OAK RIDGE NATIONAL LABORATORY

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CRITICAL THREE-DIMENSIONAL ARRAYS OF NEUTRON-INTERACTING UNITS

PART II - U(93.2) METAL

J. T. Thomas

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Neutron Physics Division

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J. T. Thomas

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ABSTRACT

Criticality studies were made of three dimensional arrays of uranium metal cylinders enriched to 93.2 wt per cent U^{235}. Four weight groups of units, ranging from 10.5 to 26.2 kg of uranium in five sizes, were employed to determine the critical surface separation between units as a function of the number in an array. The critical uranium density (the ratio of the mass of a unit to the volume of the lattice cell it occupies in a critical array) was observed to depend upon a number of factors. Changes in k_{eff} of the individual units, caused by altering their shape, produced inverse changes in the density, provided the array shape was unchanged. The density of the array varied with its shape in a manner similar to that resulting from corresponding changes in a single critical unit. Addition of an hydrogenous reflector reduced the density of the array by factors much greater than those observed for similar reflection of a single critical unit. The density was found to be minimal when the units were separated by an hydrogenous moderator 4.9-cm thick. The separate effects of moderation and reflection of arrays are not additive. In several experiments it was observed that an array comprised of one-half of each of two different critical arrays was subcritical.

INTRODUCTION

A continuing program in support of nuclear safety in the handling of accumulations of individually subcritical units of fissile materials is being conducted at the Critical Experiments Facility of the Oak Ridge National Laboratory. Earlier experiments in this series, primarily with aqueous solutions, have been reported by Gilley and Thomas[1] and most recently by Thomas.[2,3]

In the present experiments the critical surface separation of cylindrical units of U^{235}-enriched uranium metal, usually equal in three dimensions, was measured as a function of the number of units in an array and of the thickness of a paraffin reflector surrounding the array. Five sizes of units were employed, permitting an examination of the effect of varying the unit mass and dimensions. A few definitive experiments

1- L. W. Gilley and J. T. Thomas, TRANS. Amer. Nuc. Soc. 4, 54 (1961).

2- J. T. Thomas, TRANS. Amer. Nuc. Soc. 6, 169 (1963).

3- J. T. Thomas, "Critical Three-Dimensional Arrays of Neutron Interacting Units, Part I, Aqueous U(92.6) Solutions," ORNL-TM-719 (Oct. 1, 1963).

indicate the effect of moderating the arrays, of placing the units in containers, of changing the geometric shape of the array, and of partially reflecting the array.

MATERIALS AND EQUIPMENT

The units constituting these arrays consisted of one or more cylinders of uranium metal enriched to 93.2 wt% in U^{235}, designated as U(93.2). The U^{234}, U^{236} and U^{238} content were 1.0, 0.2 and 5.6 wt%, respectively. The nominal mass and dimensions of the cylinders available for the experiments were

Mass, kg of U	Diameter, cm	Height, cm
10.5	11.5	5.4
5.2	11.5	2.7
5.2	9.1	4.3

Although the deviation in the heights from the nominal values was no greater than 0.003 cm, the diameters varied as much as 1.5% and the mass, of course, about twice that amount. The metal cylinders are shown in Fig. 1. These pieces 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 near alike as possible by careful selection of the individual cylinders.

The units were supported, with their axes vertical, on stainless steel rods, also shown in Fig. 1, passing through two 0.508-cm-diam holes in each cylinder parallel to the axis and located 8.547 cm apart on a diameter. The 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.[4] The horizontal position of the rods was adjustable.

All arrays were constructed with the centers of the units at the corners of rectangular parallelepipeds. In a few cases the 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/cc; in all other reflectors it was 0.93 g/cc. Various thicknesses of Plexiglas, a methacrylate plastic having a density of 1.18 g/cc and containing 60.5 wt% C and 8.3 wt% H, was the moderator material in one series of experiments.

4. E. R. Rohrer, W. C. Tunnell and D. W. Magnuson, New Critical Experiment Machines, Neutron Physics Div. Ann. Prog. Rept. for Period Ending Sept. 1, 1961, ORNL-3193, p. 168.

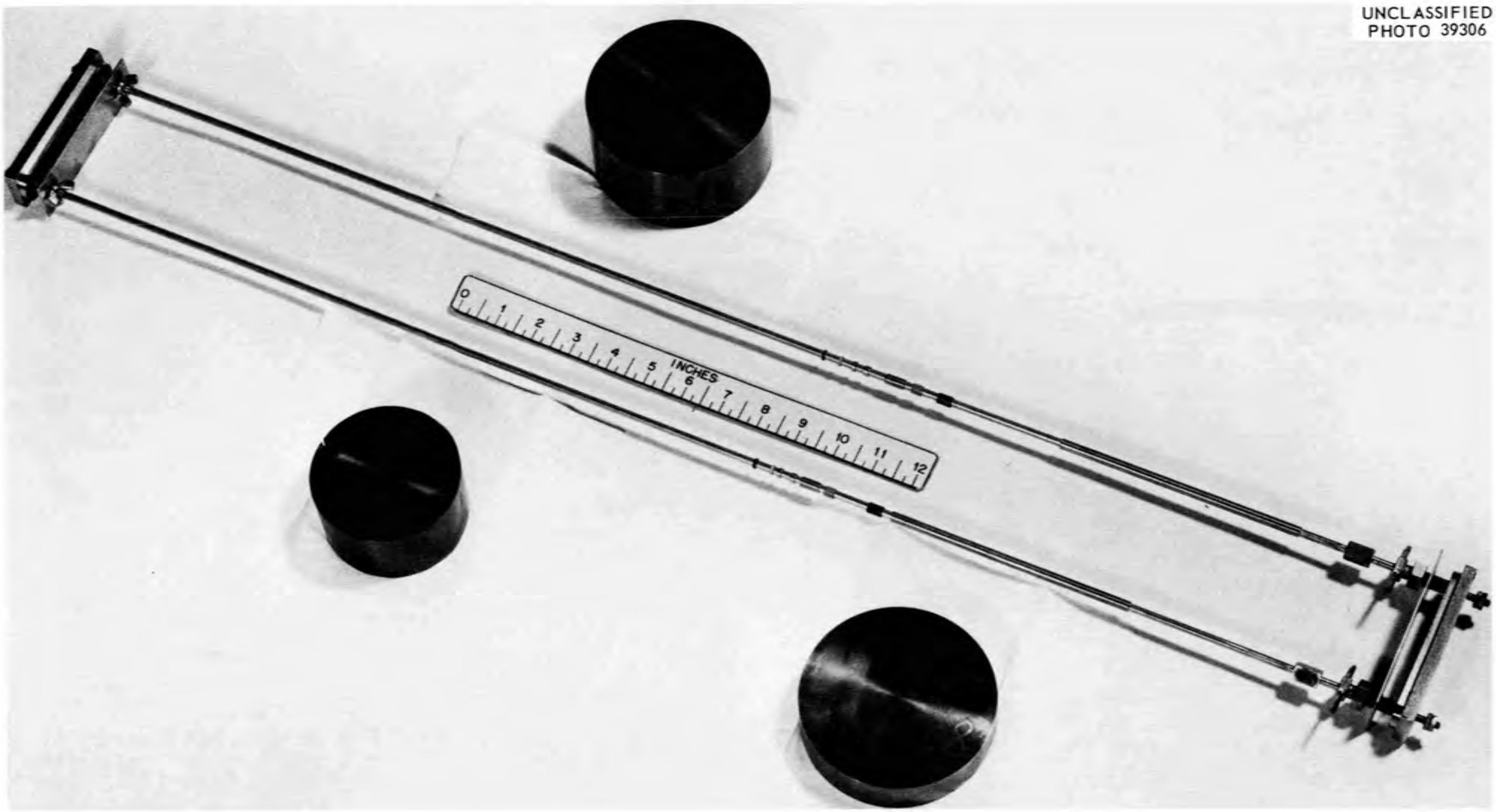

Fig. 1. Cylinders of Approximately 5 and 10 kg of U(93.2) and Their Stainless Steel Support Rods. Fixtures on the rods attach to the split-table equipment.

Figure 2 shows an unreflected array of 45 units, each having an average mass of ∿10.5 kg of uranium.

EXPERIMENTAL RESULTS

For convenience in description, average dimensions of the units in the arrays constructed in these experiments have been collected in Table 1.

Regular Three Dimensional Arrays

Data obtained from regular arrays of 8, 16, 27, 45 and 64 units, both unreflected and reflected by various thicknesses of paraffin, are presented in Table 2. Each entry represents a critical array with two exceptions noted. In all of the reflected experiments the reflector was located at the outer boundary of the peripheral lattice cells, where a lattice cell is occupied by a single unit. The average uranium density in the array, column 4, is the mass of the average unit divided by the volume of the lattice cell in which it is centered. An indication of the shape of the array is given in column 5 as the ratio of the height of the array to the square root of its base area.

The following notation will be used throughout this paper to reduce recurring descriptions of arrays:

$$X_n^i \{t;\ \delta;\ \rho;\ r\}$$

where X^i ≡ average unit in array described in Table 1,
n ≡ number of units in the array,
t ≡ paraffin reflector thickness, cm,
δ ≡ surface separation of units, cm (equal in three directions),
ρ ≡ average uranium density in array, g of U/cm^3, and
r ≡ ratio of array height to the square root of its base area.

