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CRITICAL PARAMETERS OF A URANIUM SOLUTION SLAB-CYLINDER SYSTEM

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CRITICAL PARAMETERS OF A URANIUM SOLUTION SLAB-CYLINDER SYSTEM

Grover Tuck and Harold E. Clark

Abstract. Critical parameters are reported for a 490-gram per liter uranyl nitrate (93.2 weight-percent uranium 235) system which consisted of an array of vertical cylinders resting on and interacting with a 120-centimeter square horizontal slab. The parameters varied were the array solution height, the number of cylinders, the cylinder diameter, and the slab thickness. The slab-array system, having nine and sixteen 13.6-centimeter diameter cylinders, was also reflected with a 10.2-centimeter thick reflector. All other measurements were essentially unreflected. The critical thickness of the slab alone was measured also.

In addition, two cases of special interest to the criticality engineer were investigated. These included the effect of two 2-liter bottles of solution near the center of a 16-cylinder array and the effect of vertical separation between the array of cylinders and the solution slab.

INTRODUCTION

Frequently, the designer of fissile processing plants and process equipment becomes involved with the criticality safety of systems consisting of cylinders of fissile solution, interacting at right angles to the surface of a fissile solution slab. Typical examples of this type of system are: (1) floor drains, (2) leak in one of a group of vessels in a glove box, (3) drip pans under safe-geometry storage tanks or plumbing, (4) disengagement sections of solvent extraction systems, and (5) interaction of safe-geometry cylinders with any system whose geometry can be approximated by a slab.

In the past, the criticality specialist used overly conservative approximations in these situations. Data are presented which permit better critical analysis of these systems for the concentrations representing conditions of minimum volume. The experimental data can also be used to determine the accuracy of computer programs.

All of the experimental data[1] were obtained using 490 ±30 grams per liter of uranyl nitrate solution with uranium enriched to 93.2 percent of uranium 235 (^{235}U). A 10.2-centimeter (cm) thick Plexiglas[2] reflector was used to reflect some of the arrays.

One experiment simulated passing a container of fissile solution through a glove box full of cylinders; and one measurement was made with an array of cylinders spaced some distance above a fissile solution slab.

EXPERIMENTAL CONFIGURATION AND EQUIPMENT

Cylinders:

The dimensions of each Type-316 stainless steel cylinder are given in Table I. The array of cylinders was held in place by two 152-cm square by 0.158-cm thick mild steel plates. These plates were fastened to a minimal mass framework and positioned 36 and 95 cm above the slab-tank bottom. The cylinders were positioned in a square lattice array with equal spaces between the cylinder center lines and a half space (S/2) between the outer cylinder center lines and the slab edge as shown in Figure 1. The half spacing values are 60.3, 30.2, 20.1, and 15.1 cm for 1, 4, 9, and 16 cylinders, respectively.

Slab Tank:

The Type-316 stainless steel slab tank was 120.7-cm square inside and 20.3 cm in height. The bottom thickness was 0.635 cm and the wall thickness was 0.150 cm. The tank was

[1] Grover Tuck and Harold E. Clark. "Critical Parameters of a Uranium Solution Slab Cylinder System. *Nuclear Science and Engineering*, 40:407-413. 1970.

[2] Trademark of Rohm and Haas Company, Philadelphia, Pennsylvania.

TABLE I. Cylinder dimensions.

Inside Diameter	Bottom and Wall Thickness (centimeters)	Length
11.0	0.198	131
13.6	0.280	131
16.3	0.280	131
21.3	0.280	131
22.4	0.308	274
22.9	0.308	274
23.4	0.308	183
23.9	0.308	183

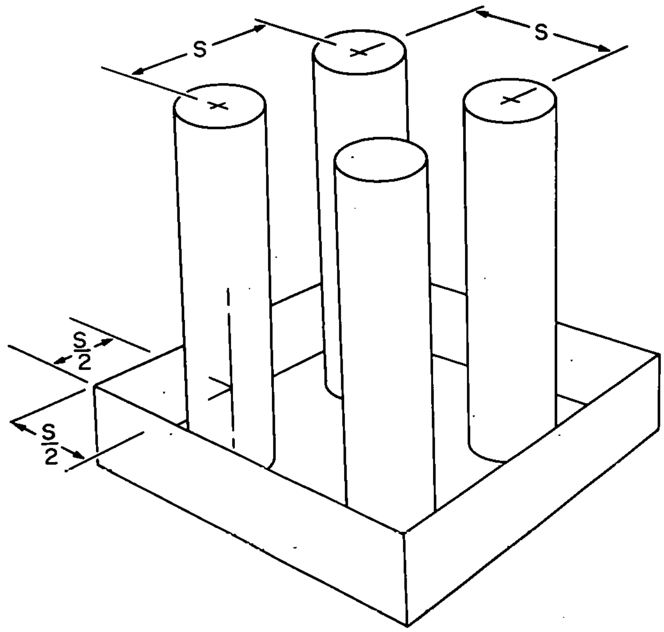


FIGURE 1. Experimental configuration of slab tank with an array of four cylinders. (S = center-to-center spacing and S/2 = center line to slab-edge spacing.)

TABLE II. Fissile solution Properties.

	Test Beginning	End of Unreflected Measurements	Test End
Concentration (grams of uranium per liter)	466.	499.	520.
Density (grams per cubic centimeter)	1.636	1.685	1.704
Normality	0.59	0.70	0.77
*Atomic Ratio (hydrogen / uranium 235)	50.	46.	43.

*Derived from laboratory analysis data.

supported by six mild-steel pipes, 15 cm in diameter, 31.8 cm high, and 0.6-cm thick walls. The fill and drain hoses of both the slab tank and the individial cylinder were of Tygon.[3] The mild-steel supporting legs stood on a 1.91-cm thick steel table, 152.4-cm square, and 137.2-cm high. The nearest large wall of concrete was greater than 3 meters away.

Fissile Solution:

The uranyl nitrate [$UO_2(NO_3)_2$] solution properties were determined by a laboratory analysis and are given in Table II. The uranium was 93.2 weight percent (wt %) ^{235}U.

[3]Trademark of U.S. Stoneware Company, New York.

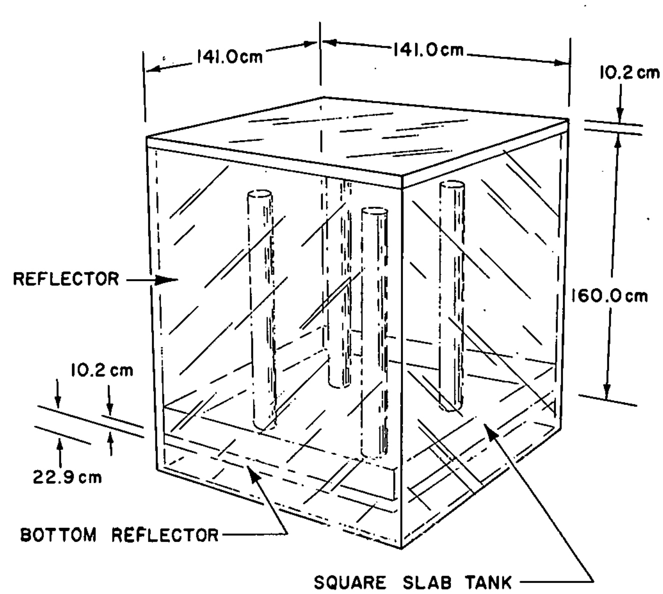


FIGURE 2. Experimental reflector configuration.

Reflector:

Two of the configurations were reflected with Plexiglas [methyl methacrylate, $CH_2:C(CH)_3CO_2(CH_3)$]. Figure 2 shows the reflector configuration. The reflector closely fitted the slab-tank sides and bottom to within 0.3 cm. The reflector thicknesses used were 10.2, 7.7, 5.1, and 2.5 cm.

