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ANNUAL PROGRESS REPORT

FOR PERIOD ENDING SEPTEMBER 1, 1961

OAK RIDGE NATIONAL LABORATORY
operated by
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NEUTRON PHYSICS DIVISION

ANNUAL PROGRESS REPORT

for Period Ending September 1, 1961

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Oak Ridge, Tennessee
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3.5. CRITICAL ARRAYS OF NEUTRON-INTERACTING UNITS[1]

L. W. Gilley, D. F. Cronin,* J. K. Fox, and J. T. Thomas

A series of experiments using as many as 100 subcritical vessels of U^{235}-enriched uranyl nitrate aqueous solution has been performed. In one group of experiments neither reflector about the arrays nor moderator between the units was present. (The terms "moderator" and "reflector" when used in this text refer to the addition of hydrogenous material between the units or about the array.) In another set the thickness of the moderator and partial reflector was varied to exhibit its maximum effect. Additional experiments simulated various conditions of interest to nuclear safety. A brief description of the materials used is presented, and the results appear in both tabular and graphical form.

Units and Arrays

Each unit consisted of a quantity of 92.6 wt% U^{235}-enriched $UO_2(NO_3)_2$, having an average concentration of 410 g of uranium per liter and a specific gravity of 1.55, contained in one of three different types of vessels. The Type A container was a $5\frac{3}{8}$-in.-OD seamless polyethylene bottle, approximately 48 in. long, which had a $1\frac{1}{2}$-in.-dia capped opening and a nominal capacity of ~13 liters. This container had a wall thickness which varied from 0.45 in. at the bottom to 0.20 in. at the top, resulting in a volume-averaged inside diameter of ~4.67 in. The Type B container was a $5\frac{5}{8}$-in.-OD polyethylene bottle, approximately 48 in. long, which had a wide capped opening, a welded bottom, and a nominal capacity of ~15 liters. The walls had a uniform thickness of 0.25 in. The Type C container was an aluminum cylinder. Seven of the Type C containers had a 6-in. inside diameter, a 72-in. height, and a 0.06-in. wall thickness. An additional 12 Type C containers had a 6-in. outside diameter, a 60-in. height, and a wall thickness of 0.05 in. The 6-in.-ID cylinders could be remotely filled with solution and were those used in previous interaction experiments.[2]

Units in each array were arranged with the vessel axes vertical and their bases in a linear, in a square, or in a triangular pattern. Most of the experiments with unreflected and unmoderated arrays were performed with a single tier of units, that is, with all bases in a common horizontal plane, although in one series two such tiers were arranged, one above the other, with the solution separated vertically. The outer boundary of an array was either square or hexagonal, depending upon whether a square or triangular pattern was used. Figure 3.5.1 is a photograph of a double-tier array containing 98 Type A units. The method of securing the units in the aluminum framework is clearly visible. Each unit in this array contained ~5 kg of U^{235} except for five control units located in the center of the lower tier. Criticality was achieved by remotely filling the five control units.

[1]A portion of this work has previously been published in *Trans. Am. Nuclear Soc.* 4, No. 1, 54 (1961).

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[2]J. K. Fox, L. W. Gilley, and A. D. Callihan, *Critical Mass Studies, Part IX, Aqueous U^{235} Solutions*, ORNL-2367 (Feb. 1958).