The regular arrays of Table 2 are also described in Figs. 3 through 7 where the number of units in a critical array is plotted against the density of uranium in the array. In most instances lines are drawn through points representing arrays constructed of like units arranged in equal numbers in the three directions and surrounded by a reflector of uniform thickness. For example, Fig. 3 shows this relation for arrays of 64, 27 and, in some cases, 8 units each containing 10.5 kg of uranium and enclosed in paraffin reflectors ranging in thickness up to 15.2 cm. These arrays are designated as A_{64}^{6}, A_{27}^{2} and A_{8}^{1}. The ratio of the height of a unit to its diameter was 0.47. The ratio of the height of an array to the square root of its base depends, of course, upon the separation of the units, which

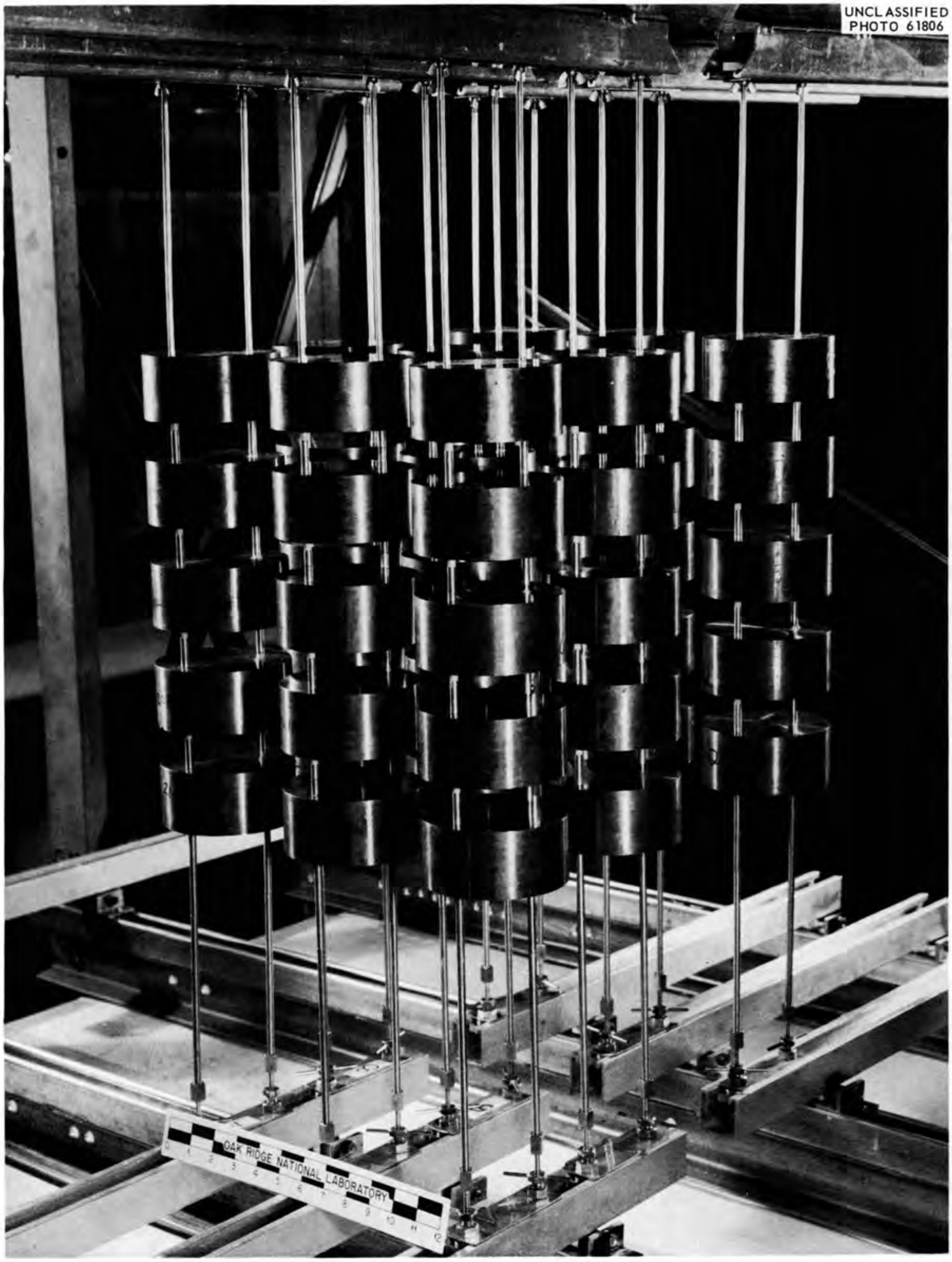

Fig. 2. An Unreflected and Unmoderated Array of Forty-Five 10.5-kg U(93.2) Cylinders.

Table 1. Dimensions of Average U(93.2) Metal Units Constituting Arrays

Uranium density = 18.76 g/cm^3

Unit Designation	Mass (kg of U)	Diameter, d (cm)	Height, h (cm)	h/d
A^1	10.480	11.506	5.382	0.47
A^2	10.484	11.509	5.382	0.47
A^3	10.507	9.116	8.641	0.95
A^4	10.489	9.116	8.641	0.95
A^5	10.458	11.494	5.382	0.47
A^6	10.434	11.481	5.382	0.47
A^7	10.384	11.454	5.382	0.47
B^1	15.692	11.494	8.077	0.70
B^2	15.683	11.490	8.077	0.70
B^3	15.696	a		
B^4	15.807	9.116	12.962	1.42
C^1	20.805	11.464	10.765	0.94
C^2	20.960	11.506	10.765	0.94
C^3	20.877	11.484	10.765	0.94
C^4	20.896	11.488	10.765	0.94
C^5	20.892	b		
C^6	21.008	9.116	17.282	1.90
D^1	26.218	11.509	13.459	1.17
D^2	26.113	11.486	13.459	1.17
E^1	5.225	11.494	2.691	0.23
E^2	5.254	9.116	4.320	0.47
E^3	5.245	9.116	4.320	0.47

a. This unit consisted of one E^3 mounted coaxially with and between two E^1's.

b. This unit consisted of one A^7 mounted coaxially with and between two E^2's.

is determined by the number of units in the array, and upon the reflector; this characteristic of the unreflected arrays reported in Fig. 3 ranged from 0.61 to 0.47. Shown for comparison are two additional unreflected arrays, one of 16 units (in a 2 x 2 x 4 pattern), A^{1}_{16}, and another of 45 units (in a 3 x 3 x 5 pattern), A^{5}_{45}, in which the ratio of height to square root of base area was very near unity. It is apparent that the reactivity is greater (the mass required for criticality at a given density is less) for these latter arrays. The result is not unexpected from the analogy with single critical units where the mass requirement is minimal in the geometry near that having the least surface to volume ratio.

The results from arrays A^{3}_{8} and A^{4}_{27}, of 8 and 27 units, respectively, also of ~10.5 kg mass each but having a height to diameter ratio near unity, are given in Fig. 4. The arrays were near cubic in outline. Included for comparison are the unreflected 16- and 45-unit arrays (A^{1}_{16} and A^{5}_{45}) from Fig. 3 in which the height to diameter ratio of the units was 0.47 and the arrays were also nearly cubic. A short extrapolation of the critical densities of the reflected A^{3}_{8} arrays yielded 14.830 g/cm^3 as the density of an unreflected array. This value is greater than that predicted by an extension of the line defined by the unreflected A^{1}_{16} and A^{5}_{45} arrays and also greater than the density, 14.632 g/cm^3, measured in the subcritical A^{3}_{8} array with units in contact (Table 2). That the critical density of the A^{4}_{27} array falls on the line established by the A^{1}_{16} and the A^{5}_{45} arrays is apparently fortuitous.

A comparison of the results from unreflected arrays reported in Figs. 3 and 4 indicates that the shape of an array is more important in determining the specific reactivity than is the shape of the units themselves.

Data describing arrays of units of 15.6, of 20.9, and of 26.2 kg of uranium surrounded by paraffin reflectors of several thicknesses are presented in Figs. 5, 6, and 7, respectively. All of these data show the relatively large effect of a 15.2-cm-thick paraffin reflector. In each case investigated the addition of this reflector reduced the number of units required for criticality at the same uranium density within the array by about an order of magnitude. This value is to be compared with the reduction in the critical mass of a single unit by about a factor of two upon addition of a similar reflector. The enhanced reflector saving is associated with the relatively high neutron leakage otherwise occurring through the area between the units of the array.

<u>Arrays Partly Enclosed in a Thick Paraffin Reflector</u>

The effect of a 15.2-cm-thick reflector on three sides of an array, simulating the location of fissile units on a floor adjacent to two intersecting walls, was investigated in two assemblies of units having average masses of 20.9 kg and a height to diameter ratio of 0.94. The results are given in Table 3 and are plotted in Fig. 6 for comparison with arrays completely enclosed by paraffin. It is apparent that the thick reflector on three sides of the array was slightly less effective than was one 2.5-cm-thick completely surrounding the arrays.

Table 2. Critical Conditions for Regular Three Dimensional Arrays with Various Paraffin Reflectors

Array Description[a]	Paraffin Reflector Thickness (cm)	Surface Separation[b] of Units (cm)	Average Uranium Density in Array (g/cm^3)	Ratio of Array Height to $\sqrt{\text{Base Area}}$
A_8^1 (2x2x2)	0	0[c]	14.709	0.47
	1.3	0.229	13.563	0.48
	3.8	1.981	7.825	0.55
	7.6	3.416	5.350	0.59
	15.2	3.696	4.995	0.60
A_{27}^2 (3x3x3)	0	2.007	7.767	0.55
	1.3	2.992	5.954	0.58
	3.8	5.872	3.085	0.65
	7.6	8.258	1.967	0.69
	15.2	8.689	1.826	0.70
A_8^3 (2x2x2)	0	0[d]	14.632	0.95
	1.3	0.602	12.037	0.95
	3.8	2.362	7.248	0.96
	7.6	3.970	4.865	0.96
	15.2	4.308	4.503	0.97
A_{27}^4 (3x3x3)	0	2.436	7.096	0.96
	1.3	3.426	5.526	0.96
	3.8	6.579	2.798	0.97
	7.6	9.017	1.807	0.97
	15.2	9.434	1.686	0.97
A_{16}^1 (2x2x4)	0	1.349	9.422	1.05
A_{45}^5 (3x3x5)	0	3.442	5.313	0.99
A_{64}^6 (4x4x4)	0	3.952	4.693	0.61
	15.2	12.360	1.035	0.74
B_8^1 (2x2x2)	0	0.902	11.374	0.73
	1.3	1.905	8.756	0.75
	3.8	4.961	4.445	0.79
	7.6	7.391	2.845	0.82
	15.2	7.823	2.645	0.82

Table 2, Continued

Array Description[a]	Paraffin Reflector Thickness (cm)	Surface Separation[b] of Units (cm)	Average Uranium Density in Array (g/cm^3)	Ratio of Array Height to $\sqrt{\text{Base Area}}$
B^2_{27} (3x3x3)	0	4.204	5.185	0.78
	1.3	5.677	3.869	0.80
	3.8	10.190	1.827	0.84
	7.6	13.693	1.137	0.86
	15.2	14.194	1.067	0.87
C^1_8 (2x2x2)	0	2.217	8.562	0.95
C^2_8 (2x2x2)	0	2.248	8.514	0.95
	1.3	3.678	6.295	0.95
	2.5	5.710	4.292	0.96
	3.8	8.207	2.843	0.96
	7.6	11.509	1.777	0.97
	15.2	11.986	1.669	0.97
C^3_{27} (3x3x3)	0	6.363	3.827	0.96
	1.3	8.574	2.683	0.96
	3.8	14.764	1.187	0.97
	7.6	18.720	0.776	0.98
	15.2	19.147	0.744	0.98
D^1_8 (2x2x2)	0	3.543	6.806	1.18
	1.3	5.423	4.843	1.12
	3.8	11.532	1.976	1.09
	7.6	15.697	1.215	1.07
	15.2	16.378	1.130	1.07
D^2_{27} (3x3x3)	0	8.494	2.980	1.10
	1.3	11.323	2.025	1.09
	3.8	19.606	0.817	1.06
	7.6	24.498	0.531	1.05
	15.2	24.991	0.510	1.05

a. The letter and the superscript identify the average unit in the array described in Table 1; the subscript is the number of units in the array; the numbers in parentheses are the horizontal and vertical dimensions, respectively, of the array expressed in number of units.

b. Errors on all surface separations are ±0.013 cm for unreflected arrays and ±0.026 cm for reflected arrays.

c. Array was subcritical with an apparent neutron source multiplication of ∿3.

d. Array was subcritical with an apparent neutron source multiplication of ∿10.