EXPERIMENTAL UNCERTAINTIES

Solution Heights:

The solution height in the cylinders was measured with a sight gauge and a 2-meter scale. The system was viewed through a remote television (TV) hook-up. Little difficulty was encountered with the system until measurements began on the 21.3-cm diameter cylinders. These cylinders were from a previous experiment and had an inverted *L* tube inside the cylinder on the cylinder fill nipple. The *L* tube produced bubbles in the fill sight-gauge hoses giving inaccurate readings. An electrical level gauge was installed. It consisted of a series of electrical contacts which became closed by the solution passing the location of each contact. The electrical level gauge was used for the balance of the measurements to obtain a number of check points for the sight gauge on each measurement. The accuracy of the sight gauge was determined for both types of cylinders; i.e., with or without the inverted *L* tube. The accuracy of the gauge depended on whether the desired cylinder height was obtained by filling or draining the cylinders. The single 21.3-cm diameter cylinder was the only measurement affected by the bubbles in the line. For this one configuration, the maximum total error on cylinder height was determined to be ±5 cm when the height was reached by filling, and ±10 cm when the height was reached by draining. The result is reflected in the quoted accuracy for the data on the single 21.3-cm diameter cylinder height.

The accuracy quoted[4] for all other cylinder heights from measurements, prior to the installation of the electrical level gauge, is ±5 cm. The value is based on comparison of the 2 gauges over the remaining half of the measurements and allowances for errors in the reference points.

The accuracy of measurements of cylinder height with the electric-level gauge installed, varied with the distance from a check point and was from 0.5 to 1.4 cm. This value includes the accuracy of the reference point location.

Solution Slab Thickness:

The solution level in the slab tank was initially read from a sight gauge. The sight gauge was correlated to centimeter marks on a strip of stainless steel in the tank. The method has meniscus problems and an accuracy of ±0.2 cm on readings. A ruler was installed permitting a reading accuracy of 0.05 cm. The ruler was used for the remainder of the measurements, by mounting it in the slab tank for the convenience of lighting and viewing through remote TV. To correlate the average slab bottom with the ruler, one centimeter of uranyl nitrate solution was pumped into the slab. Then using another ruler, the depth of solution was measured. Twenty-five depths were measured at evenly spaced locations over the slab. The variation in depth was a measure of the departure of the slab bottom from a horizontal plane. The reading accuracy of these measurements was 0.05 cm.

The height of the slab-bottom supports was varied with shims, until the maximum tip of the slab, any side to the opposite, was 0.05 cm. Then 25 solution-depth measurements were taken to obtain a correlation of the average slab bottom to the ruler.

With 1.00 cm on the slab ruler, the average solution depth read 1.15 cm, giving a correction for slab-ruler readings of +0.15 cm for the value of the average slab bottom. Maximum deviation from a horizontal plane was 0.15 cm and average deviation, ±0.07 cm. The average slab bottom was used as the reference point for all reported slab thicknesses.

During the experiment, the slab mounting had to be disturbed three times. The slab reference-point measurement was taken after each new setup. The ruler corrections obtained were +0.15, +0.13, and +0.17 cm. The average and maximum deviation from the horzontal did not change significantly.

The accuracy of obtaining the average slab bottom was estimated to be ±0.05 cm.

Some distortion in the slab bottom must occur as the cylinders in the array are filled during an experiment. The distortion was considered as extremely small since the slab bottom measured 0.635 cm thick and the maximum unsupported distance across the slab was 30.0 cm.

Evaporation Losses:

During each experimental measurement, the slab tank was exposed to the atmosphere. The tank was difficult to drain completely. Consequently, the solution evaporated to some extent during the seven months of experimentation. The evaporation of the solution caused some precipitation which collected on the slab-tank bottom. Frequently, the precipitate in the tank was cleaned and an estimate made of the uranium loss. The rate of loss of solution volume from the storage tanks gave a better measure of the amount of precipitation.

The precipitation in the slab and the change in solution properties did produce small effects on the data. The magnitude of these effects was measured directly by a series of 8 critical slab-thickness measurements over the course of the test.

The effect of the precipitation in the slab tank was determined by obtaining critical slab heights with a clean tank and with a large amount of precipitate in the tank. Two pairs of measurements were made. For each pair, the measured difference was less than 0.05 cm.

The change in the physical properties of the solution over the seven months was more significant than the effect of the presence of the precipitate. The average of two early slab-thickness measurements was 12.7 (±0.3 cm on each measurement), and the average of three measurements toward the end was 13.0 (±0.2 cm on each measurement). The difference between the two average values is overlapped by the experimental accuracy, hence the total difference on slab thickness because of solution property changes was probably about 0.3 cm.

[4] The quoted uncertainties are for the two-sigma confidence levels.

A total of 8 critical slab measurements were taken. The average of the values was 12.8 cm The range of the measured values over the period of the experiment was ±0.2 cm. Since the 12.8-cm value came within 2 percent of any measured value, it was used for all data analysis.

The day-by-day storage tank solution-volume loss provided a good measure of the rate of precipitation as a function of time. The loss rate and the above data were used to determine the solution properties over the period of experimentation. This, and one measurement of concentration at the end, represent the basis for the concentrations reported in the data tables. The estimated accuracy was ±2 percent (±10 grams per liter) for concentration, ±4 percent for density, and ±20 percent for normality.

The ambient temperature of the experimental area during the experiment was 25 °C ±4.

Techniques:

Seven configurations were taken to delayed critical at the beginning of the experimental work. The greatest difference between an extrapolated critical-slab thickness, with a maximum indicated multiplication greater than 100, and the achieved critical height was 0.05 cm. Since this worked so well, the remaining measurements were extrapolated [multiplication (M) >100]. Three more critical measurements made during the course of the work checked the extrapolations.

Thus, the estimated accuracy for the 11.0-cm diameter cylinders equals ±0.3 cm on slab thickness and ±3.0 cm on array height. The estimated accuracies for the 13.6, 16.3, and 21.3 cm (except single 21.3-cm diameter cylinder array) diameter cylinder would be ±0.2-cm slab thickness and ±3.0 cm on array height. The estimated accuracies for single 21.3-cm diameter cylinder were ±0.2 cm on slab thickness and ±5.0 cm on cylinder height. The estimated accuracies for the single 22.4, 22.9, 23.4, and 23.9-cm diameter cylinders were ±0.2 cm on slab thickness and ±2.0 cm on cylinder height.

MEASUREMENTS, ANALYSIS, AND DISCUSSION

Slab-Cylinder Systems With Minimum Reflection:

Measurements of the critical slab thickness with minimum reflector[5] as a function of the solution height in the array have been made for: (1) slab plus 1-, 4-, 9-, or 16-cylinder arrays with cylinder diameters of 11.0, 16.3, and 21.3 cm; (2) slab plus sixteen 13.6-cm diameter cylinders in the array; (3) slab plus single cylinder having diameters of 22.4, and 23.9 cm; and (4) slab plus single cylinders of diameters 22.4 and 22.9 cm, which were essentially infinite height. These measurements, along with the uranyl nitrate concentrations, are given in Table III and are plotted in Figures 3, 4, 5, and 6 and represent the basis for all further data anaylsis.

These data can be made more useful by presentation in a form which allows easy, accurate interpolation between the experimental data points. For example, proceed by empirically fitting an equilateral hyperbola to each experimental data curve of critical slab thickness and array-cylinder diameter at various heights and number of cylinders. These series of hyperbolas provide accurate extrapolations for the zero-slab condition. The zero-slab condition is a series of critical arrays at different heights in terms of the individual array-cylinder diameter.