PHOTO 52448

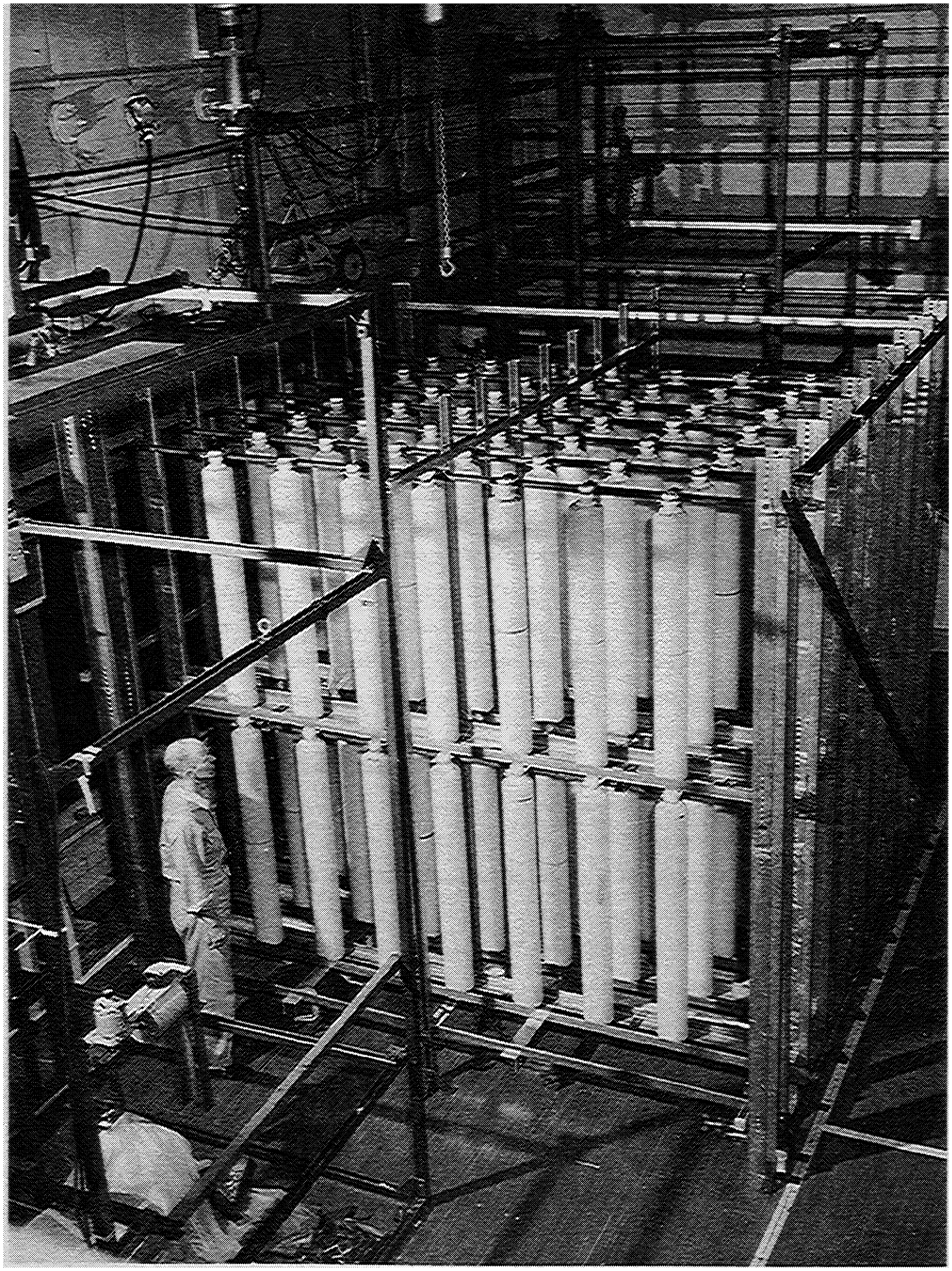
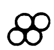
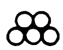
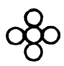


Fig. 3.5.1. Double-Tier Array of Interacting Type A Units.

Experimental Results with Type A Containers

The experiments conducted with Type A units in contact, with no moderator between units and reflector present only in the linear arrays, are summarized in Table 3.5.1. It may be seen that slightly more than 18 units in a linear arrangement against a hydrogenous reflector are required to form a critical array.

Table 3.5.1. Critical Conditions for Type A Units in Contact

Number of Units in Array	Geometry of Array	Solution Height (in.)	Comment
3		44.25	Not critical
4		44.25	Not critical
4		34.56	Critical
5		15.70	Critical
5		44.25	Not critical
19	Linear	44.25	Critical with array against a 6-in.-thick Plexiglas wall; solution height in 5 control units in center of array, 41.70 in.
18	Linear	44.25	Not critical with array against 6-in.-thick Plexiglas wall

In the unreflected and unmoderated arrays in which containers were separated, three different solution heights were used: $22\frac{1}{2}$, $33\frac{3}{8}$, and $44\frac{1}{4}$ in., corresponding to 5.90, 9.30, and 12.76 liters per unit, respectively. Thus, the variables studied were the volume content of the container, the spacing, and the geometric pattern within an array. The number of units in a critical array as a function of their surface-to-surface separation is shown in Fig. 3.5.2 for each of three different solution volumes. The data are also reported in Table 3.5.2. The results from the experiments with the double tier are plotted with ordinate equal to the number of units in one of the tiers, i.e., one half the total number at a particular spacing. In this manner a double tier is shown to have characteristics resembling a single tier but with extended solution height. It is clear that for finite arrays the triangular pattern is more reactive than the square-pattern arrays; i.e., they require a greater surface-to-surface separation.

