were mounted in steel
cylinders, actually short sections of pipe, and, in
still another, both unit and pipe were located with-
in a Plexiglas box. A unit was always centered in
its container. Figure 4 is a photograph of an
eight-unit assembly illustrating the mode of
assembly with the steel and Plexiglas containers.
The critical dimensions of these assemblies and
their descriptions are reported in Table VII.

An investigation was made of the effect on the
array reactivity of the thickness of hydrogenous
material between adjacent units. An array of
eight units of cylinder index $i = 11$ of Table II was
subcritical when the center separation of the units
was 26.26 cm horizontally and 25.53 cm vertically.
Each unit was contained in a box having 1.27-cm-
thick Plexiglas walls, described in Table VII. The
array was surrounded by a 15.2-cm-thick paraffin
reflector. The thickness of only those container
walls which separated units was increased. The
maximum resulting reactivity addition to the array
was observed to occur when the total thickness of
Plexiglas was ~4.9 cm. The results of the experi-
ments are summarized in Fig. 5, where the reac-
tivity of the array is given as a function of the
total Plexiglas thickness separating the units. The
assembly having a total Plexiglas thickness of 7.6
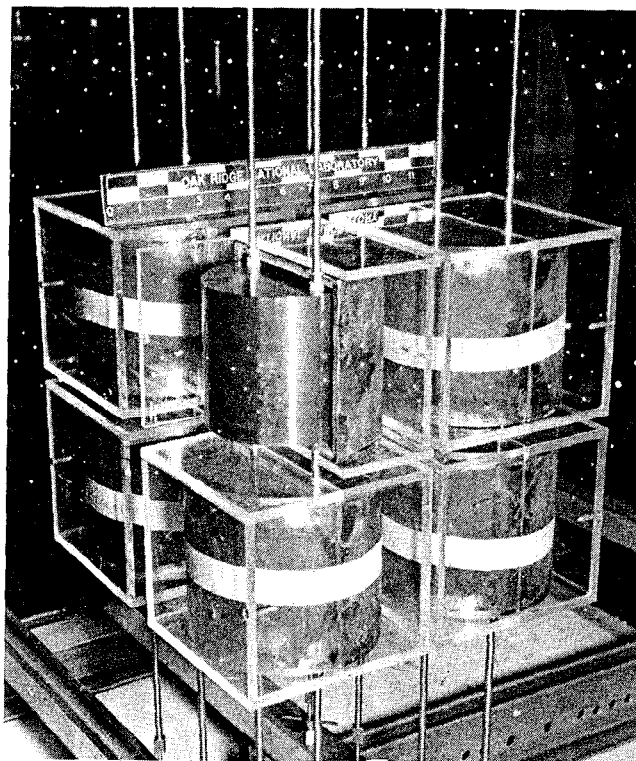cm between units was subcritical by an amount in
excess of one dollar.

Fig. 4. Combined moderator of iron and Plexiglas
in an array of eight 20.9-kg U(93.2)-metal units.

Uranium Cylinder

An experiment established the subcriticality of
an unreflected U(93.2) cylinder having an average
diameter of 11.48 cm and a length of 140 cm. The
total mass was 271.8 kg U(93.2). Negligible change
in the apparent neutron source multiplication was
observed upon addition of the final ~42 kg U(93.2).
This experiment confirms the subcriticality of an
unreflected cylinder of this diameter when ex-
tended indefinitely in length.

CALCULATIONS

The neutron multiplication factors of a number
of the experimental arrays were computed by the
KENO Monte Carlo code utilizing Hansen-Roach[9]
16-group neutron cross-section sets. The urani-
um was characterized by its two principal con-
stituents since the influence of the remaining
isotopes on k_{eff} are negligible. The cross-section
set U(235)-1R and the set U(238)-5R were selected

[8]A. F THOMAS and R. A. SCRIVEN, "Neutron
Interaction in Fissile Assemblies," *Technology, Engi-
neering and Safety,* Progress in Nuclear Engineering,
Series IV, Vol. 3, Pergamon Press, New York (1960).

[9]GORDON E. HANSEN and WILLIAM H. ROACH,
"Six and Sixteen Group Cross Sections for Fast and
Intermediate Critical Assemblies," LAMS-2543, Los
Alamos Scientific Laboratory (1961).