These curves may be empirically fitted to a mathematical equation for easy and accurate interpolation. The equilateral hyperbola equation follows:

$$(x - x_0)(y - y_0) = k \qquad (1)$$

Equation 1 was chosen since it is simple, fits the data, has two interpretable asymptotes, and has been used in previous studies.[6,7]

Plotting the data from Figures 3, 4, and 5 as critical slab thickness versus diameter of cylinders in array at 78, 47, and 26-cm solution height produces a hyperbolic curve Its orthogonal asymptotes are (1) critical slab thickness (T), (12.8cm) with no array, and (2) diameter (D_0) of the cylinders when the array alone is critical. Thus, Equation No. 2 is:

$$(T - 12.8)(D - D_0) = C_{TD} \qquad (2)$$

The hyperbola curvature, C_{TD}, and the diameter, D_0, of each cylinder in the critical array with no slab are given

[5] *Minimum Reflector* refers to the system with only the unavoidable reflection of the experimental fixtures and floors and walls of the experimental area.

[6] C. L. Schuske and J. W. Morfitt. *An Empirical Study of Some Critical Mass Data.* Y-533. Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee. December 6, 1949.

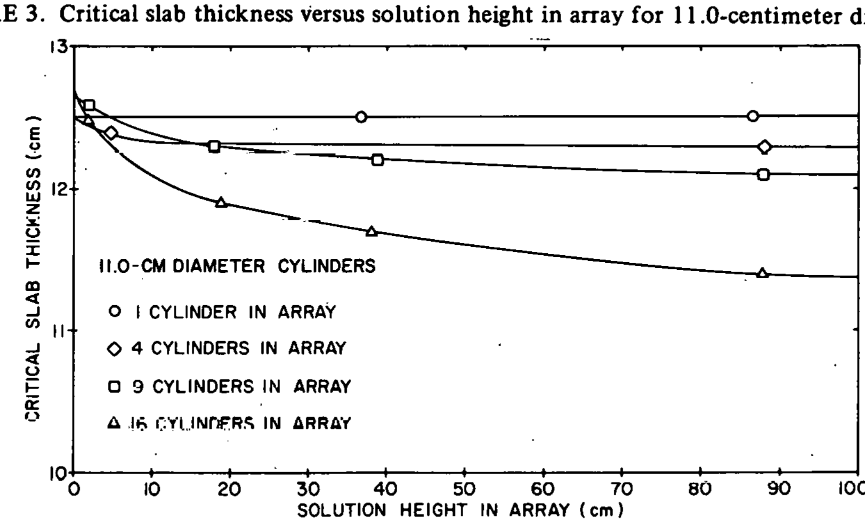
[7] C. L. Schuske, B. B. Ernst, and H. W. King. *Empirical Analysis of Critical Bare Arrays of Cylinders Containing Enriched $UO_2(NO_3)_2$.* RFP-315. Rocky Flats Division, The Dow Chemical Company, Golden, Colorado. May 29, 1963.

TABLE III. Experimental data for critical slab-array configuration with minimum reflector.

Cylinder Diameter [a](cm)	Array Configuration Number of Cylinders	Slab Thickness (cm)	[b]Array Height (cm)	Uranium Concentration (grams per liter)
11.0	1	12.6	87	465
		12.6	37	
	4	12.3	88	465
		12.4	5	
		12.5	0	
	9	12.1	88	465
		12.2	39	
		12.3	18	
		12.6	2	
	16	11.4	88	465
		11.7	38	
		11.9	19	
		12.5	2	
		12.7	0	
13.6	16	10.0	108	520
		10.4	69	
		11.3	26	
		12.3	4	
16.3	1	12.2	88	470
		12.2	40	
		12.3	19	
		12.3	14	
		12.5	6	
	4	12.0	88	480
		12.2	25	
		12.3	12	
		12.6	1	
	9	10.5	90	485
		11.0	40	
		11.8	14	
		12.4	3	
		12.7	0	
	16	0	78	495
		2.6	64	
16.3	16	5.5	50	495
		7.7	37	
		10.0	20	
		11.4	8	
		12.4	3	
		12.6	0	
21.3	1	11.1	88	500
		11.1	39	
		12.4	3	
	4	8.8	91	500
		10.1	39	
		11.0	19	
		11.8	10	
		12.7	2	
	9	0	47	500
		1.5	43	
		5.9	32	
		8.6	23	
		10.0	15	
		11.6	7	
		12.7	1	
	16	0	26	500
		2.7	22	
		7.5	14	
		9.1	11	
		9.5	9	
		11.8	3	
22.4	1	10.8	108	505
22.9	1	10.1	110	505
23.4	1	8.9	111	525
		10.3	33	
		11.4	15	
23.9	1	0	112	525
		7.7	66	
		9.7	34	
		11.9	8	

[a]cm – Centimeters. [b]Solution height in cylinders of array, measured from top of solution slab.

FIGURE 3. Critical slab thickness versus solution height in array for 11.0-centimeter diameter cylinders.



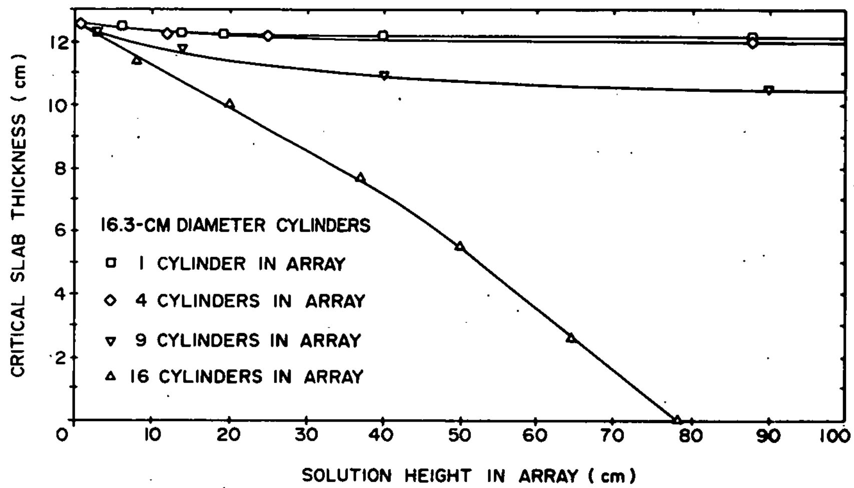


FIGURE 4. Critical slab thickness versus solution height in array for 16.3-centimeter diameter cylinders.

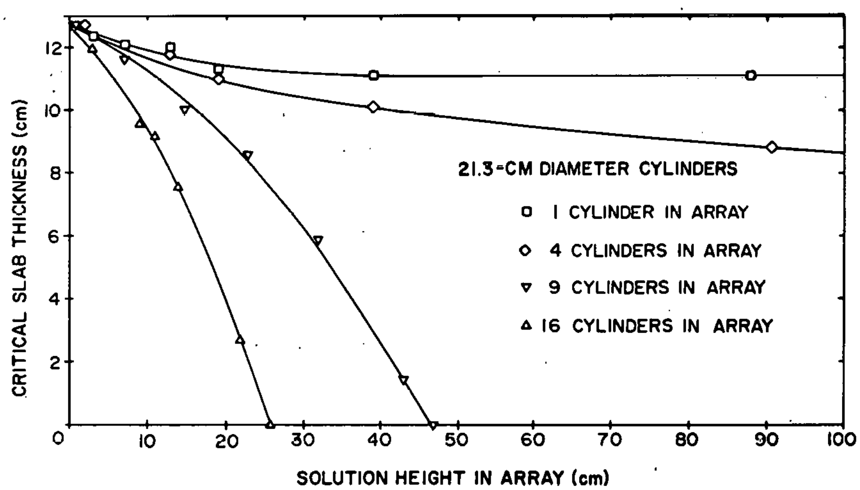


FIGURE 5. Critical slab thickness versus cylinder height in array for 21.3-centimeter diameter cylinders.