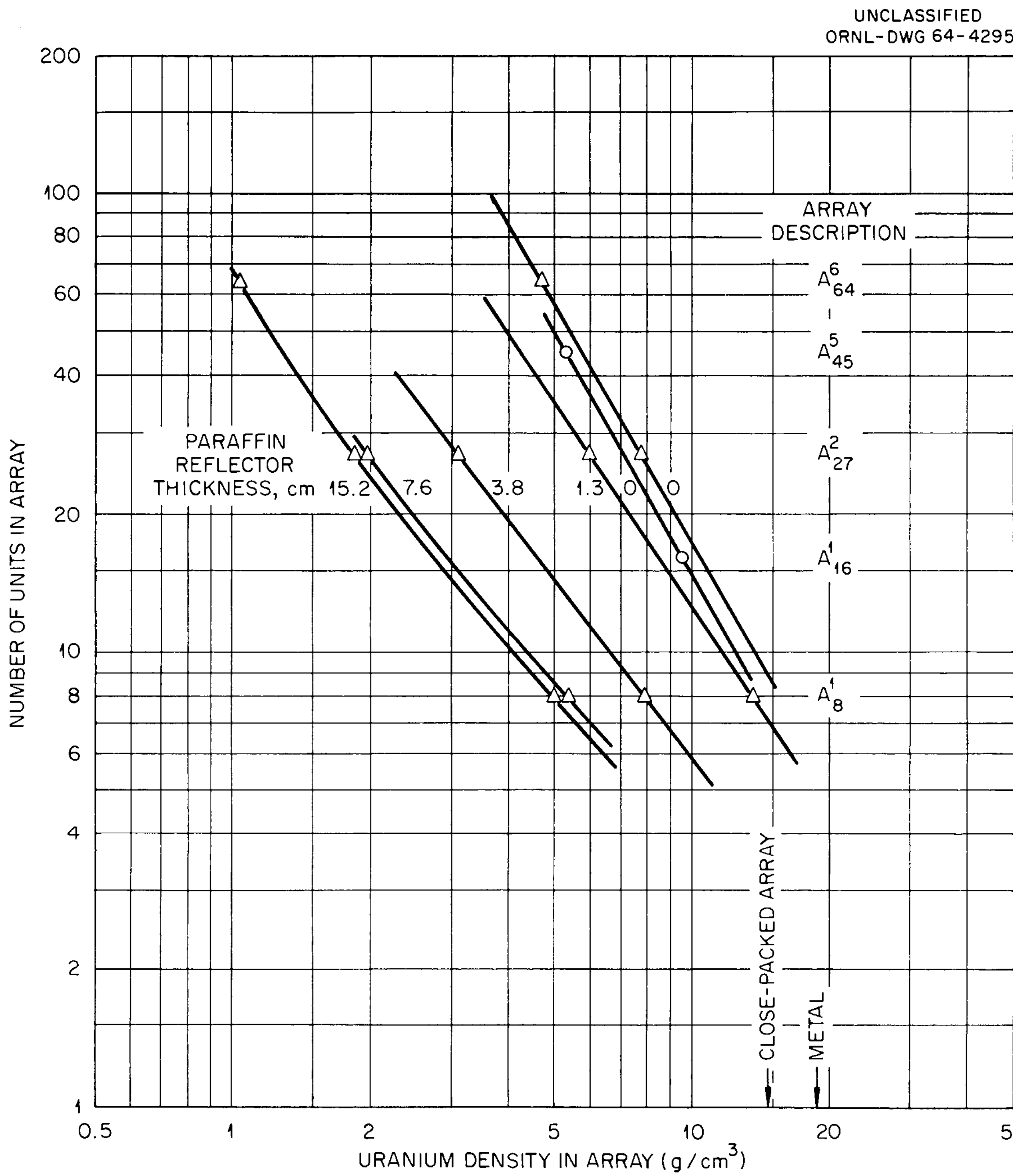

Fig. 3. Number of 10.5-kg U(93.2) Units with h/d = 0.47 in Critical Arrays as a Function of the Uranium Density and the Paraffin Reflector Thickness.

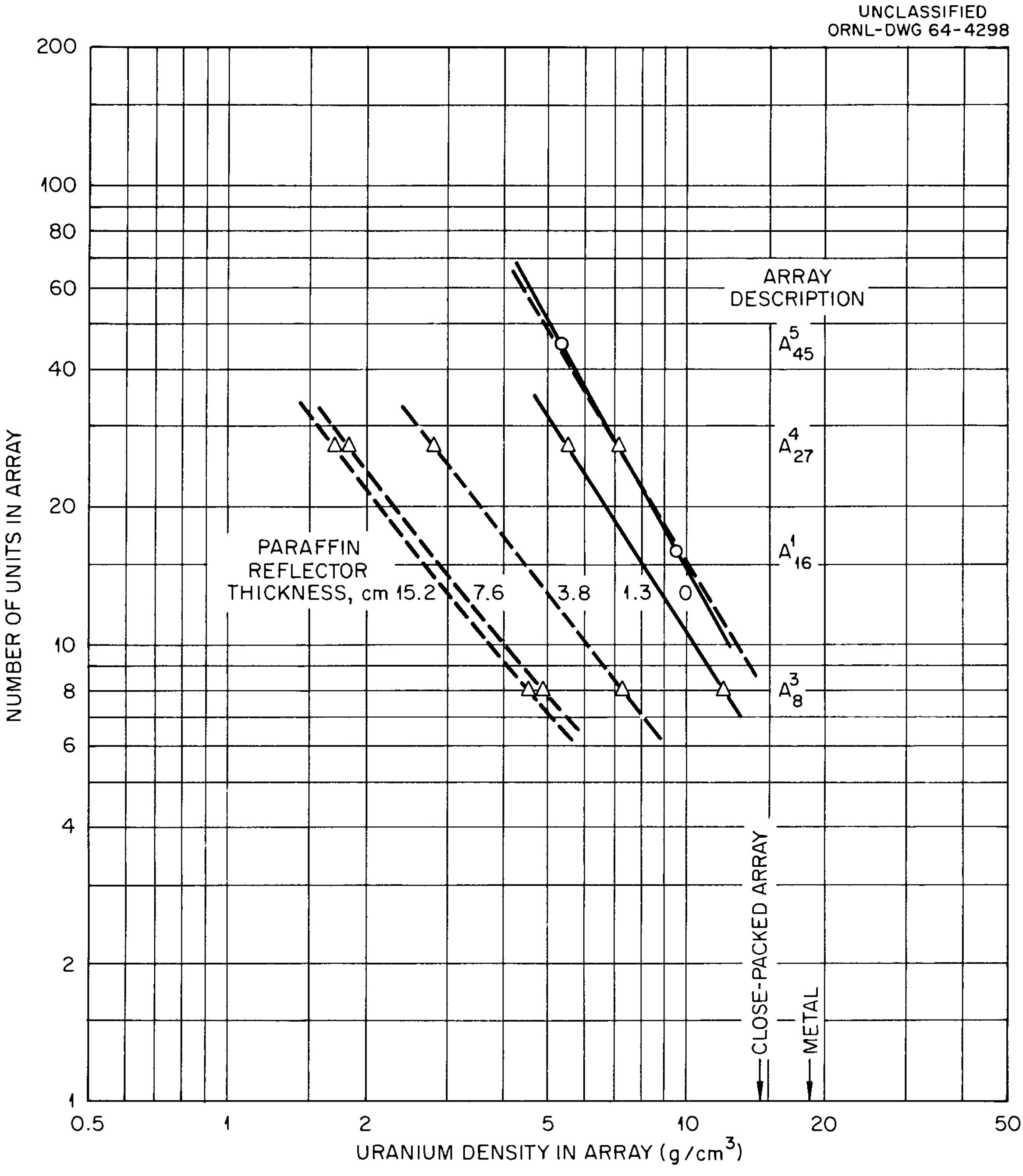

Fig. 4. Number of 10.5-kg U(93.2) Units with h/d = 0.95 in Critical Arrays as a Function of the Uranium Density and the Paraffin Reflector Thickness.

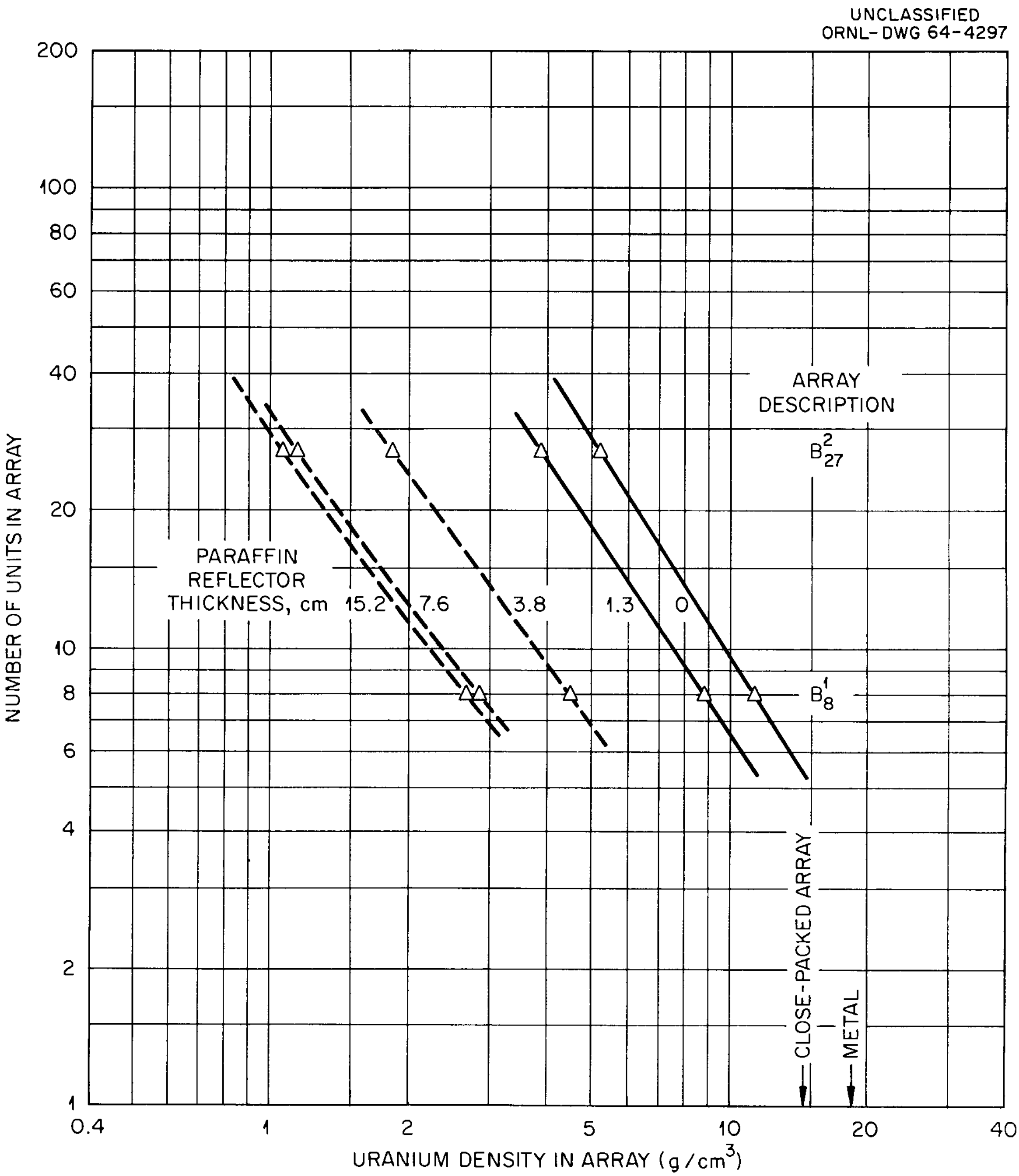

Fig. 5. Number of 15.6-kg U(93.2) Units with h/d = 0.70 in Critical Arrays as a Function of the Uranium Density and the Paraffin Reflector Thickness.