Experiments were conducted with 16 Type A units that were reflected and moderated with Plexiglas (methyl methacrylate). For these experiments, the vessels were arranged in a 4×4 unit array with each unit containing 12.76 liters of solution. In most of the experiments the Plexiglas formed a matrix of square cells in each of which a unit was centrally located; however, in one experiment the Plexiglas was in the form of $\frac{1}{2}$-in.-thick cylindrical shells which were placed tightly around each unit in the array. The data are shown in Table 3.5.3. Included in the table, for comparison, are the number of units required to achieve criticality at the same surface-to-surface separation in the absence of Plexiglas, obtained from Fig. 3.5.2. It may be seen that a 1-in. thickness of Plexiglas centered between the units of an array effects the greatest change in the critical number. The first two entries of the table describe arrays with equal quantities of Plexiglas associated with each unit. The Plexiglas is seen to be more effective when

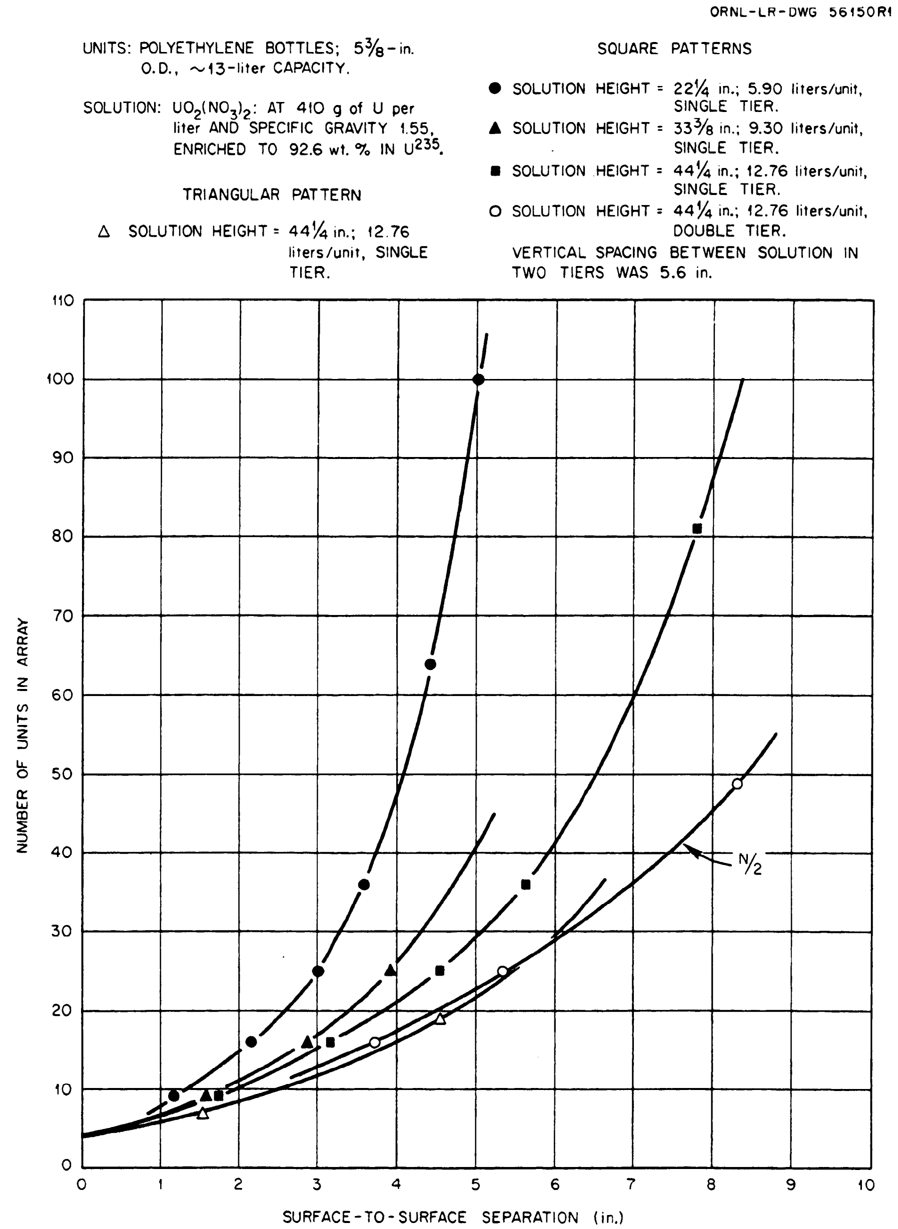


Fig. 3.5.2. Number of Type A Units in a Critical Array as a Function of Surface-to-Surface Spacing.

arranged in a matrix than when the same amount tightly surrounds the units. Later experiments, described by the last two entries in the same table, show that the presence of the ¼-in.-thick reflector is not entirely responsible for this increased reactivity.