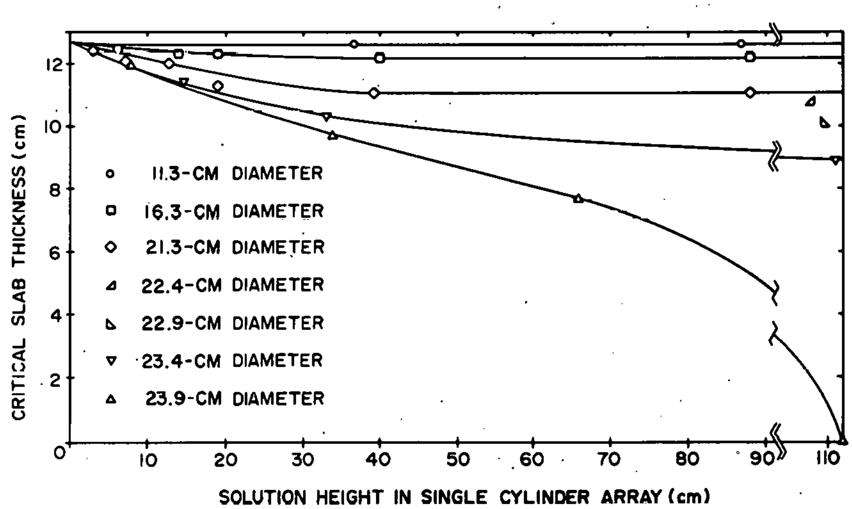


FIGURE 6. Critical slab thickness versus solution height in single cylinder arrays.

in Table IV at various cylinder heights, H. Using these values, Equation 2 is plotted in Figures 7, 8, 9, and 10.

From Figures 7, 8, 9, and 10, note that before the slab thickness is decreased by 5 percent, the diameter of the cylinders in the array must be at least 17, 15, 11, and 5 cm for 1, 4, 9, and 16 cylinders, respectively.

TABLE IV. Constants in Equation No. 2 for critical arrays with minimum reflector.

Number of Cylinders	${}^{a}C_{TD}$ (cm^2)	^{b}Diameter (D_o) (cm)	^{c}Height (H) (cm)
1	5.36	24.7	78
		25.1	48
		26.1	26
4	6.38	23.0	78
		23.6	48
		24.0	26
9	8.18	20.3	78
		^{d}21.3	48
		22.9	26
16	10.56	^{d}16.3	78
		17.4	48
		^{d}21.3	26

${}^{a}C_{TD}$ = Hyperbola curvature.
${}^{b}D_o$ = Diameter of each cylinder in the critical array.
${}^{c}H$ = Solution in the array.
^{d}These are experimental data points. The other values were obtained from Equation 2.

$$(T - 12.8)(D - D_o) = C_{TD}$$

Also from these figures, the diameter D_O, of the critical array alone was plotted against array solution height, H, yielding a hyperbolic curve parametric in the number of cylinders. The two orthogonal asymptotes are (1) the diameter, D_∞, of a critical array at infinite solution height, and (2) a critical slab, 12.8 cm, when the diameter is infinitely large. Thus, Equation 3 includes C_{DH} and D_∞ as given in Table V:

$$(D_O - D_\infty)(H - 12.8) = C_{DH} \qquad (3)$$

Equation 3 was plotted in Figure 11 to show the array alone. In Figures 7 through 11, the open data points are interpolated values from Figures 3, 4, and 5. In Figures 9, 10, and 11, the solid data parts are experimental values.

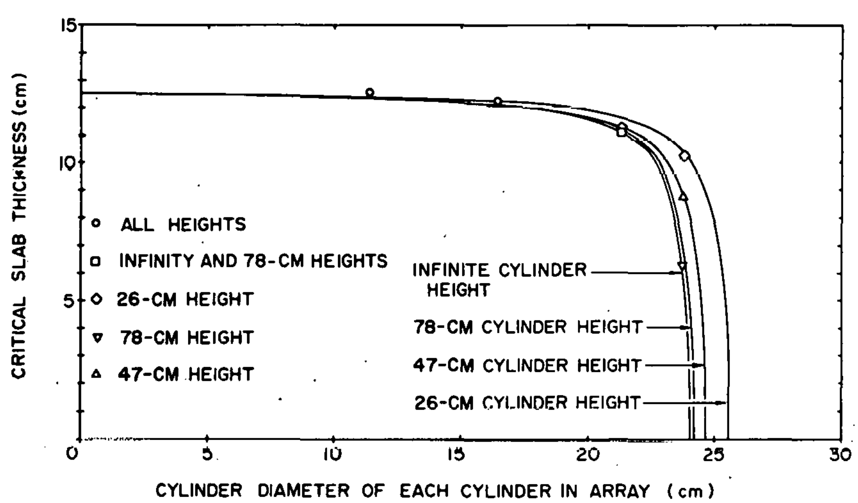
TABLE V. Constants in Equation No. 3 for critical arrays with minimum reflector.

Number of Cylinders	D_∞ (cm)	C_{DH} (cm^2)
1	24.25	30.62
4	22.4	41.80
9	19.3	60.02
16	14.93	86.36

H – Array solution height.
D_O – Diameter of critical array.
D_∞ – Diameter of a critical array at infinite (∞) solution height.
C_{DH} – Hyperbolic curve (parametric).

$$(D_o - D_\infty)(H - 12.8) = C_{DH}$$

FIGURE 7. Slab thickness versus cylinder diameter from hyperbolic fit for one cylinders in the array at various array solution heights.



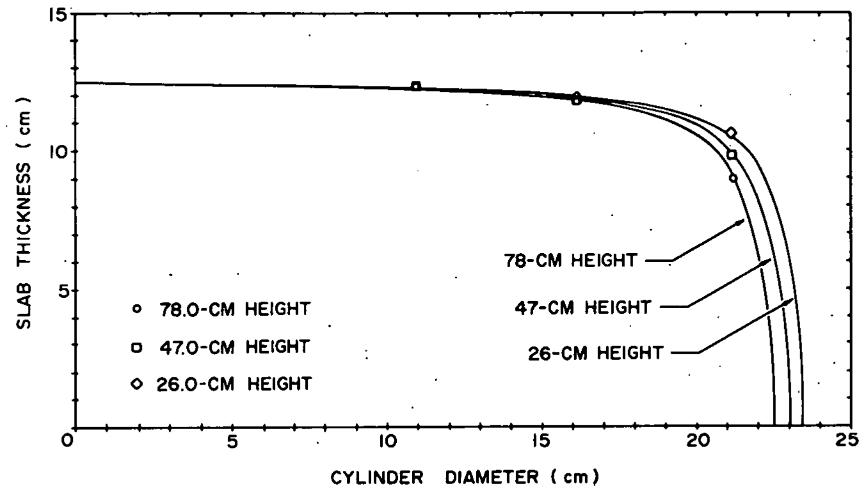


FIGURE 8. Slab thickness versus cylinder diameter from hyperbolic fit for four cylinders in the array at various array solution heights.

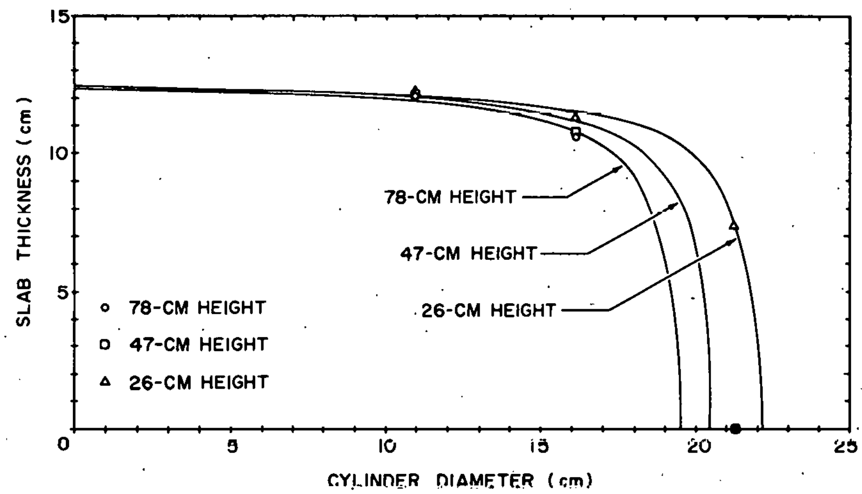


FIGURE 9. Slab thickness versus cylinder diameter from hyperbolic fit for nine cylinders in the array at various array solution heights.