TABLE VII

Conditions for Criticality of Plexiglas-Moderated Arrays of ~20.9-kg U(93.2)-Metal Units

Moderator Description				Paraffin Reflector Thickness (cm)	Unit Center Spacing	
	Outside Dimensions (cm)				Horizontal (cm)	Vertical (cm)
Material	Base	Height	Thickness			
Array: n_x, n_y, n_z = 2,2,2 Unit Description: radius = 5.748 cm; height = 10.765 cm; mass = 20.962 ± 0.004 kg U(93.2)						
Plexiglas box	12.9 × 12.9	12.1	0.64	0.0 15.2	15.58 24.16	14.85 23.43
Plexiglas box	15.6 × 15.6	14.8	0.64	0.0 1.3 7.6 15.2	15.74 17.37 24.07 24.43	15.00 16.64 23.34 23.69
Plexiglas box	17.9 × 17.9	17.2	1.27	0.0 1.3 15.2	18.12 20.11 26.00	17.38 19.38 25.27
Plexiglas box	21.4 × 21.4	20.7	2.38	0.0 15.2	21.74 27.94	10.24 27.21
Steel cylinder	r = 7.05	13.2	0.66	0.0	14.74	14.00
Steel cylinder in Plexiglas box	r = 7.05 15.6 × 15.6	13.2 14.8	0.66 0.64	0.0	16.67	15.93
Array: n_x, n_y, n_z = 3,3,3 Unit Description: radius = 5.736 cm; height = 10.765 cm; mass = 20.877 ± 0.026 kg U(93.2)						
Plexiglas	21.4 × 21.4	20.7	2.38	0.0	27.79	27.05

NOTE: 1. Spacings have an error of ±0.01 cm for unreflected assemblies and ±0.03 for reflected assemblies.
2. Units are centered in cuboidal cells defined by center spacing and result in equal surface separation of units along the three principal axes of the array.
3. The reflector is located at the boundaries of peripheral cells of the array.
4. The isotopic content of U(93.2) metal is 1.0 wt% ^{234}U, 93.2 wt% ^{235}U, 0.2 wt% ^{236}U, and 5.6 wt% ^{238}U, and the density is 18.76 g/cm^3.
5. Units are centered in moderating materials fabricated as cuboidal boxes.
6. Steel is nominal 5-in. Schedule-40 iron pipe with end plates. Units are centered in pipe. In addition to iron, the significant constituents in wt% are 0.8 Mn, 0.2 Si, 0.1 Mo, and 0.2 Ni, as determined by emission spectroscopy.

and the fission-spectrum-weighted neutron cross sections were used for hydrogen in the reflector. The calculated k_{eff}'s are displayed in Table VIII and correspond to the arrays given in Table II with the exception of those having a 7.6-cm-thick paraffin reflector. The entries of Table VIII were determined by the usual neutron-batch method. Presented at the bottom of each column is the average k_{eff} with the deviation of the mean for the entries under a specified reflector thickness. Comparison of those averages as the reflector thickness is increased shows a monotonically increasing k_{eff}. Since the experimental data of

Table II are as measured, i.e., uncorrected for the effects of the assembly device on the array reactivity, the computed k_{eff} increases with the increasing shielding of the units from the assembly device.

Calculations of the two unreflected assemblies of 27 units in which the central unit was replaced were performed with 10^5 neutron histories to compare the k_{eff}'s obtained. In one, the unperturbed array of 20.9-kg U(93.2) units, Expr. (12,1), resulted in a k_{eff} of 0.9903 ± 0.0024. When the central unit was replaced by a 26.2-kg U(93.2) unit, k_{eff} was 1.0034 ± 0.0027. The reactivity

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TABLE VIII

Monte Carlo Computed k_{eff} for Some of the Experimental Arrays
of U(93.2)–Metal Units Described in Table II

| Expr. (i,j) | Reflector Index, j | | | |
Unit Index (i)	1	2	3	5
1	0.942	1.009	1.004	0.997
2	0.996	--	--	--
3	0.979	--	--	--
4	0.991	--	--	0.993
5	0.978	0.988	1.000	0.997
6	0.996	0.978	0.998	0.996
7	0.995	0.985	0.997	0.997
8	1.004	0.999	0.993	0.996
9	0.996	0.984	0.989	1.004
10	0.993	--	--	--
11	0.992	0.989	0.985	0.988
12	0.985	0.986	0.992	1.007
13	0.990	0.987	0.998	0.991
14	0.985	0.991	0.990	0.995
15	0.976	--	--	0.996
Average $k_{eff} \pm \sigma$	0.990 ± 0.008	0.990 ± 0.004	0.995 ± 0.002	0.996 ± 0.002