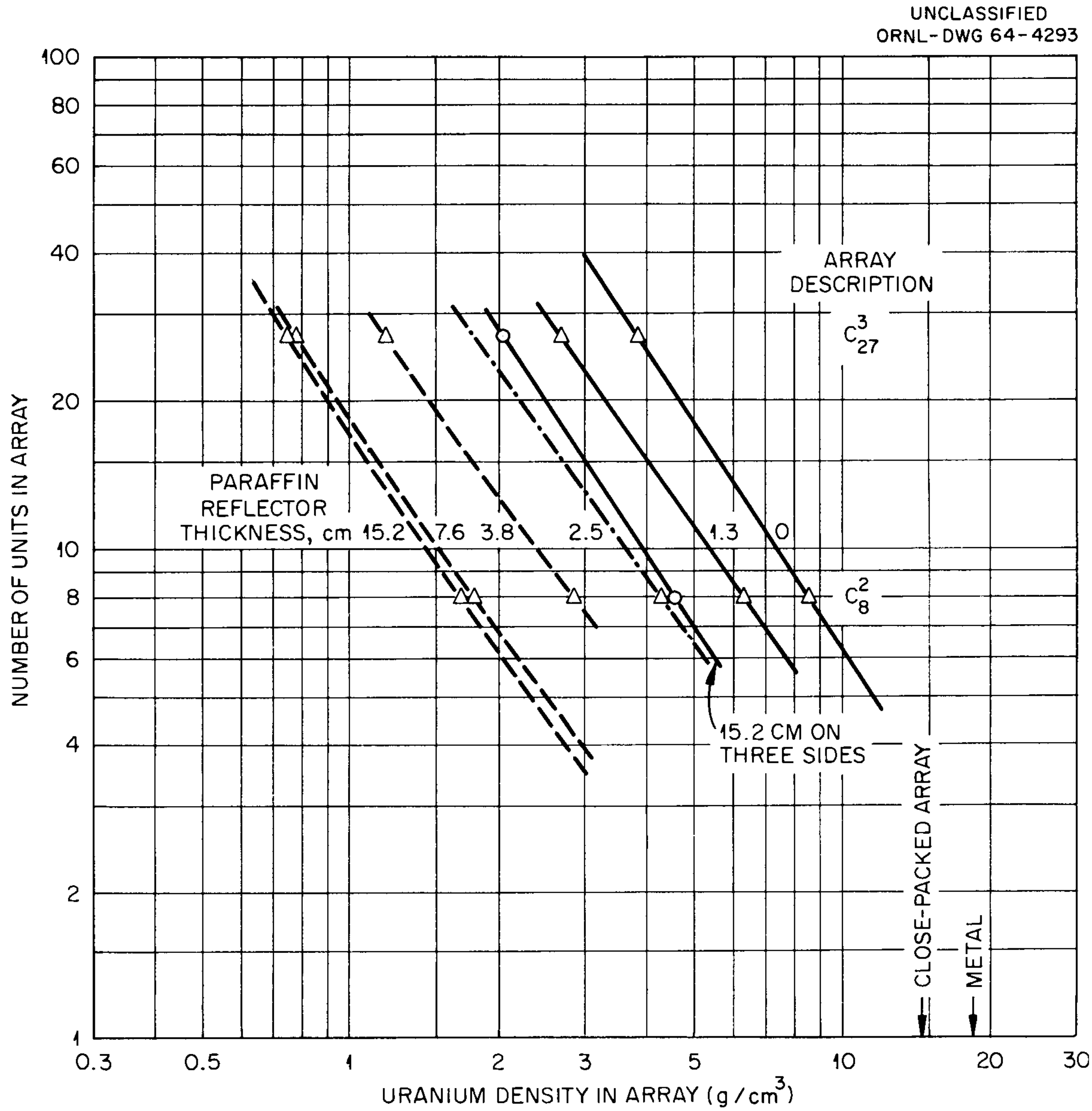

Fig. 6. Number of 20.9-kg U(93.2) Units with h/d = 0.94 in Critical Arrays as a Function of the Uranium Density and the Paraffin Reflector Thickness.

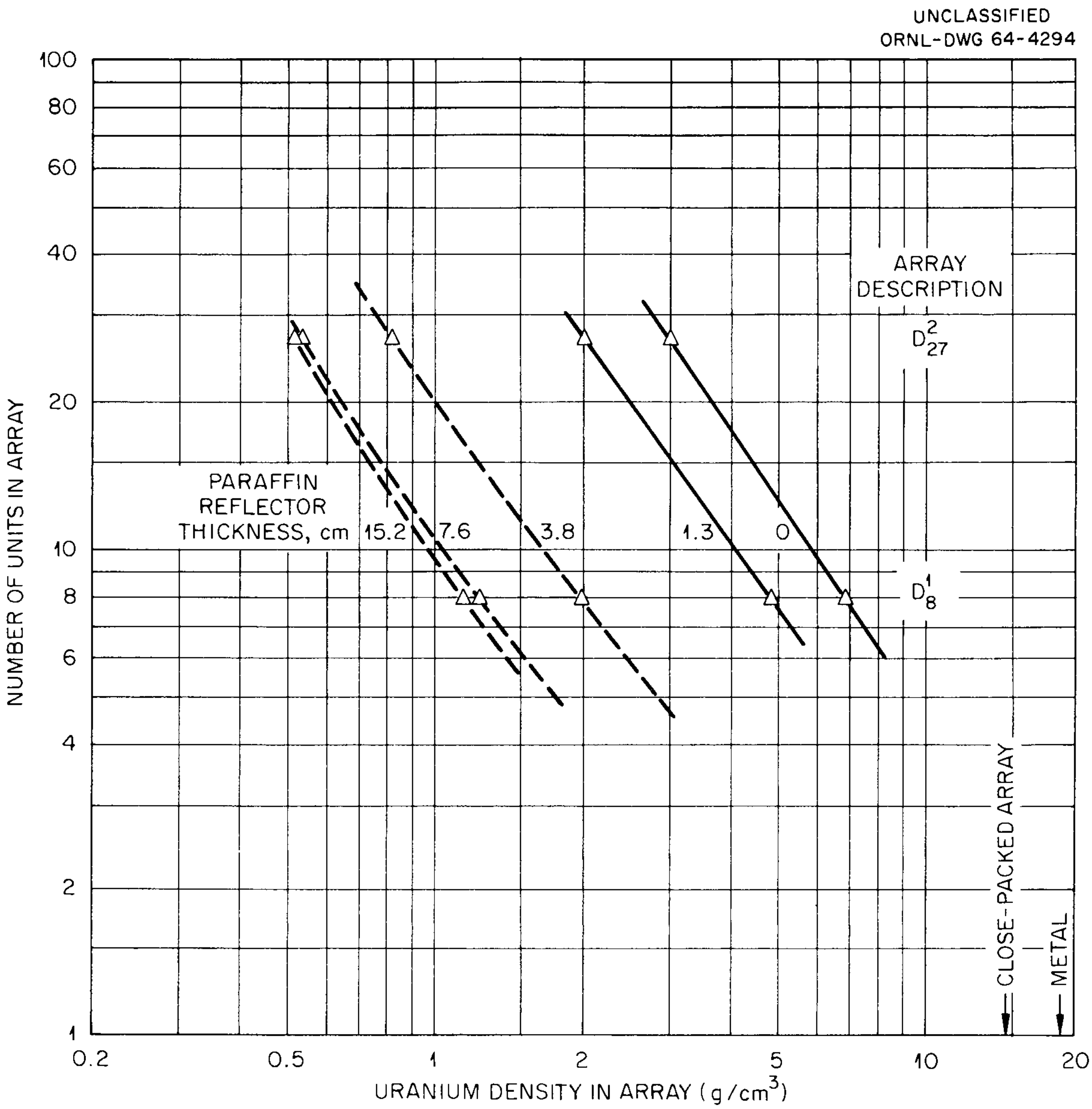

Fig. 7. Number of 26.2-kg U(93.2) Units with h/d = 1.17 in Critical Arrays as a Function of the Uranium Density and the Paraffin Reflector Thickness.

Table 3. Critical Conditions for Arrays Partially Enclosed in a Reflector

Array Description[a]	Paraffin Reflector	Surface Separation of Units (cm)	Average Uranium Density in Array (g/cm3)	Ratio of Array Height to $\sqrt{\text{Base Area}}$
C_8^2 (2x2x2)	b	5.398±0.013	4.538	0.96
C_{27}^3 (3x3x3)	c	10.541±0.013	2.028	0.97

a. The letter and the superscript identify the average unit in the array described in Table 1; the subscript is the number of units in the array.
b. The dimensions of the base reflector were 76.2 x 76.2 x 15.2 cm and of the two sides were 76.2 x 45.7 x 15.2 cm.
c. The dimensions of the base reflector were 106.7 x 106.7 x 15.2 cm and of the two sides were 106.7 x 76.2 x 15.2 cm.

Comparison of Array Patterns

Essentially all of the arrays were constructed with the surface spacing of the units equal in three directions. Since in no case were the height and diameter of the units equal, the centers of the units were at the corners of rectangular parallelepipeds. Some operational convenience derived from the selection of this pattern, and more important, it was possible to construct many more critical arrays in a greater variety of shapes than would have been possible had only cubic arrays, i.e., units spaced at equal center distances, been built. Four arrays were constructed, however, with units at equal center spacing. These arrays are described in Table 4 where, for comparison, are also the dimensions of arrays of the same units located at equal surface distances.