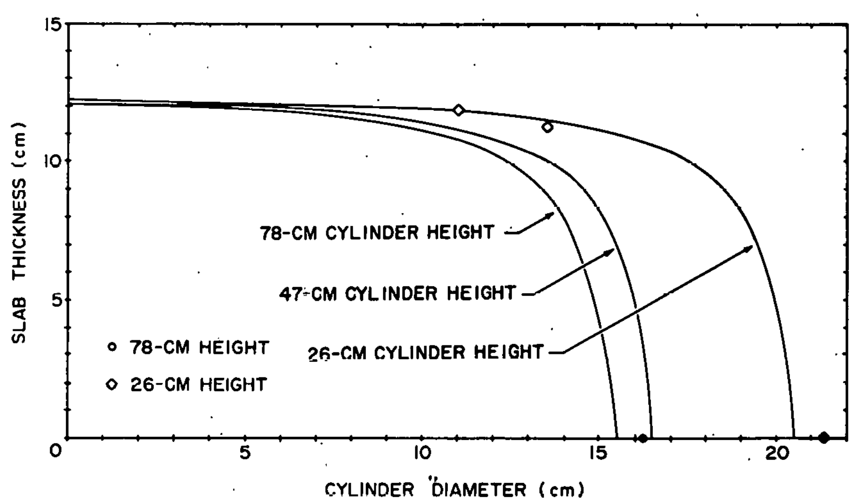


FIGURE 10. Slab thickness versus cylinder diameter from hyperbolic fit for sixteen cylinders in the array at various array solution heights.

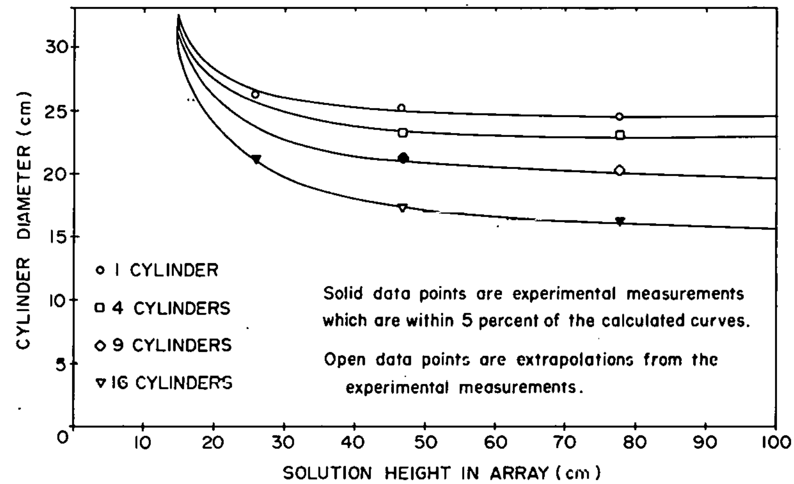


FIGURE 11. Array cylinder diameter versus cylinder height from hyperbolic fit.

EXPERIMENTAL EQUIPMENT EFFECT

A series of measurements of the critical slab thickness with minimum reflection were used to determine the magnitude of the perturbing effect of the experimental equipment. The results of these measurements are summarized in Table VI.

The array cylinders and the fill and drain hoses rested on the slab-tank bottom. To measure the effect of that portion of the experimental equipment which was usually submerged in the slab-tank solution during a measurement, 16 dummy cylinders were fabricated. Each dummy cylinder was 21.34 cm in diameter, and 20 cm high. A vertical slot 0.6 cm wide was cut in the 0.3-cm thick side to allow rapid solution-height equalization during an experimental run. These dummy cylinders and a set of fill and drain hoses were placed in position in the slab tank and a critical slab thickness obtained. The difference in indicated critical heights between this setup and the slab tank alone was less than 0.05 cm (too small to be reliably measured). This measurement made unnecessary any correction for the array hardware immersed in the solution.

The DTF calculations[8] were performed to show how well the 120.7-cm square slab approximates an infinite slab. Comparing the calculated, unreflected, critical infinite slab thickness *to* calculated, unreflected, critical experimental slab thickness (14.43 to 14.66 cm) indicates that the experimental slab is 98 percent of the infinite slab thickness.

[8] B. G. Carlson, W. J. Worlton, W. Guber, and M. Shapiro. *DTF Users Manual,* UNC Physics Mathematics 3321. United Nuclear Corporation, White Plains, New York. Volume I, November 1963. Volume II, May 1964.

TABLE VI. Critical slab thicknesses.

[a]Critical Slab Thickness (centimeters)	[b]Estimated Accuracy (centimeters)	Uranium Concentrations (grams per liter)	Condition of Slab
Slab With Minimum Reflector:			
12.7	±0.3	465	Clean slab tank only.
12.7	±0.3	465	Clean slab tank only.
12.7	±0.3	465	Slab tank plus 16 dummy cylinders and hoses.
12.6	±0.3	465	Clean slab tank only.
12.7	±0.3	465	Slab tank plus 0.5 cm of precipitate.
12.8	±0.2	495	Slab tank plus 1 cm of precipitate.
13.0	±0.2	500	Clean slab tank only.
13.0	±0.2	510	Clean slab tank only.
13.0	±0.2	520	Slab tank including 1 cm of precipitate.
[c]Reflected Slab:			
10.3	±0.2	505	Clean slab tank only.

[a] Includes any precipitate present in the slab tank.
[b] Repeatability of measurements was ±0.1 cm.
[c] Reflected slab tank without cylinders, as shown in Figure 2, Page 2.

Array Spaced above Solution Slab:

Critical slab thicknesses were measured as a function of solution height when the array was spaced above the solution slab by 14.1 and 28.2 cm (±0.4 cm). Because of the fixed spacings, the distances from the top of the slab-tank solution to the array bottom was a function of slab-tank solution thickness. The array consisted of sixteen 16.3-cm diameter cylinders.

The experimental data are noted in Figure 12. Data were derived to show the effect of constant spacing on slab thickness versus array solution height and are given in Figure 13. The critical slab thickness for the zero array height for the spaced array is 12.4 cm. This measured value was lower than the 12.8 cm used previously because of the suspended array hardware reflection. The hardware included approximately 0.25 cm of undrained solution in the array. The 12.4-cm measurement and the previously used 12.8-cm value provide an upper limit of 0.4 cm on slab thickness for the worth of the suspended array as a reflector. The accuracies for these data are:

Figure 12, ±0.2 cm on slab height and ±2.0 cm on array height;
Figure 13, ±0.2, ±0.4, ±0.5, ±0.7 cm on slab thickness, ±3, ±3, ±5, and ±7 cm on array height for the 0, 5, 15, and 25-cm spacings, respectively.

Figure 13 shows that each 5-cm spacing near the midportion of the curves had the same effect as the preceding 5-cm spacing, out to the 25-cm spacing range of the graph. Yet the effect of a 25-cm spacing was approximately 75 percent of the infinite spacing. Hence, the effect of a 5-cm spacing must decrease rapidly within the next 2- or 3.5-cm steps.

