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CRITICAL EXPERIMENTS WITH  $UF_6$  CYLINDER  
MODEL 8A CONTAINERS

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**UNION  
CARBIDE**

OAK RIDGE Y-12 PLANT  
OAK RIDGE, TENNESSEE

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CRITICAL EXPERIMENTS WITH UF<sub>6</sub> CYLINDER MODEL 8A CONTAINERS

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## CRITICAL EXPERIMENTS WITH $UF_6$ CYLINDER MODEL 8A CONTAINERS

J. T. Thomas

### ABSTRACT

Some critical conditions were measured for  $U(97.7)F_6$  contained in Model 8A shipping containers. As many as 16 cylinders were available and were arranged in a number of arrays under various reflector conditions. Polyethylene and concrete were utilized as the reflector materials and Plexiglas was used as an hydrogenous material interspersed between the cylinders in a few experiments. Among the many experiments with and perturbations to the critical arrays are several demonstrating neutron coupling between two arrays through a 50.8-cm thickness of concrete.

## INTRODUCTION

The U.S. AEC has recently evaluated the anticipated need for shipping containers for highly enriched uranium. In view of the expected growth in gas cooled reactors, the number of shipping containers is expected to increase rapidly. At present, highly enriched uranium is shipped in 5-in.-diam cylinders, each containing a maximum of 55 lbs of  $UF_6$ . It would be desirable to be able to use larger shipping containers and thereby reduce the number of containers required. The 8-in.-diam "UF<sub>6</sub> Model 8A" container which could be loaded with a maximum of ~250 lbs of  $UF_6$  has been considered. The nuclear criticality safety of the Model 8A container had been evaluated by calculational techniques. In view of the possible increased container demand, it was felt desirable to conduct critical experiments with Model 8A cylinders containing highly enriched uranium to validate the available calculations. The experiments reported were conducted to serve this purpose. In addition, measured perturbations were introduced in several critical arrays to permit confirmation of neutronics calculations involving concrete as both a reflector and a separator of fissile materials.

## MATERIAL AND EQUIPMENT

The fissile material was  $UF_6$  contained in a 20.3-cm-ID cylinder having a 4.8-mm wall thickness, a height of 1.25 m, fabricated of Monel steel and designated<sup>(1)</sup> as a "UF<sub>6</sub> Cylinder Model 8A." A copy of a drawing (ORGDP No. D-P-35721BR1) showing typical dimensions as well as the details of a protective cylindrical skirt welded to the top and bottom of the cylinders is given in the appendix.

The isotopic analysis of the uranium is given in Table 1. The hydrogen-to-uranium atomic ratio of the material did not exceed 0.088.

Sixteen cylinders were available for this series of experiments. Each was X-rayed to determine the height of  $UF_6$  in the cylinder. The height of  $UF_6$  in a cylinder, as given in Table 2, was averaged from several independent readings of an X-ray. These measured heights

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1. "Uranium Hexafluoride Handling Procedures and Container Criteria," ORO-651, Rev. 3, U.S. AEC, Oak Ridge Operations Office (1972).

Table 1. Uranium Isotopic Analysis.

<u>Isotope</u>	<u>wt %</u>
234	0.77
235	97.66
236	0.23
238	1.34

permitted calculation of the volume of UF<sub>6</sub> which with the weighed mass of UF<sub>6</sub> for each cylinder were used to calculate the density of UF<sub>6</sub> for each cylinder as shown in Table 2. Each cylinder was uniquely identified by a number shown in Table 2. These numbers were used to identify the composition and array of the various experimental assemblies.

Table 2. Description of UF<sub>6</sub> Cylinders.

<u>Cylinder Number<sup>a</sup></u>	<u>UF<sub>6</sub> Mass (kg)</u>	<u>Average<sup>b</sup> Height (cm)</u>	<u>Calculated Density (g UF<sub>6</sub>/cm<sup>3</sup>)</u>
460	108.024	72.4	4.60
494	110.178	74.4	4.57
453	111.562	76.0	4.53
451	110.904	79.0	4.33
439	110.904	79.0	4.33
483	110.043	80.3	4.23
437	110.610	81.0	4.21
475	111.313	83.8	4.13
351	111.494	83.8	4.10
438	111.993	85.3	4.05
492	109.589	83.8	4.03
491	110.178	84.6	4.02
468	112.242	89.9	3.85
423	113.353	98.8	3.54
485	110.451	98.0	3.47
462	109.884	103.1	3.28

a. The average tare weight of the cylinders was  $45.4 \pm 0.2$  kg.

b. Height value is the average of 5 readings of X-rays. Density calculated from mass of UF<sub>6</sub>, height, and assumed uniform inside diameter of 20.3 cm.