The arrays of A^2 and of B^1 units at equal center spacing could not be made critical. As expected, arrays of C^2 and of C^3 units were critical at substantially the same density in both patterns since the units were of approximately equal height and diameter. The critical uranium density in the array of D^1 units at equal center spacing, however, was less than that in the array at equal surface spacing.

Table 4. Comparison of Uranium Densities of Unreflected Cubic and Rectangular Parallelepiped Arrays

Array[a] Description		Center Spacing[b] (cm)	Surface Spacing[b] (cm) Horizontal	Vertical	Average Uranium Density in Array (g/cm^3)	Ratio of Array Height to √Base Area	Ratio of Unit Height to Diameter
A^2_{27}	(3x3x3)	11.509	0	6.127	6.877[c]	1.00	0.47
A^2_{27}		-	2.007	2.007	7.767	0.55	0.47
B^1_8	(2x2x2)	11.494	0	3.417	10.334[d]	1.00	0.70
B^1_8		-	0.902	0.902	11.374	0.73	0.70
C^2_8	(2x2x2)	13.503	1.997	2.738	8.513	1.00	0.94
C^2_8		-	2.248	2.248	8.514	0.95	0.94
C^3_{27}	(3x3x3)	17.602	6.118	6.837	3.828	1.00	0.94
C^3_{27}		-	6.363	6.363	3.827	0.96	0.94
D^1_8	(2x2x2)	15.778	4.269	2.319	6.675	1.00	1.17
D^1_8		-	3.543	3.543	6.806	1.13	1.17

a. The letter and the superscript identify the average unit in the array described in Table 1; the subscript is the number of units in the array.
b. The error on all spacing values is ±0.013 cm.
c. Array subcritical, maximum apparent source neutron multiplication ∿70.
d. Array subcritical, maximum apparent source neutron multiplication ∿81.

The results suggest that, given a number of units, if the maximum achievable density with equal center spacing is less than the critical density at equal surface spacing, the array at equal center spacing cannot be made critical.

Effect of Unit Replacements

The effect on reactivity of replacing a unit in a critical array by one having a different mass was evaluated in two experiments. In one experiment, the central unit of the critical array C^3_{27}\{0; 6.363; 3.827; 0.96\} was replaced by a D^2 unit without a change in lattice cell volume.

The substitution of a unit having both a larger mass and a greater k_{eff} produced a reactivity increase in excess of 1.50 dollars. The central position occupied by the D^2 unit is shown in Fig. 8. In the second experiment, the central unit of the critical array $B^2_{27}\{0;\ 4.204;\ 5.185;\ 0.78\}$ was replaced by a B^4 unit and the cell volume maintained. Although the uranium content of the B^4 unit was 124 g more than that of the B^2 unit, its k_{eff} was less and the replacement resulted in a decrease of 5 cents in the reactivity of the array.

Additional experiments utilizing parts of critical 8-unit arrays were performed to illustrate the effect of multiple component replacement. In this series one half each of two different critical arrays were brought together along a common center line until their cell boundaries coincided. The units of one of the critical arrays were right circular cylinders of aqueous uranyl nitrate solution contained in 0.64-cm-thick Plexiglas vessels 20.32 cm in outside diameter and 19.05 cm in outside height. Each unit contained 2.066 kg of uranium enriched to 92.6 wt% U^{235} at an H/U^{235} atomic ratio of 59.*

Three assemblies of mixed units were attempted. In one, four C^2 units of the critical array C^2_8 described in Table 2 were assembled with four D^1 units of the critical array D^1_8 of Table 2. In another, four of the solution units at their critical spacing were mated with four units of the critical array of C^2 units; the composite array is shown in Fig. 9. In the third, four of the solution units were mated with four C^6 units. Each of the composite arrays was more than one dollar subcritical. A description of the arrays and their apparent source neutron multiplication are given in Table 5. The array of solution units and C^2 units was made critical by reducing the spacing between the C^2 units from 2.248 to 1.689 cm.

Effect of Array Geometry on Three Dimensional Arrays

The Class C units of Table 1 produce arrays having ratios of array height to the square root of base area, r, near unity when the arrays had an equal number of units along each of the three dimensions. The C^4 units of Table 1, each containing 20.9 kg of uranium, were used to explore the effect on the critical uranium density of having an unequal number of units along the three dimensions of arrays, i.e., producing values of r differing significantly from unity. The critical conditions for the various arrangements are given in Table 6 with, for comparison the critical densities, from Fig. 6, in arrays having the same number of units, were it possible to arrange them with equal numbers in each dimension. The comparative densities show a decrease in attainable reactivity when values of r are changed from unity, a result consistent with the increased neutron leakage. The opposite effect, changing values of r to near unity, has already been pointed out for the Class A units.

* See Reference 3 for a complete description of the critical conditions of arrays of these units.

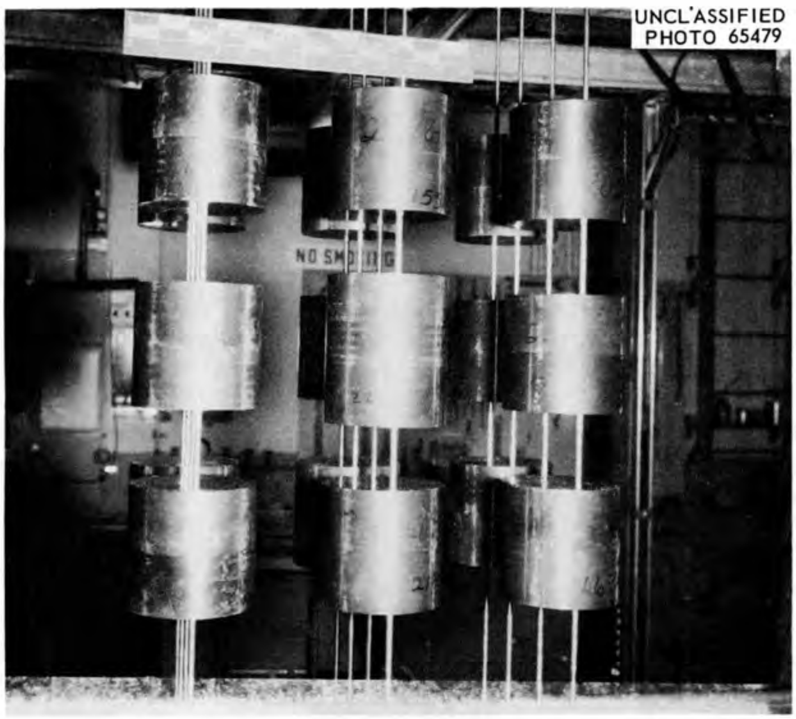

Fig. 8. Section of a Modified Unreflected 27-Unit Array.

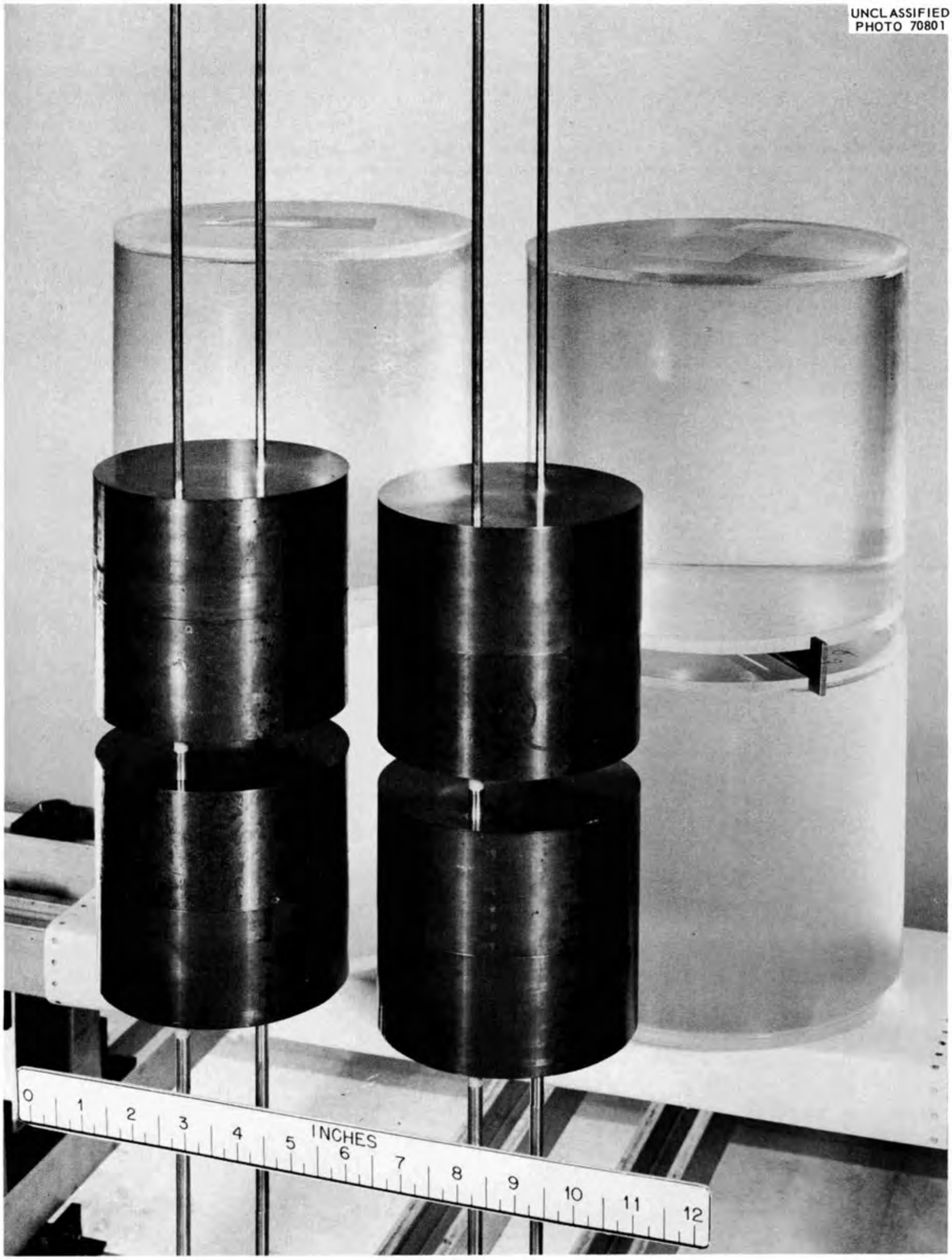

Fig. 9. Composite Array of Four 20.9-kg U(93.2) Metal Units and Four 2.1-kg U(92.6) Units of $UO_2(NO_3)_2$ Solution.