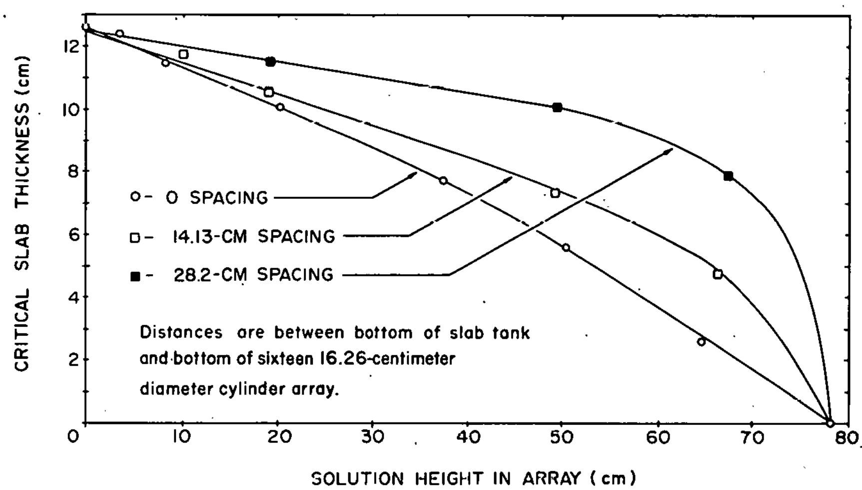
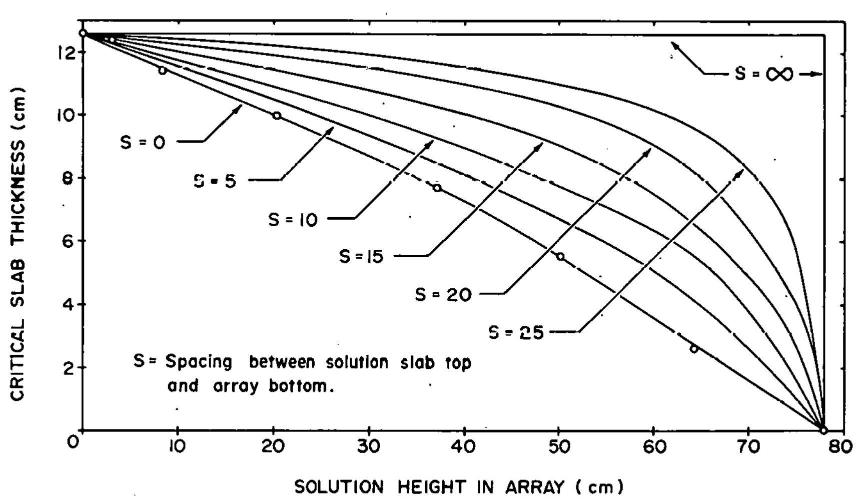


FIGURE 12. Spaced slab-array system experimental data.

FIGURE 13. Slab-array system constant spacing data derived from Figure 12 for sixteen 16.3-centimeter diameter cylinders in the array with minimum reflector.



Observe the regions near the ends of the curves in Figure 13. When most of the system reactivity is in the slab, the effect of spacing on the array height becomes large and vice versa.

Reflected Measurements:

The first series of reflected measurements were slab thickness versus array height for arrays of nine and sixteen 13.6-cm diameter cylinders. The reflector thickness was 10.2 cm. These experimental data are shown in Figure 14. The second series of measurements included slab thickness versus array height for an array of sixteen 13.6-cm diameter cylinders with the side- and top-reflector thickness varied and a constant bottom-reflector thickness of 10.2 cm. These data are shown in Figure 15. All reflected experimental data have been summarized in Table VII.

Note the bend of the high-array height end of the 2.5-cm curve in Figure 15. At this end of the curve, the array solution was approaching the top reflector.

In a third series of measurements, the thickness of the reflector on the slab-tank bottom was varied from 10.2 to 0 cm. This configuration had no top or side reflector. The experimental data are given in Table VII and noted graphically in Figure 16.

TABLE VII. Reflected slab-array critical configuration data. (The array consisted of 13.6-centimeter diameter cylinders.)

Number of Cylinders	Top and Side Reflector Thickness (centimeters)	Slab Tank Bottom-Reflector Thickness (centimeters)	Slab Thickness (centimeters)	[a]Array Height (centimeters)	Uranium Concentration (grams per liter)
9	10.2	10.2	7.1 ±0.2	112 ±1	505
			8.8 ±0.2	42 ±1	
			9.5 ±0.2	20 ±1	
			[b]10.3 ±0.2	0 ±0	
16	10.2	10.2	0 ±0.2	92 ±1	505
			3.8 ±0.2	61 ±4	
			8.1 ±0.2	26 ±1	
			[b]10.3 ±0.2	0 ±0	
16	7.6	10.2	0 ±0.5	96 ±1	510
			4.7 ±0.2	59 ±2	
			7.9 ±0.2	26 ±2	
			10.5 ±0.2	0 ±2	
16	5.1	10.2	0 ±0.5	105 ±1	510
			3.4 ±0.2	75 ±1	
			7.4 ±0.2	36 ±1	
			10.6 ±0.2	2 ±1	
16	2.5	10.2	0 ±0.5	[c]149	515
			3.3 ±0.2	114 ±1	
			6.0 ±0.2	72 ±1	
			8.6 ±0.2	30 ±1	
			9.8 ±0.2	9 ±1	
16	0	10.2	8.3 ±0.2	110.0 ±0.6	515
			8.7 ±0.2	67.5 ±0.6	
			9.6 ±0.2	27.5 ±0.6	
16	0	5.1	8.7 ±0.2	109.0 ±0.5	515
			9.0 ±0.2	69.5 ±0.5	
			9.9 ±0.2	26.0 ±0.5	
			11.0 ±0.2	7.5 ±0.5	
16	0	0	10.0 ±0.2	108 ±1	520
			10.4 ±0.2	69 ±1	
			11.3 ±0.2	26 ±1	
			12.3 ±0.2	4 ±1	

[a]Array height measured from top surface of solution in slab.
[b]These measurements were made with the slab tank alone.
[c]Extrapolated from a solution height of 120 centimeters.

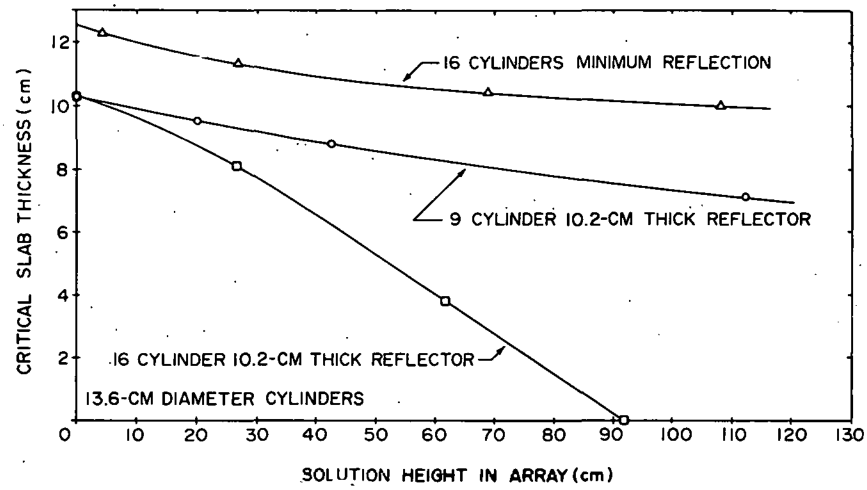


FIGURE 14. Reflected and unreflected slab-array data for constant reflector thickness for sixteen 13.6-centimeter diameter cylinders in the array.

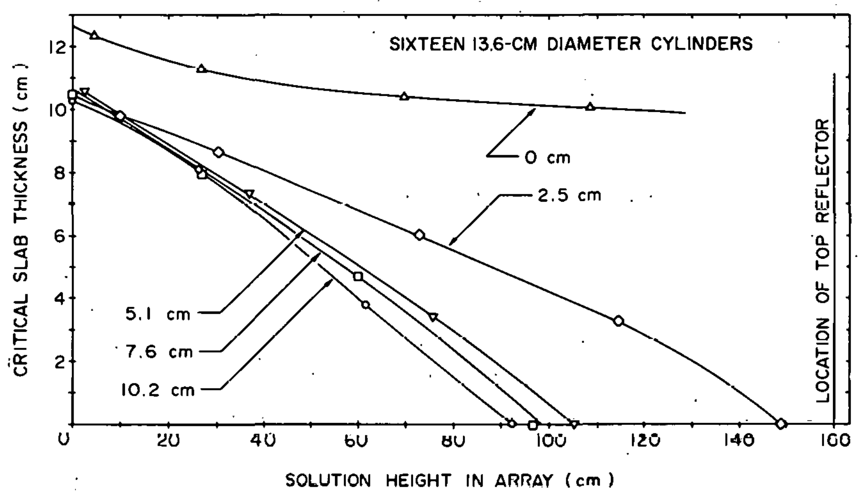


FIGURE 15. Reflected slab-array data with varied reflector thickness for sixteen 13.6-centimeter diameter cylinders in the array.