The split table apparatus<sup>(2)</sup> located in the South Experiment Area of the CEF was used in this series of experiments. The table top measures 1.8 x 3.0 m at closure and is of 2.5-cm-thick steel. The reflector materials utilized were polyethylene at a density of 0.92 g/cm<sup>3</sup> and concrete shielding blocks at an average density of 2.15 g/cm<sup>3</sup>. The chemical and spectrographic analyses of the concrete is given in Table 3. Plexiglas at a density of 1.18 g/cm<sup>3</sup> was used as a neutron energy moderating material in a few experiments. The polyethylene and Plexiglas did not contain significant impurities. The location of the side reflector was

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Table 3. Chemical and Spectrographical Analysis of Concrete.<sup>a</sup>

Element	Atom Densities (cm <sup>-3</sup> )	Element	Atom Densities (cm <sup>-3</sup> )
H	4.24 x 10 <sup>21</sup>	Cl	1.90 x 10 <sup>19</sup>
C	1.13 x 10 <sup>22</sup>	K	3.11 x 10 <sup>20</sup>
O	4.02 x 10 <sup>22</sup>	Ca	7.27 x 10 <sup>21</sup>
Na	7.9 x 10 <sup>19</sup>	Ti	4.0 x 10 <sup>19</sup>
Mg	4.99 x 10 <sup>21</sup>	Mn	1.2 x 10 <sup>19</sup>
Al	3.75 x 10 <sup>20</sup>	Fe	1.29 x 10 <sup>20</sup>
Si	1.93 x 10 <sup>21</sup>	Sr	8.9 x 10 <sup>18</sup>
S	1.00 x 10 <sup>20</sup>	Ba	3.9 x 10 <sup>18</sup>

a. Concrete shielding blocks, 10.2 x 20.3 x 40.6 cm, at a density of 2.15 g/cm<sup>3</sup>.

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at the cell boundaries defined by the center separation of the cylinders unless described otherwise. The given center separation of cylinders are averaged values and were known to within  $\pm 0.04$  cm.

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2. E. R. Rohrer, W. C. Tunnell, and D. W. Magnuson, "New Critical Experiment Machines," Neutron Phys. Div. Ann. Prog. Rept. Oct. 31, 1961, ORNL-4193, p. 168, Oak Ridge National Laboratory (1961).

## EXPERIMENTAL PROGRAM AND RESULTS

Initial attempts to define a critical configuration were with unreflected linear arrays. The assembly device could accommodate only 13 cylinders in this geometry and criticality was not achieved. A similar assembly, shown in Fig. 1, reflected on the bottom and two sides by 15.2-cm-thick polyethylene was also subcritical. An unreflected assembly utilizing the entire inventory of fissile material arranged as a 2 x 8 array, shown in Fig. 2, was subcritical and evidenced an apparent neutron source multiplication of  $\sim 2$ . The cylinders were in contact in these experiments (center separation of 22.525 cm established by the stabilizing cylindrical metal skirts welded to the top and bottom of the vessel).

Criticality was achieved with an unreflected array of 12 cylinders arranged in the 3 x 4 configuration described in Table 4. The succeeding experiments listed report changes and perturbations performed on the initial arrangement as described in the indexed notes. Experiments 6-10 evidence the influence of the variation in density of  $UF_6$  by the exchanges of cylinders No. 460, 462, 423, and 438. Increased density resulted in increased reactivity even though the mass was slightly decreased.

The experiments with an unreflected 4 x 4 array are summarized in Table 5. This assembly was used to explore the influence of steel thickness as a bottom reflector to the array. The thickness of the table top (2.54 cm) was increased by 0.64 cm and resulted in an increase in reactivity of  $\sim 60$  cents. Experiment 16 was an attempt to reconstruct experiment 14 and illustrates the reproducibility of reassembling an array.

A 2 x 2 array of cylinders in contact, reflected on the bottom and 4 sides by 15.2-cm-thick polyethylene, was subcritical--Experiment 17 of Table 6. Criticality was achieved by the insertion of Plexiglas between the cylinders as described in experiments 19 and 22.