Table 5. Subcritical Composite Arrays[a]

1/2 Array I +	1/2 Array II	Apparent Source Neutron Multiplication
C_8^2\{0; 2.248; 8.514; 0.95\}	D_8^1\{0; 3.543; 6.806; 1.18\}	∿5
C_8^2\{0; 2.248; 8.514; 0.95\}	$[UO_2(NO_3)_2]_8$\{0; 1.43; 0.214; 0.94\}	∿20
C_8^6\{0; 1.466; 10.002; 1.77\}	$[UO_2(NO_3)_2]_8$\{0; 1.43; 0.214; 0.94\}	∿20

a. The error in each value of the spacing is ±0.013 cm. See page 4 for description of array notation.

Units of Non-Cylindrical and of Extreme Geometry

A brief study was made to determine the effect on the critical density in eight-unit arrays of changing the shape of the units. For one experiment, B^3 units, described in Table 1, were constructed from three 5.2-kg cylinders arranged coaxially, with one of smaller diameter (9.1 cm) between two larger ones (11.5 cm). The critical density in both reflected and unreflected arrays of these irregularly shaped units was greater than that in arrays of regular cylinders. In an unreflected array of C^5 units, formed with a piece of larger diameter, 11.5 cm, between two 9.1 cm in diameter, the critical density was also greater than in the unreflected array of C^2 units. The densities of arrays of these regular and irregular cylinders when reflected by paraffin 15.2-cm-thick were approximately equal.

In another experiment the units were regular cylinders having a height to diameter ratio of 1.90 and a mass of 21 kg. These were the C^6 units of Table 1. The resulting critical densities of both the reflected and the unreflected arrays were greater than those of arrays of more equilateral cylinders. The data are compared in Table 7. Figure 10 shows the average uranium density as a function of the ratio of the surface-to-volume ratio of the cylinders to that of a sphere of the same mass.

Table 6. Effect of Array Geometry on Critical Uranium Densities in Unreflected Arrays of U(93.2) Metal Units

Array Description[a]	Surface Separation of Units[b] (cm)	Ratio of Array Height to $\sqrt{\text{Base Area}}$	Average Uranium Density in Arrays of Identical Units (g/cm^3): Unequal Number of Units in Three Dimensions	Equal Number of Units in Three Dimensions[c]
C_8^4 (2x4x1)	1.062[d]	0.35	12.232	8.514
C_9^4 (3x3x1)	0.658	0.31	12.400	7.83
C_{18}^4 (3x3x2)	4.641	0.64	5.212	4.97
C_{16}^4 (2x2x4)	3.907	1.91	6.008	5.38
C_{16}^4 (2x4x2)	3.891	0.67	6.027	5.38
C_{16}^4 (4x4x1)	1.516	0.24	10.059	5.38

a. The letter and superscript identify the average unit in the array described in Table 1; the subscript is the number of units in the array.
b. The error on the separation values is ±0.013 cm.
c. Values from Fig. 6 for ratio of array height to $\sqrt{\text{base area}}$ of 0.95.
d. This array consisted of two clusters of four units each with lateral surfaces in contact. This dimension is the horizontal separation between the two clusters.

In each case the change in geometry of the unit resulted in an increase in the surface area and in a decrease in its k_{eff}. If the effect of array shape is neglected, these results indicate that reducing the k_{eff} of a unit in an array will require an increase in the array density to maintain criticality.

Table 7. Comparison of Critical Densities of Arrays of Regular and Irregular U(93.2) Metal Units

Array Description[a]	Paraffin Reflector Thickness (cm)	Surface Separation of Units[b] (cm)	Average Uranium Density in Array (g/cm^3)	Ratio of Unit Height to Diameter	Ratio of Array Height to √Base Area
B_8^1	0	0.902	11.374	0.70	0.72
	15.2	7.823	2.645	0.70	0.82
B_8^3	0	0.229	11.497		0.85
	15.2	6.904	2.792		0.90
C_8^2	0	2.248	8.514	0.94	0.95
	15.2	11.986	1.669	0.94	0.97
C_8^5	0	1.013	8.941		1.21
	15.2	10.945	1.668		1.12
C_8^6	0	1.466	10.002	1.90	1.77
	15.2	10.328	2.013	1.90	1.42

a. The letter and superscript identify the average unit in the array described in Table 1; the subscript is the number of units in the array. The irregular shapes of the B^3 and C^5 units are also described in Table 1.

b. The error in the separation of units in the unreflected arrays is ±0.013 cm; in the reflected arrays it is ±0.026 cm.

Effect of Plexiglas and Steel as Moderators

The effect of hydrogenous material, placed between adjacent units, on the critical dimensions of arrays was examined in assemblies of units having an average mass of 20.9 kg. Boxes of several sizes and wall thicknesses, fabricated from Plexiglas and described in Table 8, were mounted on the rods supporting the uranium units. In one array the units were mounted in steel cylinders, actually short sections of pipe, and, in another, both unit and pipe were located within a Plexiglas box. Some of the arrays were enclosed in a paraffin reflector. In each instance the unit was centered in its container. Examples of these arrays are illustrated in Figs. 11 and 12. The results appear in Table 9.

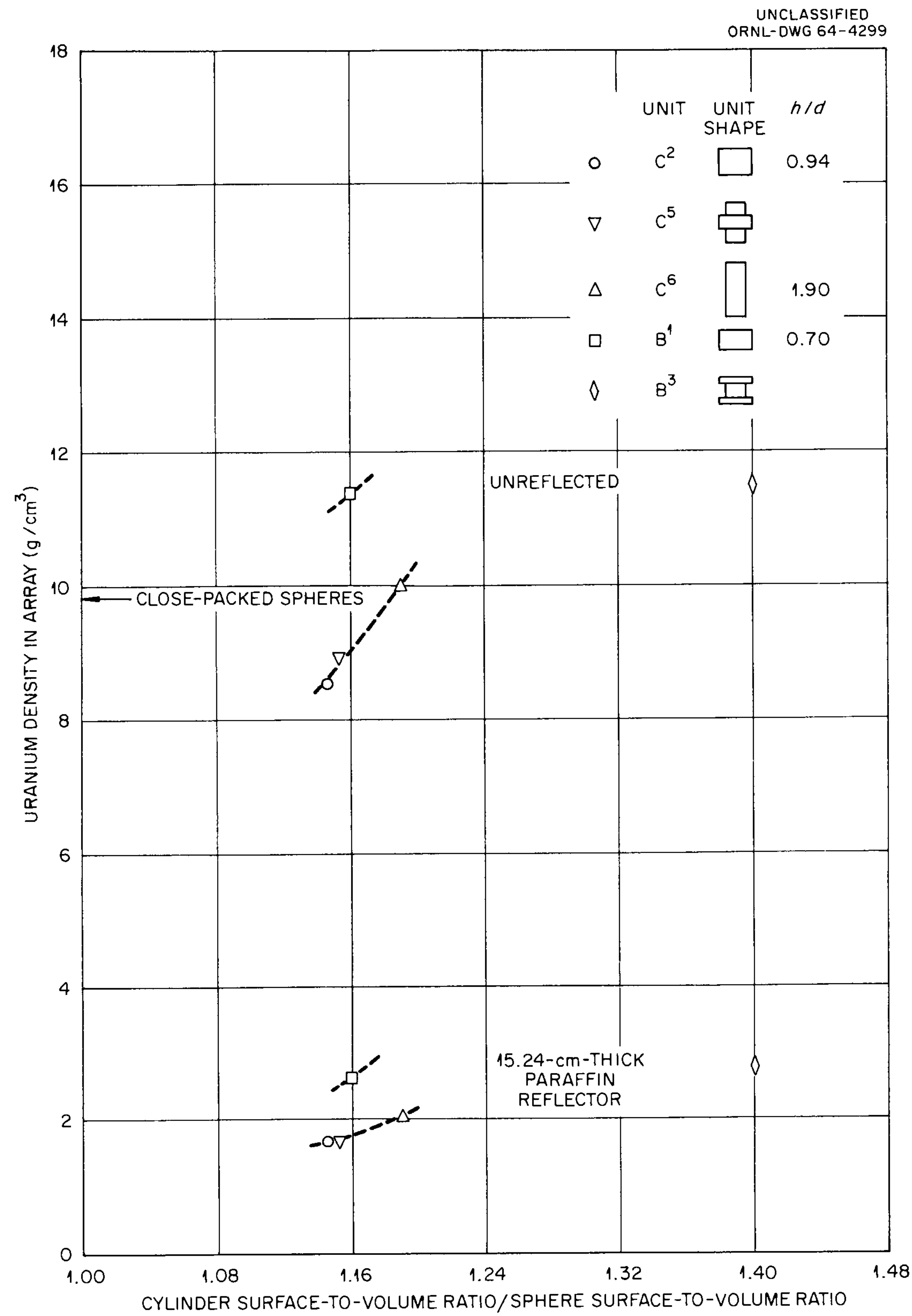

Fig. 10. Effect of the Shape of Units on the Critical Density in Reflected and Unreflected Eight-Unit Arrays.

Table 8. Dimensions of Containers for Units in Moderated Arrays

Container Designation	Material	Wall Thickness (cm)	Outside Dimensions (cm) Base	Height
P^1	Plexiglas	0.64	12.9 x 12.9	12.1
P^2	Plexiglas	0.64	15.6 x 15.6	14.8
P^3	Plexiglas	1.27	17.9 x 17.9	17.2
P^4	Plexiglas	2.38	21.4 x 21.4	20.7
S^1	Iron*	0.66	14.1 diam.	13.2

* 5-in. Schedule 40 iron pipe provided with end plates of thickness equal to the pipe wall.

Comparison of the average densities of corresponding arrays indicate that iron is a less effective moderator than the same thickness of Plexiglas.

An investigation was made of the effect on reactivity of the thickness of hydrogenous material separating adjacent units. An array of eight C^2 units, each in a P^3 box was subcritical when assembled at an average uranium density of 1.189 g/cm^3. The array was surrounded by a 15.2-cm-thick paraffin reflector. Additional Plexiglas was inserted within the array by increasing the thickness of only those container walls which separated units and resulted in an increase in reactivity until the total thickness became approximately 4.9 cm; further increase reduced the reactivity. The detailed results of the experiment are shown in Fig. 13 where the reactivity of the array is plotted as a function of the Plexiglas thickness, including the walls of the P^3 boxes, separating the units.