An additional series of experiments with Type A containers was conducted in a 9.0-ft-dia by 10-ft-high stainless steel-lined tank into which water could be introduced as a moderator and a reflector. Each unit contained 12.76 liters and a constant surface-to-surface separation of 5.64 in., corresponding to the spacing required for a critical unreflected and unmoderated 6 × 6 array, was maintained. Table 3.5.4

Table 3.5.2. Critical Spacings for Type A Containers

Number of Units in Array	Geometry of Units		Surface-to-Surface Separation (in.)
	5.90 liters per Unit; Single Tier		
9	3 × 3	Square pattern	1.18
16	4 × 4	Square pattern	2.16
25	5 × 5	Square pattern	3.00
36	6 × 6	Square pattern	3.58
64	8 × 8	Square pattern	4.43
100	10 × 10	Square pattern	5.04
	9.30 liters per Unit; Single Tier		
9	3 × 3	Square pattern	1.59
16	4 × 4	Square pattern	2.89
25	5 × 5	Square pattern	3.92
	12.76 liters per Unit; Single Tier		
9	3 × 3	Square pattern	1.75
16	4 × 4	Square pattern	3.32
25	5 × 5	Square pattern	4.55
36	6 × 6	Square pattern	5.64
81	9 × 9	Square pattern	7.79
7	Triangular pattern		1.53
19	Triangular pattern		4.56
	12.76 liters per Unit; Double Tier*		
32	4 × 4	Square pattern	3.72
50	5 × 5	Square pattern	5.35
98	7 × 7	Square pattern	8.33

*Vertical spacing between solution in two tiers was 5.6 in.

Table 3.5.3. Comparison of Plexiglas-Moderated and Unmoderated Arrays of Type A Containers

Sixteen 12.76-liter units in 4×4 array

Configuration and Description of Plexiglas	Plexiglas Reflector	Surface-to-Surface Separation (in.)	Number of Units in Unreflected and Unmoderated Array, N'	Ratio: $\frac{N'}{16}$
0.50 in. surrounding each unit	None	3.72	19.2	1.20
0.50 in. centered in open space	0.25 in.	4.94	28.5	1.78
1.00 in. centered in open space	0.50 in.	5.38	33	2.06
1.50 in. centered in open space	0.75 in.	5.26	31.8	1.99
1.50 in. centered in open space	None	(4.82)*	27.3	1.71

*Interpolated value.

Table 3.5.4. Effect of Water as a Moderator and Reflector on a Critical Array of Type A Units

Surface-to-Surface Separation 5.64 in.

Number of Units in Array	Geometry of Array	Solution Height in 5 Control Units (in.)	Comments
36	6×6	44.25	Outside tank; no water reflector or moderator
36	6×6	29.03	Inside tank; no water reflector or moderator
30	5×6	34.67	Inside tank; bottom reflector only and no moderator
36	6×6	44.25	Inside tank; subcritical fully submerged
32.6	$5 \times 6 + 2.6$	39.70	Inside tank; no water reflector or moderator
32	$5 \times 6 + 2$	39.16	Inside tank; water sprayed at 66.8 liters/min

summarized the results. The first three entries indicate that a full array of 36 filled containers in the tank would be supercritical. Although these units are subcritical when submerged at this spacing, interaction between subcritical units has been observed[2] up to distances slightly less than 12 in. The last two entries evaluate the effect of water being sprayed by a nozzle centered about 3 ft above the array. The reactivity value of water being introduced at this rate is less than that of an additional unit.

Experimental Results with Type B Containers

Experiments were performed with the solution in the Type B plastic cylindrical containers at a constant height of $22\frac{1}{4}$ in., corresponding to 7.41 liters per unit. The units in all arrays were arranged in a square pattern and were unreflected and unmoderated. The number of units in a critical array as a function of surface-to-surface separation is presented in Table 3.5.5 and Fig. 3.5.3. The results of the experiments with Type A units at a solution height of $22\frac{1}{4}$ in. are reproduced in Fig. 3.5.3 for comparison. The data show that the increased solution content of the Type B units requires an increase in spacing over that for the Type A units for the same uniform solution height. The result of altering the over-all geometry of the array from a square to a rectangle is seen to require a decrease in the surface-to-surface separation, as illustrated by the two cases of 3×8 and 3×9 arrays. The effect of introducing a plastic liner into the Type B units, thus reducing the inside diameter of the units to ~4.7 in., which approximates the inside diameter of the Type A unit, is to require a decrease in surface-to-surface separation. Although the diameters and heights of the contained solutions were approximately the same, the two arrays are observed not to be equivalent because of the increased amount of plastic among the Type B units and the slightly larger solution volume of the modified Type B units, 6.33 liters per unit compared to 5.90 liters per unit for Type A units.