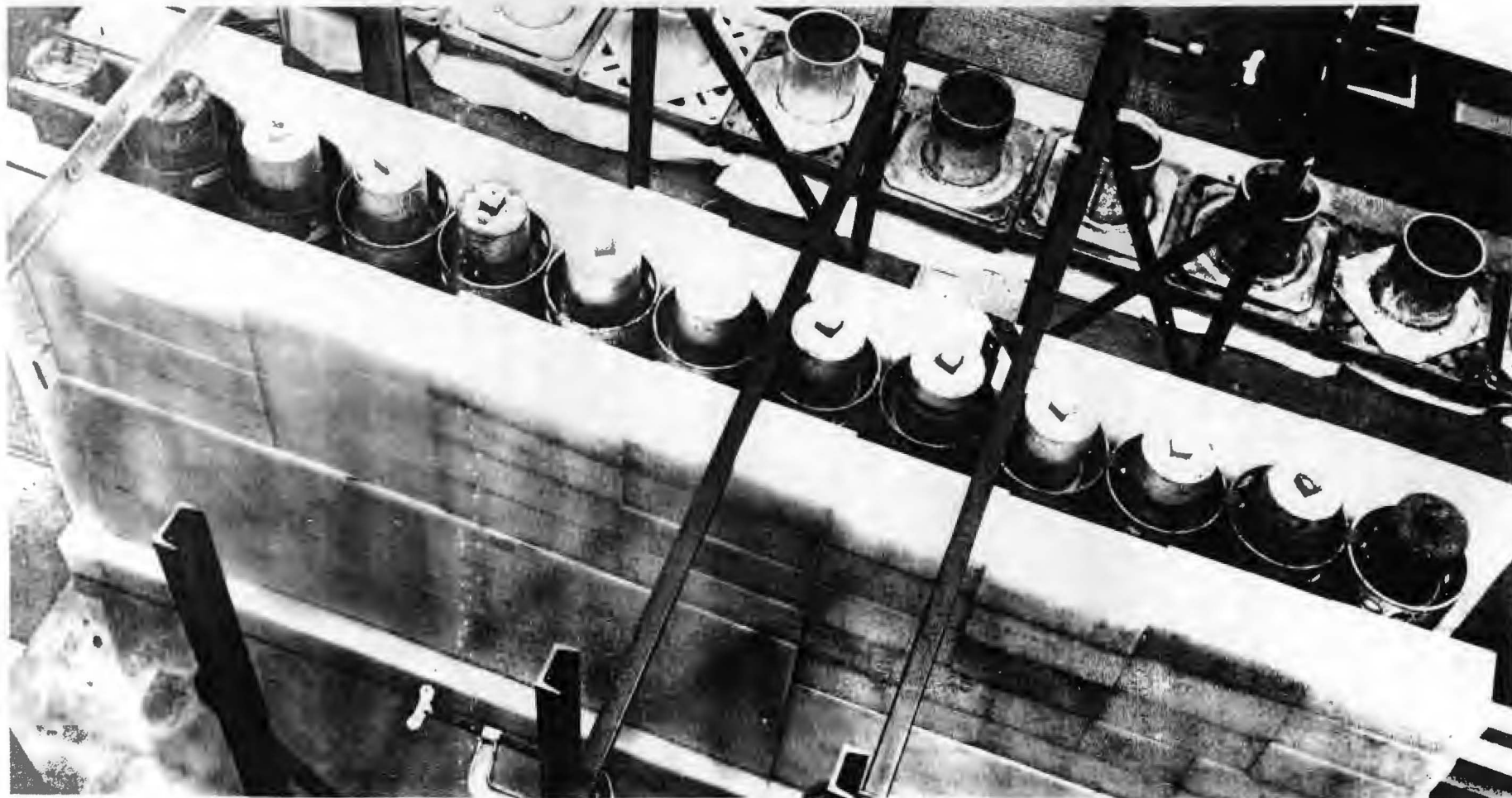


Fig. 1. A Subcritical Linear Configuration of 13 Cylinders Reflected on 3 Sides by 15.2-cm-thick Polyethylene.