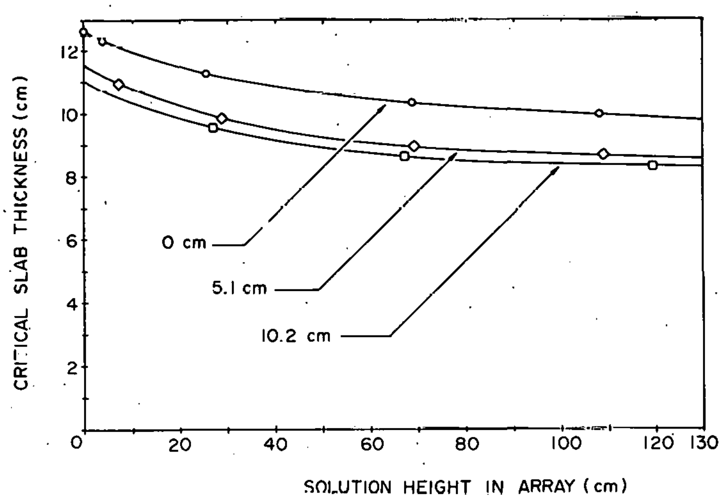


FIGURE 16. Slab-array configuration data with varied bottom reflector thicknesses.

The curves, in Figure 16, for the different bottom-reflector thicknesses are parallel within experimental accuracy. Therefore, the reflector savings because of the bottom reflector are independent of the solution height of the array and effect only the critical slab thickness. Therefore, to convert to a system with a constant thickness of Plexiglas on all six sides, the corresponding reflector savings because of the outer reflector layers on the slab-tank bottom should be added, pointwise, to the experimental data. As an example of this conversion, consider the 5.1-cm curve of Figure 17. The curve was obtained by adding 0.4 cm to the corresponding points of the 5.1-cm curve of Figure 15. The 0.4-cm value represents the reflection savings because of the outer 5.1 cm of slab-bottom reflector. This was obtained from Figure 18 by subtracting the savings of 5.1-cm thickness (1.3 cm) from the savings of 10.2-cm thickness (1.7 cm).

These reflector savings data at different reflector thicknesses are plotted in Figure 17 in order to determine intermediate values. Using the reflector savings data, the slab-array data of Table VII were converted to constant reflector thickness and then plotted in Figure 19.

These data conversions introduced additional inaccuracies resulting in an estimated accuracy of ±0.4 cm on slab thickness and ±3 cm on array height for the 2.5, 5.1, and 7.6 cm curves. The 10.2- and 0-cm curves required no conversion and have an estimated accuracy of ±0.2 cm on slab thickness and ±2 cm on array height. Note that the effect of the solution in the array approaching the top reflector in the 2.5-cm line may have driven this array critical prior to 160 cm.

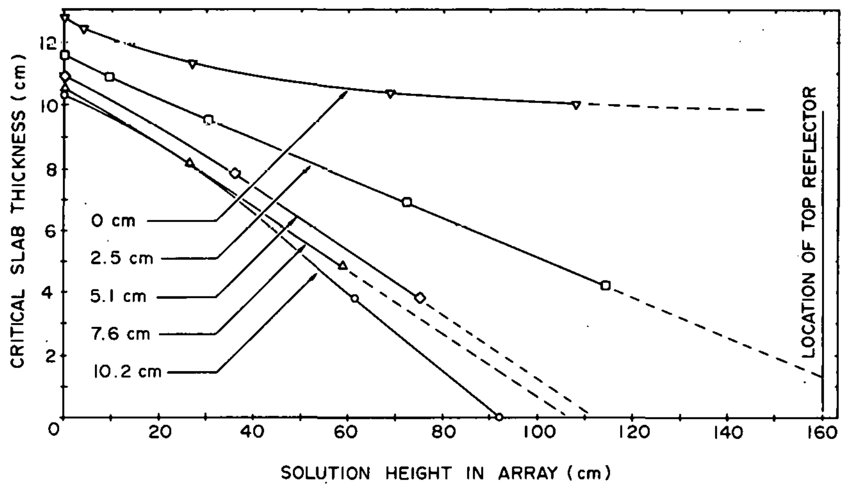
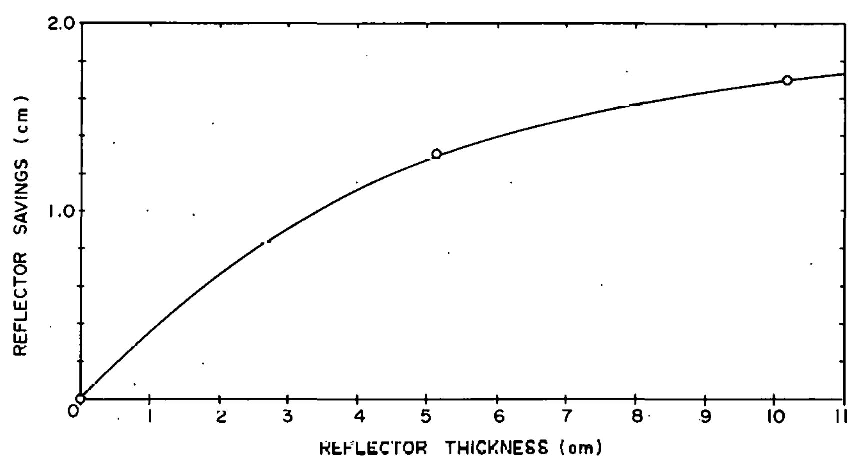


FIGURE 17. Reflected slab-array configuration constant reflector thickness for sixteen 13.6-centimeter diameter cylinders in array.

FIGURE 18. Slab-bottom reflector savings versus reflector thickness.



The dashed lines in Figure 17 are extrapolations to a zero-slab thickness which represent an array resting on the 0.635-cm steel bottom of the slab tank and reflected by Plexiglas of the same thickness on all sides, top and bottom. Using these extrapolated array values and the measured values for the array with a constant bottom-reflector thickness from Figure 15, the critical height of the array as a function of the reflector thickness was graphed as Figure 19. The lower curve is ±2 cm, while the upper curve being obtained from longer extrapolations is estimated to be −5, +10 cm for the region above a 5-cm reflector thickness.

For nuclear safety work, it is convenient to have the reflector savings in terms of the diameter of the cylinders in the array. In the experimental measurements, the critical array height, with a 10.2-cm thick reflector, was 92 cm, leaving 68 cm between the array top and the top reflector. An upper limit for the reflector savings of the top reflector alone is $\frac{1}{6}$ the total reflector savings. Hence, if the top reflector had been in contact with the top of the array solution for the measurement, the array would have been critical at not less than $\frac{5}{6}$ of the height measured in the actual experiment or 78 cm. (Refer to the point in Figure 19 labelled *upper limit for reflector savings.*) Therefore, the critical height of the fully reflected array with the top reflector in contact with the top of the reflector solution is between 78 and 92 cm or 85 cm ±7. Using Equation 3, Page 7, the calculated cylinder diameter for a minimum reflected 16-cylinder array at a solution height of 85 cm is 16.2 cm. This is supported by the sixteen 16.3-cm diameter cylinder array experimental measurement shown in Figure 19.