NOTE: 1. The assemblies Expr. (i,j) are described in Table II.
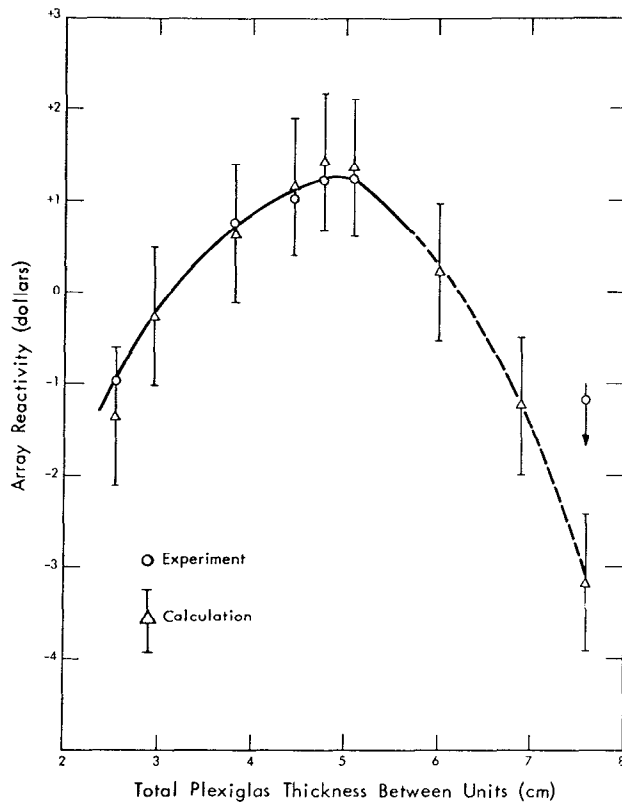   2. The standard deviation for each entry does not exceed ± 0.006.

Fig. 5. Reactivity effects of Plexiglas placed between 20.9-kg U(93.2) cylinders in an eight-unit array reflected by 15.2-cm-thick paraffin.

corresponding to this change in k_{eff} is 2.00 ± 0.38 dollars, assuming β_{eff} (Ref. 10) is 0.0066. The reactivity for the substitution was observed experimentally to be >1.50 dollars. In the second assembly, Expr. (9,1) of nominal 15.7-kg U(93.2) units, the change in the central unit of the array was one of geometry, from an h/d ratio of 0.7 to 2.8, with only a slight increase in mass, ~0.1 kg U(93.2). As was expected, no essential difference in the calculation of the unperturbed and perturbed arrays was evidenced.

Examples of calculations performed on the reflected and moderated arrays are displayed in Fig. 5 for the reflected eight-unit arrays of nominal 20.9-kg U(93.2) units in which the Plexiglas thickness between the units is varied. The cross-section set for hydrogen averaged over the fission spectrum was used for the Plexiglas region in the calculations reported. Other calculations of these arrays utilized the dE/E-averaged cross-section set[9] for the moderator; however, these failed to yield a correspondence between reactivity and Plexiglas thickness.

CONCLUSIONS

The series of experiments described herein was initiated and conducted to fulfill the need for a

[10]G. R. KEEPIN, Physics of Nuclear Kinetics, Addison-Wesley Publishing Co., Inc., Reading, Massachusetts (1965).

better understanding of how criticality may be influenced in arrays of neutron-coupled subcritical components as necessary support to nuclear criticality safety evaluations in the handling of fissile materials. Cylinders of metal with different h/d ratios, ranging in mass from 10.4 to 26.2 kg U(93.2), were examined experimentally under a variety of conditions and perturbations. These were, principally, number of units, degree of reflection and moderation by hydrogenous materials, spacing of units, and the shape of the assemblies. The data have provided a comprehensive test of Monte Carlo calculations and beneficial guidance for evaluation of the magnitude of factors affecting array criticality.

For the purposes of this work, the KENO Monte Carlo code with the Hansen-Roach neutron cross-section sets reproduces the results of the experiments with a precision determined by the number of neutron histories. The accuracy, however, depends on both the cross-section data and statistical vagaries and is $\sim 1\%$ in k_{eff}. Reliable extensions of criticality data and evaluations of conditions encountered in practical situations are possible. In the area of nuclear criticality safety, the KENO code and the Hansen-Roach 16-group neutron cross-section sets constitute a valid method for examining critical conditions for U(93.2) metal.