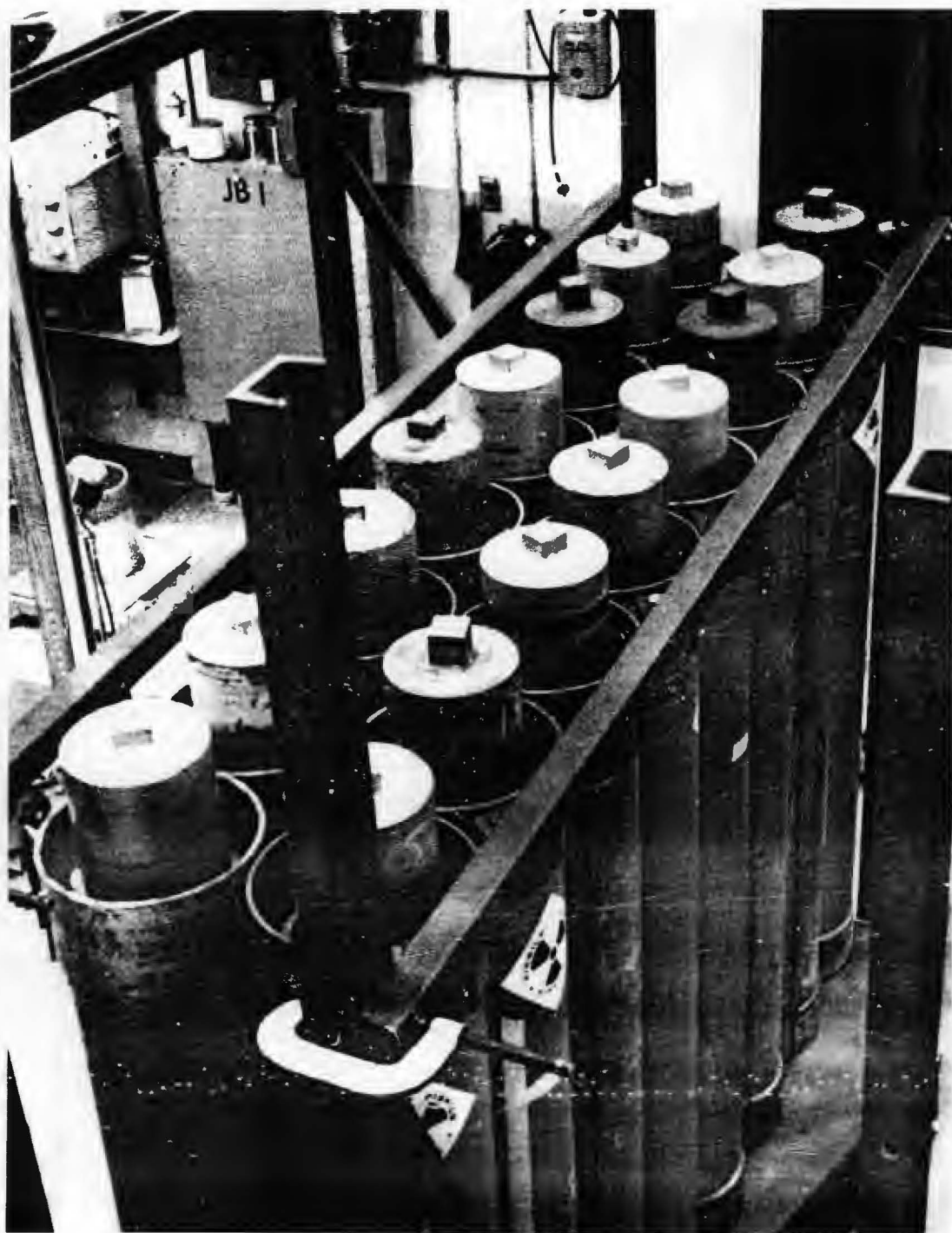


Fig. 2. An Array of 16 Cylinders in an Unreflected 2 x 8 Arrangement.

Table 4. Critical Conditions for an Unreflected 3 x 4 Array of  $U(97.7)F_6$  Cylinders.

		Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
	482	1	22.52	2.56	1
		2	22.68	0.74	-
	468	3	22.73	0.61	-
		4	22.81	0.12	2
		5	22.81	0.19	3
	492	6	22.81	1.01	4
		7	22.81	0.13	5
	438	8	22.81	1.26	6
		9	22.81	1.48	7
		10	22.81	1.21	8

NOTES:

1. The 3 x 3 array was subcritical. Cylinders are in contact in the 3 x 4 array. Assembly is subcritical with Cylinder 494 removed.
2.  $k_{eff}$  of assembly at table closure was 1.0010.
3. Assembly as in Experiment 4. Cylinder realignment performed.  $k_{eff}$  at table closure was 1.0013.
4. Exchanged Cylinder No. 460 for No. 423.
5. Exchanged Cylinder No. 423 for No. 460.  $k_{eff}$  at table closure was 1.0013.
6. Exchanged Cylinders Nos. 438 and 423.
7. Exchanged Cylinder No. 460 for No. 423.
8. Exchanged Cylinder No. 462 for No. 460.

Cylinder No.	Mass	Density
460	108.0	4.60
438	112.0	4.05
423	113.4	3.54
462	109.9	3.28

Table 5. Critical Conditions for an Unreflected 4 x 4 Array of  $U(97.7)F_6$  Cylinders.

				Experiment	Cylinder	Table		
				No.	Center	Separation	Notes	
					Separation	at Critical		
					(cm)	(cm)		
	483	475	494	423	11	24.50	4.10	1
	468	437	351	460	12	24.82	1.16	-
	492	438	453	491	13	24.91	0.88	-
	462	485	439	451	14	24.96	0.34	2
					15	24.96	1.14	3
					16	24.96	0.33	4

NOTES:

1. Assembly is subcritical upon removal of Cylinder No. 423.
2.  $k_{eff}$  of assembly at table closure was 1.0017.
3. Thickness of steel supporting assembly increased from 2.5 to 3.2 cm, i.e., 0.64-cm-thick steel plate added to table top. Reactivity increase to assembly estimated as 60 cents based upon  $\beta_{eff} = 0.0066$ .
4. Steel plate removed and cylinders reassembled,  $k_{eff}$  at table closure was 1.0014. Comparison of Experiments 14 and 16 is measure of reproducibility of assemblies.