By comparison of minimum-reflection calculated critical-array diameter (16.2 cm) with the same critical system with 10.2 cm of reflector (13.6-cm diameter), one can see that the reflector savings are 2.5 cm on array cylinder diameter for an approximately equilateral array. In using the 2.5-cm cylinder diameter decrease, for criticality purposes, caution must be exercised. This value assumed a boxlike reflector geometry, had stainless steel inside the bottom reflector, and its accuracy was ±10 percent on the cylinder diameter decrease.

The critical thickness of the slab tank with no array and 10.2 cm of reflector on all sides, top, and bottom was 10.3 cm. The minimum-reflector critical slab thickness was 12.8 cm. These two values gave a slab-reflector savings of 2.5 cm for the total reflector unit of Figure 2. The slab reflector savings because of the part of the reflector *box* above the slab thus becomes 2.5 − 1.7 = 0.8.

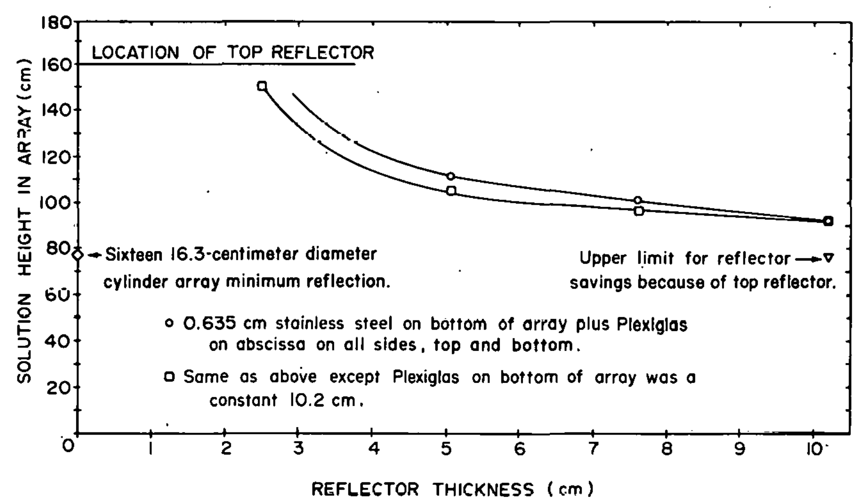
Passthrough Measurements:

In order to simulate passing a container of fissile material through a loaded dry box, measurements were made of critical array heights with and without 3 liters of uranyl nitrate near the array center. The sixteen 13.6-cm diameter cylinder array was reflected by 10.2-cm thick Plexiglas reflector (see Figure 2). The array base was 104 cm, outside edge to outside edge.

Figure 20 locates the solution bottles in the array. The bottle bottoms were 35.7 cm above the array bottom and approximately in the vertical center of the array. The polyethylene bottles were 11.4-cm outside diameter, 22.9 cm high, 0.08-cm thick walled, and each contained 2.0 liters of solution.

The critical array heights were 88 cm ±1 and 92 cm ±1 with and without the two solution bottles, respectively.

FIGURE 19. Critical array height versus reflector thickness for array of sixteen 13.6-diameter cylinders.



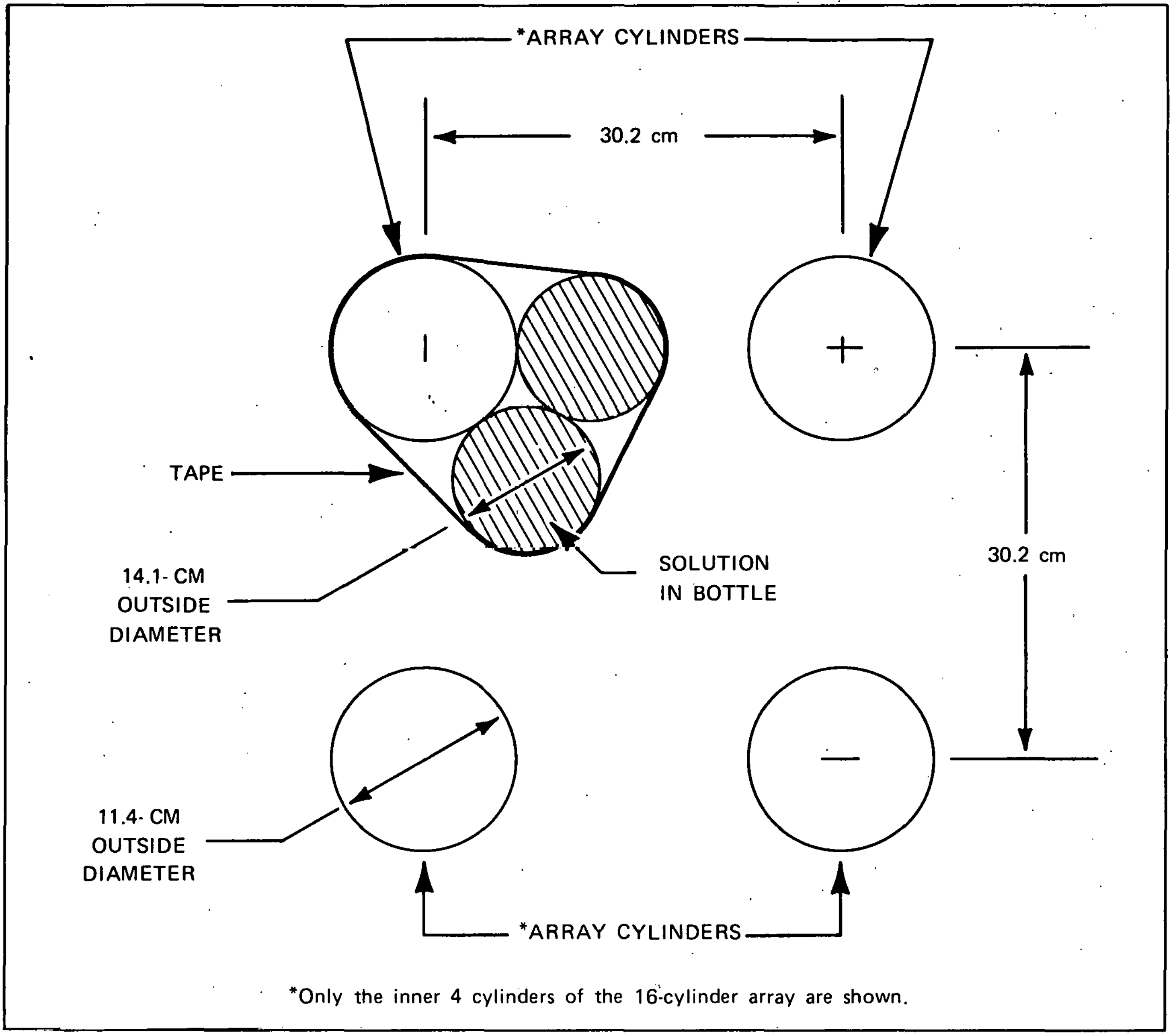


FIGURE 20. Placement of solution bottles in array.

In this situation, the 3 liters were worth 4 cm of array height (or 4.5 percent). The 4-cm array height decrease is equivalent to removing 9.3 liters from the top of the array and inserting 3 liters near the center of the array.

CONCLUSIONS

The 11.0-cm diameter cylinders in the unreflected array had little effect on the solution slab. If the array solution height were 100 cm, the change in solution slab thickness would be less than 2 percent with one cylinder and less than 10 percent with sixteen cylinders in the array. The data also indicate that if the solution slab thickness were decreased by 5 percent, then the cylinder diameter must be at least 17.0, 15.0, 11.0, and 5.0 cm for 1, 4, 9, and 16 cylinders respectively in the array.

When the array was externally reflected by a Plexiglas 10.2-cm thick, boxlike reflector (see Figure 2), the cylinder diameter in the sixteen-cylinder array was decreased by 2.5 cm. Also in a reflected array, if 9.3 liters of solution are removed from the top of the array (when the array height is 92.0 cm), then the system may again be made critical by inserting 4 liters of solution near the array center.