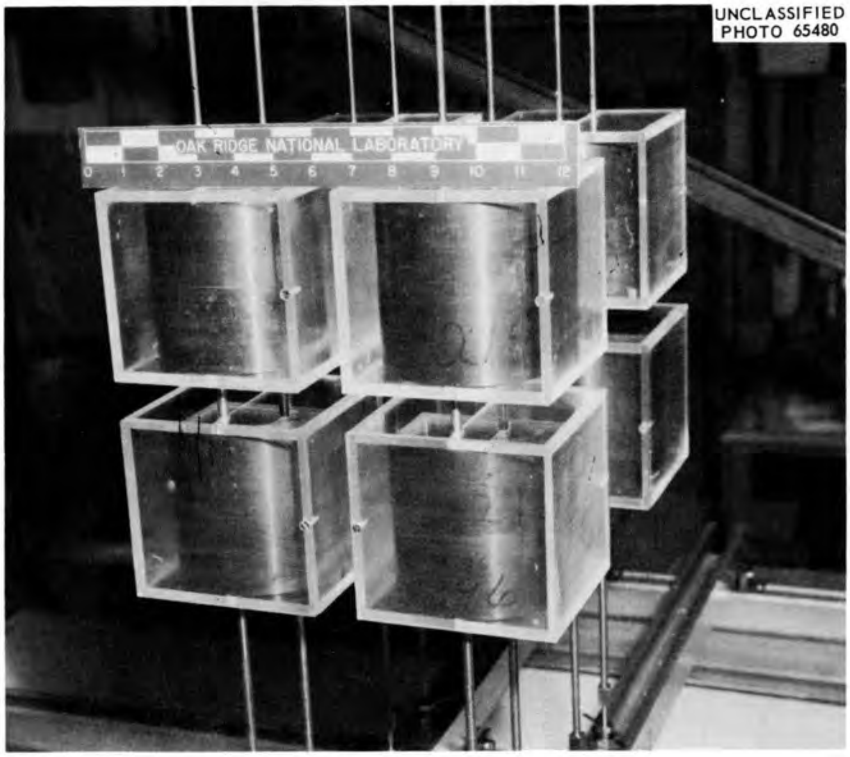

Fig. 11. Moderated Array of Eight 20.9-kg Units.

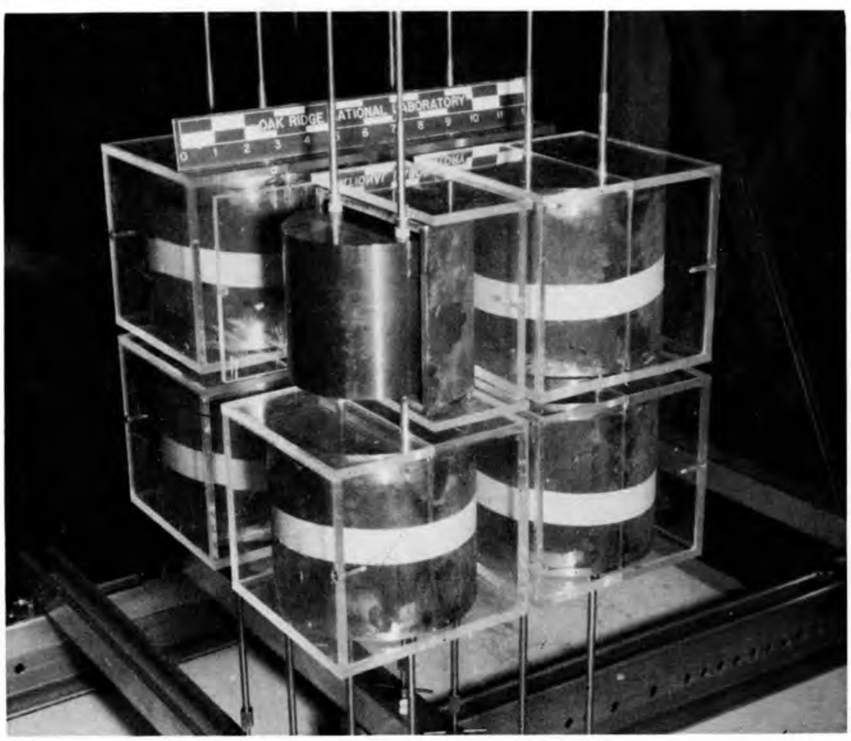

Fig. 12. Combined Moderator of Iron and Plexiglas in an Array of Eight 20.9-kg Units.

Table 9. Critical Conditions for Moderated Arrays of 20.9 kg Units

Description of Array[a]	Paraffin Reflector Thickness (cm)	Surface Separation of Units[b] (cm)	Average Uranium Density in Array (g/cm^3)	Ratio of Array Height to $\sqrt{\text{Base Area}}$
$(C^2 \rightarrow P^1)_8$	0	4.082	5.810	0.95
	15.2	12.662	1.532	0.97
$(C^2 \rightarrow P^2)_8$	0	4.239	5.635	0.95
	1.3	5.875	4.170	0.96
	7.6	12.573	1.549	0.97
	15.2	12.929	1.482	0.97
$(C^2 \rightarrow P^3)_8$	0	6.619	3.670	0.96
	1.3	8.611	2.673	0.96
	15.2	14.503	1.226	0.97
$(C^2 \rightarrow P^4)_8$	0	10.239	2.110	0.97
	15.2	16.447	0.986	0.97
$(C^3 \rightarrow P^4)_{27}$	0	16.289	1.000	0.97
$(C^2 \rightarrow S^1)_8$	0	3.239	6.884	0.95
$(C^2 \rightarrow S^1 \rightarrow P^2)_8$	0	5.169	4.731	0.96

a. The first letter and superscript identify the average unit in the array described in Table 1; the second letter and superscript identify the container (Table 8) in which each unit was centered; the subscript is the number of units in the array.
b. The error in the separation of the units in the unreflected arrays is ±0.013 cm; in the reflected arrays it is ±0.026 cm.

The uranium density as a function of the total thickness of Plexiglas between adjacent units in arrays surrounded by reflectors of various thickness are also given in Table 9 and in Fig. 14. The points plotted at Plexiglas thicknesses of 3 and 7 cm were obtained from Fig. 13. The addition of a 15.2-cm-thick paraffin reflector to an unmoderated array reduced the critical density by a factor of about five; the insertion of a 4.8-cm-thick Plexiglas moderator around the

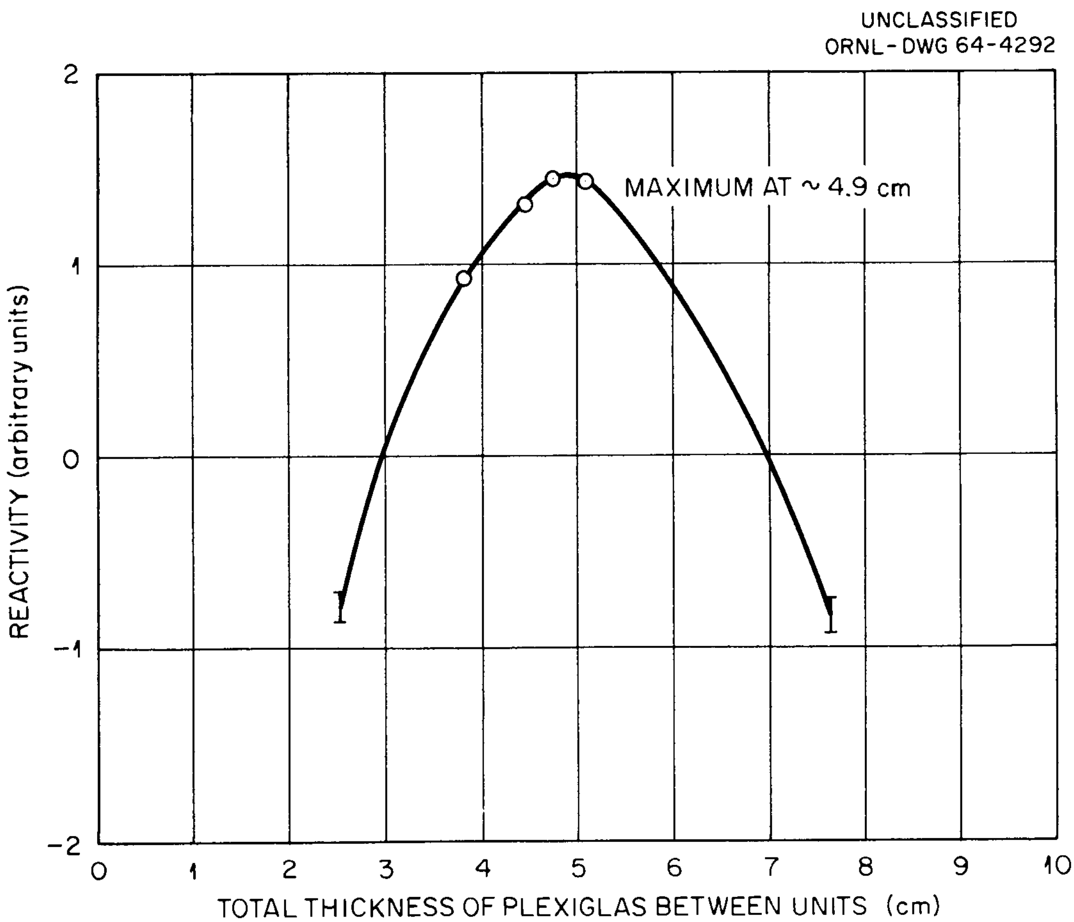

Fig. 13. The Effect on Reactivity of Varying the Thickness of Plexiglas Between the 20.9-kg Metal Units of a Paraffin-Reflected Eight-Unit Array.