Table 6. Critical Conditions for a 2 x 2 Array of U(97.7)F<sub>6</sub> Cylinders Reflected on 5 Sides by 25.3-cm Thickness of Polyethylene and Moderated by Plexiglas.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
17	22.52	--	1
18	23.66	--	2
19	25.05	1.22	3
20	25.61	--	4
21	26.24	--	5
22	25.13	0.59	6

Movable → Stationary

## NOTES:

1. Assembly subcritical. No Plexiglas moderator, cylinder in contact, and close-fitting reflector on 5 sides.
2. Assembly subcritical. Plexiglas thickness was 1.14 cm and cylinders in contact with reflector and Plexiglas. Height of Plexiglas and reflector was 147.3 cm.
3. Plexiglas thickness increased to 2.5 cm. Cylinders in contact with reflector and Plexiglas.
4. Assembly subcritical. Cylinders spaced 0.32 cm from reflector and Plexiglas.
5. Plexiglas thickness increased to 3.1 cm. Assembly subcritical.
6. Plexiglas thickness decreased to 2.5 cm and spaced 0.16 cm from reflector and Plexiglas.

Assemblies of 3 x 3 and 4 x 4 arrays reflected on the bottom and 4 sides by polyethylene are reported in Tables 7 and 8, respectively. The influence of the addition of a top reflector to the 4 x 4 array is evaluated in experiments 28 and 29. Figure 3 is a photograph of experiment 29 showing the movable half of the assembly.

The effect of concrete as a reflector was first explored with a 2 x 2 array in experiment 30, described in Table 9. The assembly was reflected on the bottom and 4 sides by a 20.3-cm thickness and was supercritical with the cylinders in contact. An increase in cylinder center separation resulted in subcriticality. Increasing the reflector thickness on 4 sides to 30.5-cm thickness resulted in criticality and a further increase in reflector thickness to 40.6 cm on 3 sides continued to increase the reactivity of the assembly. The effect of adding a top reflector, 20.3-cm thick, to the three side-reflector conditions was examined. Figure 4 is a photograph of the assembly described in experiment 39. The average  $\text{UF}_6$  density in these arrays was  $3.54 \text{ g/cm}^3$ . The total  $\text{UF}_6$  mass was 445.9 kg.

A second 2 x 2 assembly was constructed having an average  $\text{UF}_6$  density of  $4.15 \text{ g/cm}^3$ . The total mass of  $\text{UF}_6$  was 445.7 kg. These experiments are presented in Table 10. Comparison with the assemblies of Table 9 shows that although the average mass per cylinder is unchanged, the higher  $\text{UF}_6$  density cylinders require an increased center separation.

Table 11 reports experiments performed with a 3 x 3 array reflected by 20.3-cm-thick concrete. In this series of experiments, the effect of a top reflector of intermediate thickness (10.2 cm) was examined.

A linear assembly of 13 cylinders reflected on the bottom by 20.3-cm-thick concrete and on one side by 30.5 cm, shown in Fig. 5, was subcritical. Criticality was achieved by addition of a partial reflector, 20.3-cm thickness, to the second side adjacent to 4 cylinders--experiment 51 of Table 12. The worth of the extreme cylinders was evaluated by their removal from the array. Cylinder No. 453 contributed  $\sim 2$  cents, while Cylinder No. 485 contributed  $\sim 9$  cents.

A linear array of 5 cylinders completely reflected by 20.32-cm-thick concrete is described in experiment 56 of Table 13. A series of

Table 7. Critical Conditions for a 3 x 3 Array of U(97.7)F<sub>6</sub> Cylinders Reflected on 5 Sides by 15.2-cm Thickness of Polyethylene.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
23	23.56	0.56	1
24	24.17	~10.9	2
25	24.84	~ 7.1	-
26	26.09	0.31	3

Movable → Stationary

NOTES:

1. Cylinder No. 483 removed. Reflector at cell boundary, i.e., one-half cylinder surface separation.
2. Assembly as shown, i.e., cylinder No. 483 added.
3.  $k_{eff}$  at table closure was 1.0015. Assembly reflected on 5 sides; height of reflector in Experiments 23-26 was 146.7 cm.