Table 3.5.5. Critical Spacings for Type B Units

7.41 liters per unit

Number of Units in Array	Geometry of Array	Surface-to-Surface Separation (in.)
9	3×3	1.43
16	4×4	2.60
36	6×6	4.25
64	8×8	5.32
27	3×9	2.82
24	3×8	2.80
16*	4×4	2.34

*Plastic liner 0.20 in. thick inside bottle, resulting in a contained volume of 6.33 liters per unit.

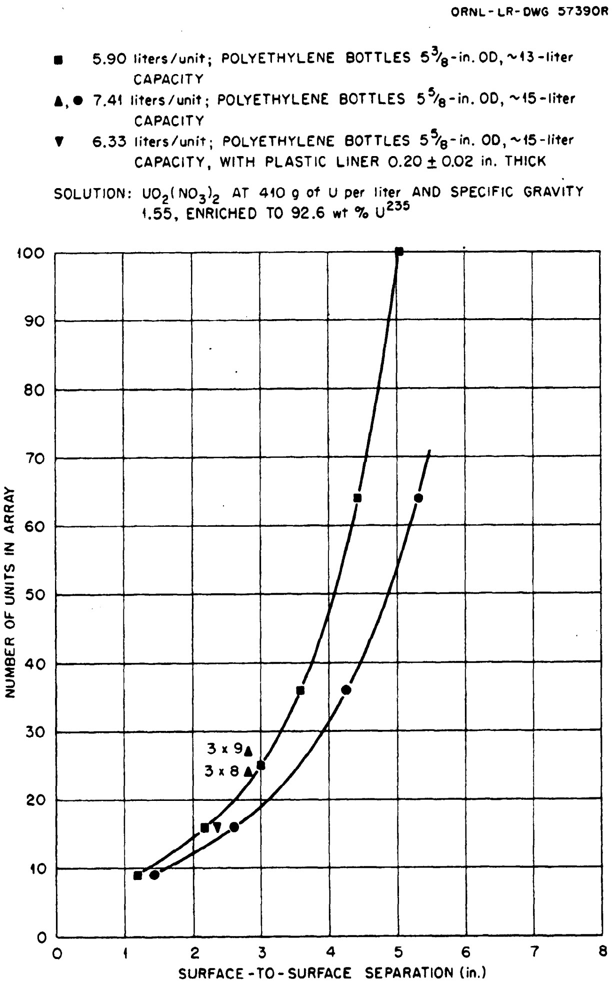


Fig. 3.5.3. Number of Type B Units in a Critical Array as a Function of Surface-to-Surface Spacing.

Experimental Results with Type C Containers

The experimental results obtained with aluminum cylinders are presented in Table 3.5.6. All arrays were unreflected, unmoderated, and single tier only. Both triangular- and square-pattern arrays were assembled. The 6-in.-ID cylinders are more reactive than the 6-in.-OD cylinders, as expected. This was confirmed by experiments which compared two 3 × 3 arrays, containing in one case seven and in the other only three 6-in.-ID cylinders.

Table 3.5.6. Critical Spacings for Type C Units

● = Remotely Filled Units, 6-in.-ID
○ = Fixed-Volume Units, 6-in.-OD

Number of Units in Array	Geometry of Array	Uniform Solution Height in Array (in.)	Surface-to-Surface Separation (in.)
4	●● ●●	26.33	0.15
4	● ● ● ●	42.8	0.38
7	●● ●●● ●●	9.76	0.15
		15.40	1.00
		27.47	2.00
		39.16	2.50
19	○○○ ○●●○ ○●●●○ ○●●○ ○○○	20.00	3.51
		30.00	4.95
		40.00	5.94
		50.00	6.64
9	●●○ ●●● ○●●	21.67	1.70
		30.65	2.30
		40.01	2.70
		49.60	3.00
9	○○○ ●●● ○○○	20.26	1.50
16	○○○○ ●●●● ○○○○ ○○○○	20.00	2.58
		30.00	3.77
		40.08	4.50
		50.40	5.00