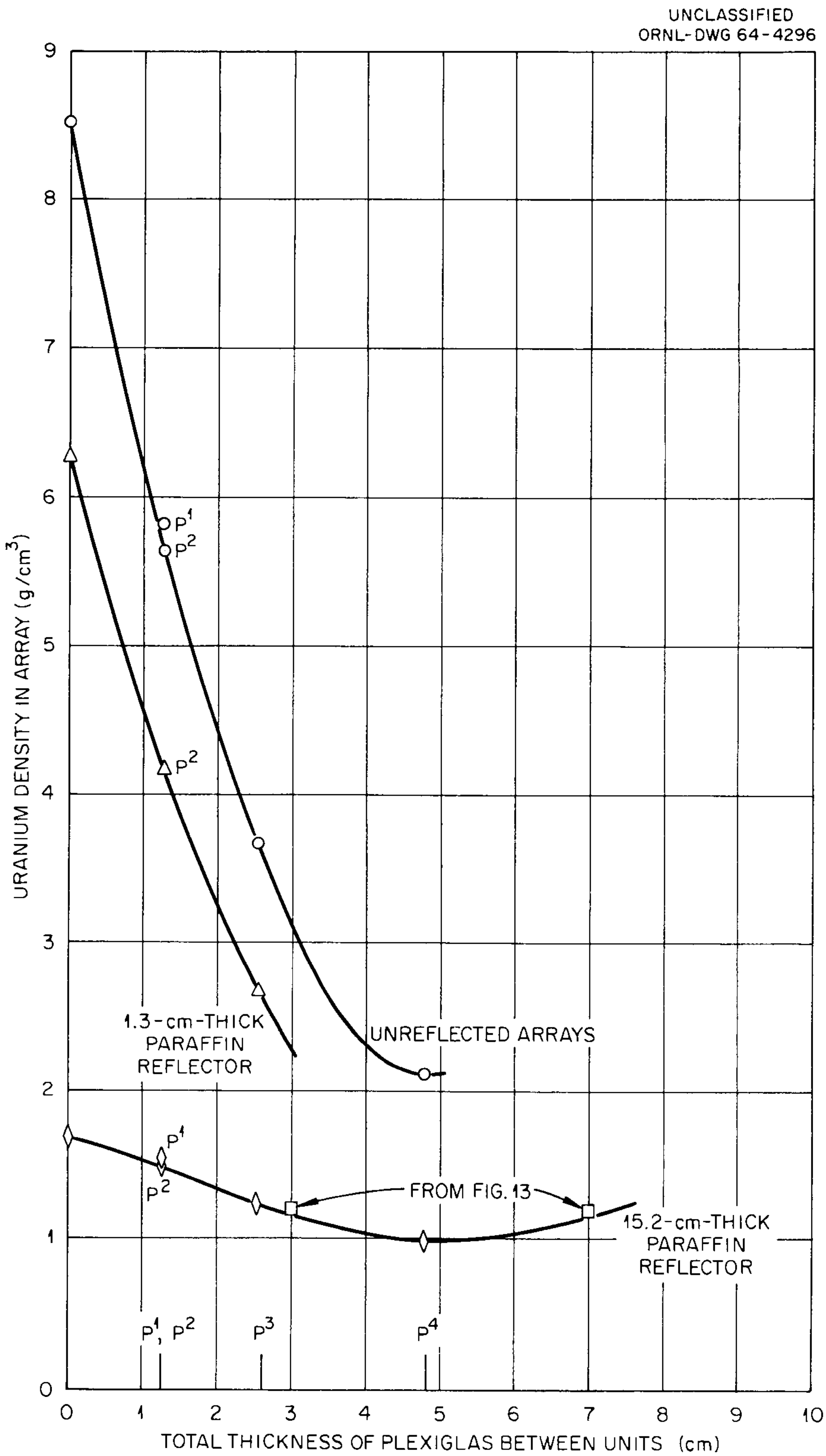

Fig. 15. Reciprocal Apparent Source Neutron Multiplication of an 11.5-cm-diam Unreflected Cylinder of Uranium Metal.

units of an otherwise unreflected array reduced the critical density by a factor of four. It is emphasized that this added moderator surrounded each unit and, consequently, introduced hydrogenous material into the reflector region. It may be observed, however, that simultaneous addition of a thick reflector and optimum moderator reduced the critical density to only about 1/8 that of the unreflected, unmoderated array. It is clear that the separate effects do not combine directly.

Other experiments also investigated the effect on reactivity of introducing additional Plexiglas into arrays. Each test array was unreflected and the units were enclosed in type P^4 Plexiglas containers providing optimum moderation. In one experiment, replacement of the central container in the array $(C^3 \rightarrow P^4)_{27}\{0;\ 16.289;\ 1.000;\ 0.97\}$ by a Plexiglas box having 2.54-cm-thick walls and outside dimensions of 22.4 x 22.4 x 21.6 cm resulted in a decrease in reactivity of about 5 cents.

In another experiment a Plexiglas sheet 41.6 x 43.2 x 0.16 cm inserted vertically in the midplane of the critical array $(C^2 \rightarrow P^4)_8$ $\{0;\ 10.239;\ 2.110;\ 0.97\}$ caused a 1.7 cent decrease in reactivity. Since the space between the P^4 containers was only 0.35 cm, the neutron leakage was not sufficiently decreased by the addition of the Plexiglas sheet to entirely compensate the negative reactivity introduced by increasing the thickness of moderator between the units. On the other hand, a 68.6 x 76.2 x 0.32 cm Plexiglas sheet located vertically midway between adjacent containers in the 27 unit array $(C^3 \rightarrow P^4)_{27}\{0;\ 16.289;\ 1.000;\ 0.97\}$ increased the reactivity by 5.6 cents. The space between the P^4 containers was ~5.7 cm and it is apparent that the decrease in leakage resulting from the addition of the Plexiglas sheet more than compensated the decrease in reactivity caused by increasing the moderator between the units. However, when the Plexiglas sheet was moved to an outer face of this array, the reactivity increased 41.3 cents.

Miscellaneous Experiments

A pair of units was embedded in hydrogenous materials to simulate submersion. Each of two C^2 units was placed in a P^1 container and the corner voids filled with paraffin. The units were mounted coaxially, i.e., with flat surfaces facing, and were surrounded with polyethylene at least 15.2 cm thick. The resulting assembly was critical with an air cavity between the containers 12.9 x 12.9 cm in cross section and 11.6 cm long; that is, the unit faces were separated 12.9 cm. Filling this cavity with Plexiglas produced a subcritical assembly. Criticality was reestablished by reducing this separation and, hence, the Plexiglas thickness, from 12.9 to 10.9 cm. Neglecting the differences between water, polyethylene and Plexiglas, two submerged uranium cylinders, each having a mass of 20.9 kg, with axes colinear will be critical when their surfaces are separated 10.9 cm.

Investigation was made of three additional configurations of two C^2 units in these modified P^1 containers assembled with the units coaxial. In one experiment, each container was completely enclosed in 0.06-cm-thick cadmium. With these composite containers in contact and surrounded by a polyethylene reflector at least 15.2 cm thick, the neutron multiplication was less than two. In another experiment, with the cadmium replaced by 2.5-cm-thick Foamglas,* a neutron multiplication of less than two was also obtained. The same result was observed for 1.3-cm-thick Foamglas.

A similar experiment was performed with two coaxial C^2 units in 5-in. schedule 40 iron pipe containers embedded in polyethylene at least 15.2-cm-thick. With the units positioned in the pipe so as to provide a separation between the flat surfaces of the units of 2.2 cm when the ends of the containers were in contact, the assembly was 86 cents supercritical. This was reduced to 12 cents when 0.64-cm-thick Plexiglas separated the containers. The assembly was subcritical with a neutron multiplication of about three when this Plexiglas was removed.

An experiment established that an unreflected uranium metal cylinder 11.5-cm in diameter could be extended indefinitely without becoming critical. Figure 15 shows the apparent source neutron multiplication of the assembly. The total mass of uranium in the cylinder was 271.8 kg.

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The author is particularly indebted to Dr. Dixon Callihan for many discussions during the program. He also expresses his appreciation to Mr. Cleois Cross for his cheerful and valuable assistance in carrying out the experimental program and to Mr. W. C. Tunnell for the assembly design and the procurement of special materials.

* Foamglas, a commercially available insulating material, is a porous borosilicate glass having a density of 0.141 g/cm^3 and a boron content of ∿2%.

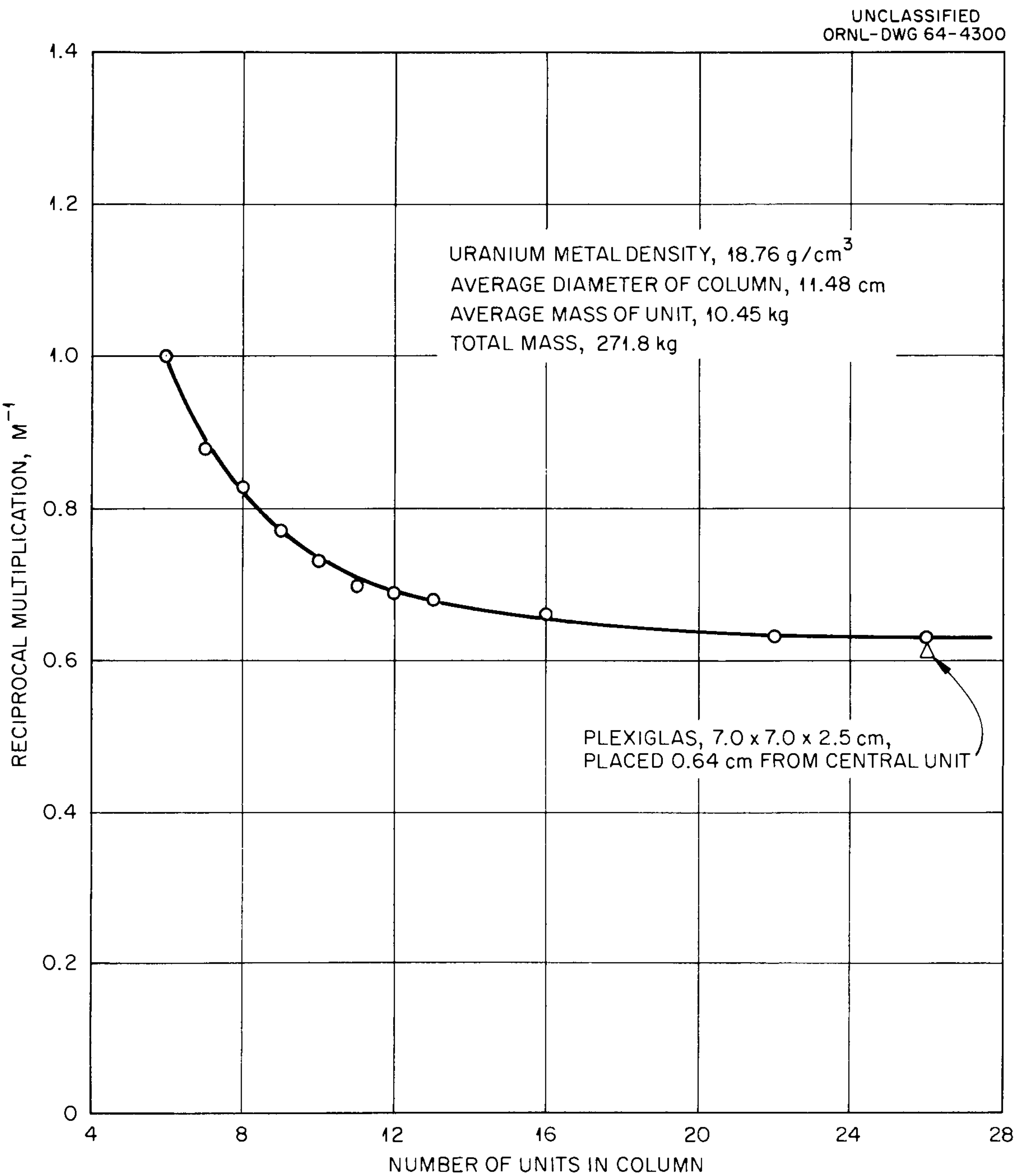

Fig. 14. The Effect of Plexiglas as a Moderator and Paraffin as a Reflector on the Critical Density of an Eight-Unit Array of 20.9-kg Units.

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