Table 8. Critical Conditions for a 4 x 4 Array of U(97.7)F<sub>6</sub> Cylinders with Various Polyethylene Reflector Conditions.

Experiment No.	Cylinder Center Separation (cm)	Table Separation At Critical (cm)	Notes
27	29.19	0.44	1
28	29.19	0.60	2
29	29.59	0.0	3

NOTES:

1. Assembly reflected on 5 sides by 15.2-cm-thick polyethylene. Height of reflector was 146.7 cm.  $k_{eff}$  of assembly at table closure was 1.0018.
2. Polyethylene reflector, 15.24-cm-thick, placed on top of stationary half of assembly. Reflector height on movable table reduced to 106.0 cm.
3. Assembly reflected on 6 sides. Inside height of reflector cavity was 146.7 cm.  $k_{eff}$  of assembly was 0.9993.



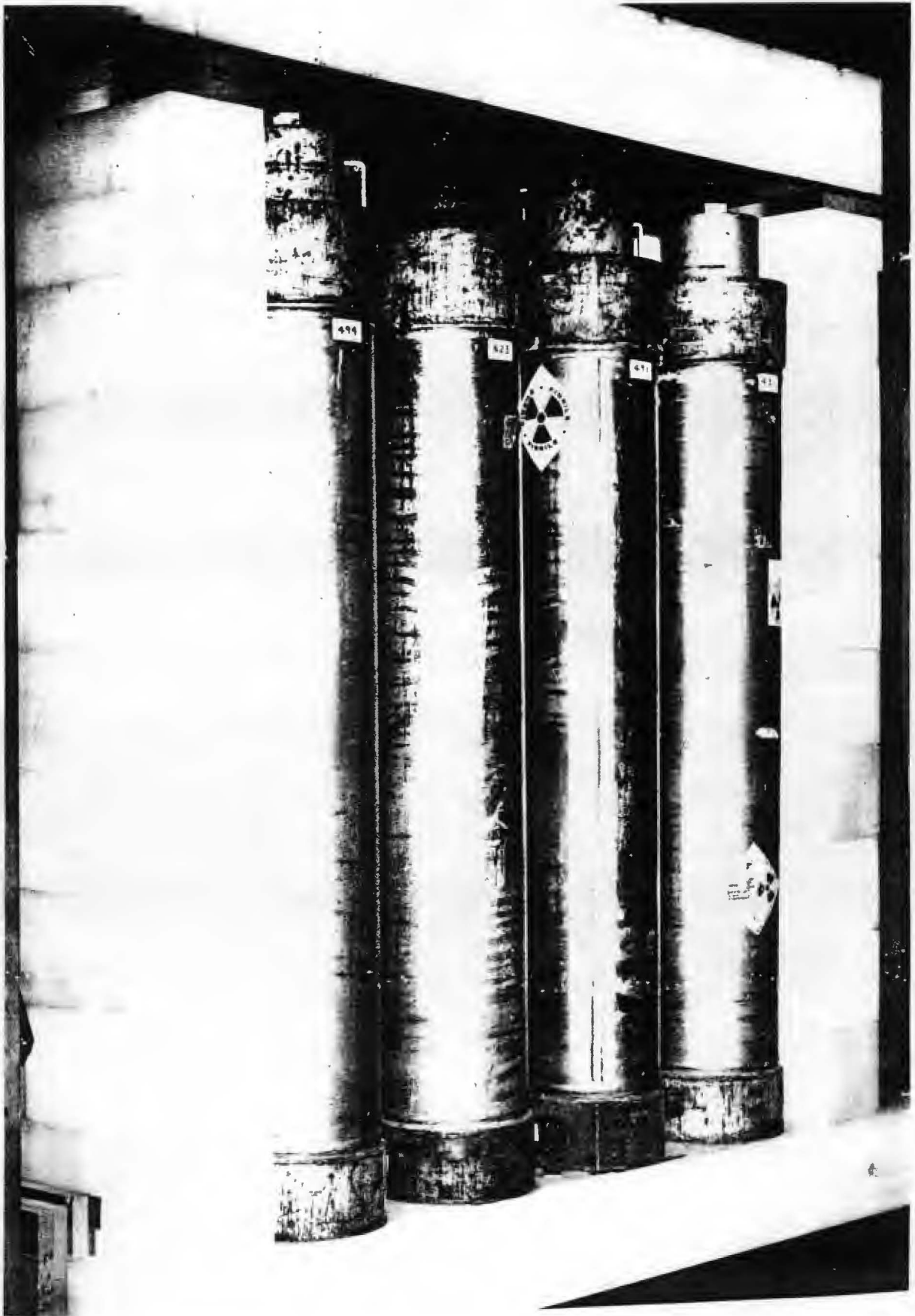
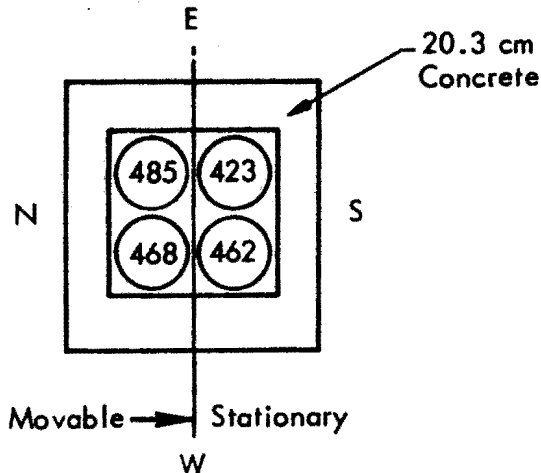


Fig. 3. A View of the Movable Portion of a 15.2-cm-thick Polyethylene Reflected  $4 \times 4$  Critical Assembly.

Table 9. Critical Conditions for a 2 x 2 Array of U(97.7)F<sub>6</sub> Cylinders Reflected on 5 Sides by a 20.3-cm Thickness of Concrete and Complete Reflection.

Experiment No.	Cylinder Center Separation (cm)	Table Separation At Critical (cm)	Notes
30	22.52	0.96	1
31	23.12	--	2
32	23.12	1.52	3
33	23.12	1.86	4
34	23.12	2.01	5
35	23.12	1.65	6
36	22.84	0.18	7
37	22.84	0.12	8
38	22.68	0.54	9
39	22.68	0.62	10



NOTES:

1. Concrete reflector (20.3-cm thickness) on bottom and 4 sides. Reflector height was 147.3 cm.
2. Assembly subcritical.  $k_{eff}$  at table closure  $\approx 0.993$ .
3. Concrete reflector thickness on 4 sides increased to 30.5 cm. Top of array was unreflected.
4. Concrete reflector thickness on 3 sides (N, E, S) increased to 40.6 cm. Top of array was unreflected.  $\Delta k_{eff}$  of perturbation was +0.0022.
5. Add top reflector of concrete 20.3-cm thick.  $\Delta k_{eff}$  of perturbation was + 0.0015.
6. Return concrete reflector thickness on 4 sides to 30.5 cm.  $\Delta k_{eff}$  of top addition to Experiment No. 32 evaluated as +0.0013.
7. Assembly reflected on 6 sides by 20.3-cm-thick concrete.  $k_{eff}$  of assembly at table closure was 1.0013.
8. Remove top reflector,  $k_{eff}$  at table closure was 1.0010.
9. Assembly reflected on 5 sides by 20.3-cm-thick concrete.
10. Add 20.3-cm-thick concrete reflector to top.  $\Delta k_{eff}$  of perturbation was +0.0009.

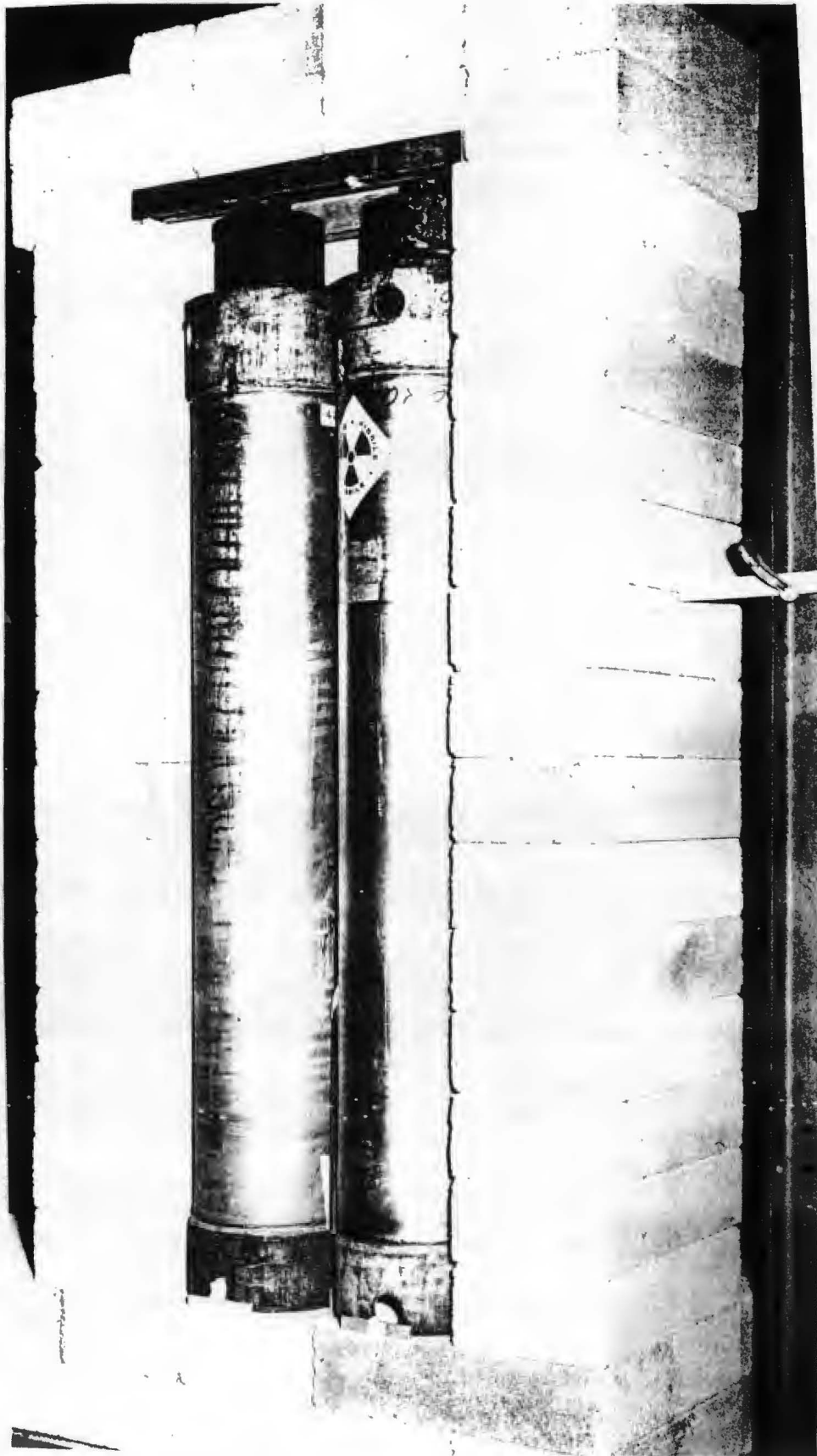


Fig. 4. The Movable Portion of a Critical 2 x 2 Array of Cylinders Reflected by Concrete 20.3-cm Thick.

Table 10. Critical Conditions for a 2 x 2 Array of U(97.7)F<sub>6</sub> Cylinders with Various Concrete Reflector Conditions.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
40	25.70	--	1
41	25.70	1.04	2
42	25.70	1.35	3
43	25.70	1.56	4
44	25.70	1.26	5
45	25.01	--	6
46	25.01	--	7

The diagram shows a 2x2 array of cylinders within a square concrete reflector. The cylinders are labeled 438 (top-left), 475 (top-right), 451 (bottom-left), and 351 (bottom-right). The reflector is labeled 'Concrete' and has cardinal directions N (North), E (East), S (South), and W (West). A 'Movable' arrow points to the West side, and a 'Stationary' arrow points to the East side.

NOTES:

1. Assembly subcritical reflected on bottom and 4 sides by 20.3-cm-thick concrete. Reflector height was 147.3 cm.
2. Assembly reflected on 4 sides by 30.5-cm-thick concrete and on bottom by 20.3-cm thickness.
3. Concrete reflector thickness increased to 40.6 cm on 3 sides (N, E, S) of assembly.  $\Delta k_{eff}$  of perturbation was +0.0021.
4. Add 20.3-cm-thick concrete reflector to top of assembly.  $\Delta k_{eff}$  of top addition +0.0019.
5. Reduced reflector thickness on 4 sides to 30.5 cm. Comparison of Experiments 41 and 44 estimate  $\Delta k_{eff}$  for top reflector as +0.0019.
6. Assembly reflected on 6 sides by 20.3-cm-thick concrete. Assembly subcritical,  $k_{eff} = 0.9987$ .
7. Remove top reflector,  $\Delta k_{eff}$  of perturbation -0.0008.

Table 11. Critical Conditions for a 3 x 3 Array of  $U(97.7)F_6$  Cylinders with Various Concrete Reflector Conditions.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
47	30.78	1.35	1
48	31.18	--	2
49	31.18	2.31	3
50	31.18	1.83	4

Movable → Stationary

NOTES:

1. Assembly reflected on bottom and 4 sides by 20.3-cm-thick concrete. Reflector height was 147.3 cm.
2. Assembly supercritical,  $k = 1.0009$  at table closure.
3. Add top reflector 20.3-cm-thick concrete. Reactivity gap sensitivity measurement extrapolated to closure indicates  $k_{eff} > 1.01$  at table closure.
4. Thickness of top reflector reduced to 10.2 cm.  $\Delta k_{eff}$  of perturbation was  $-0.0021$ .

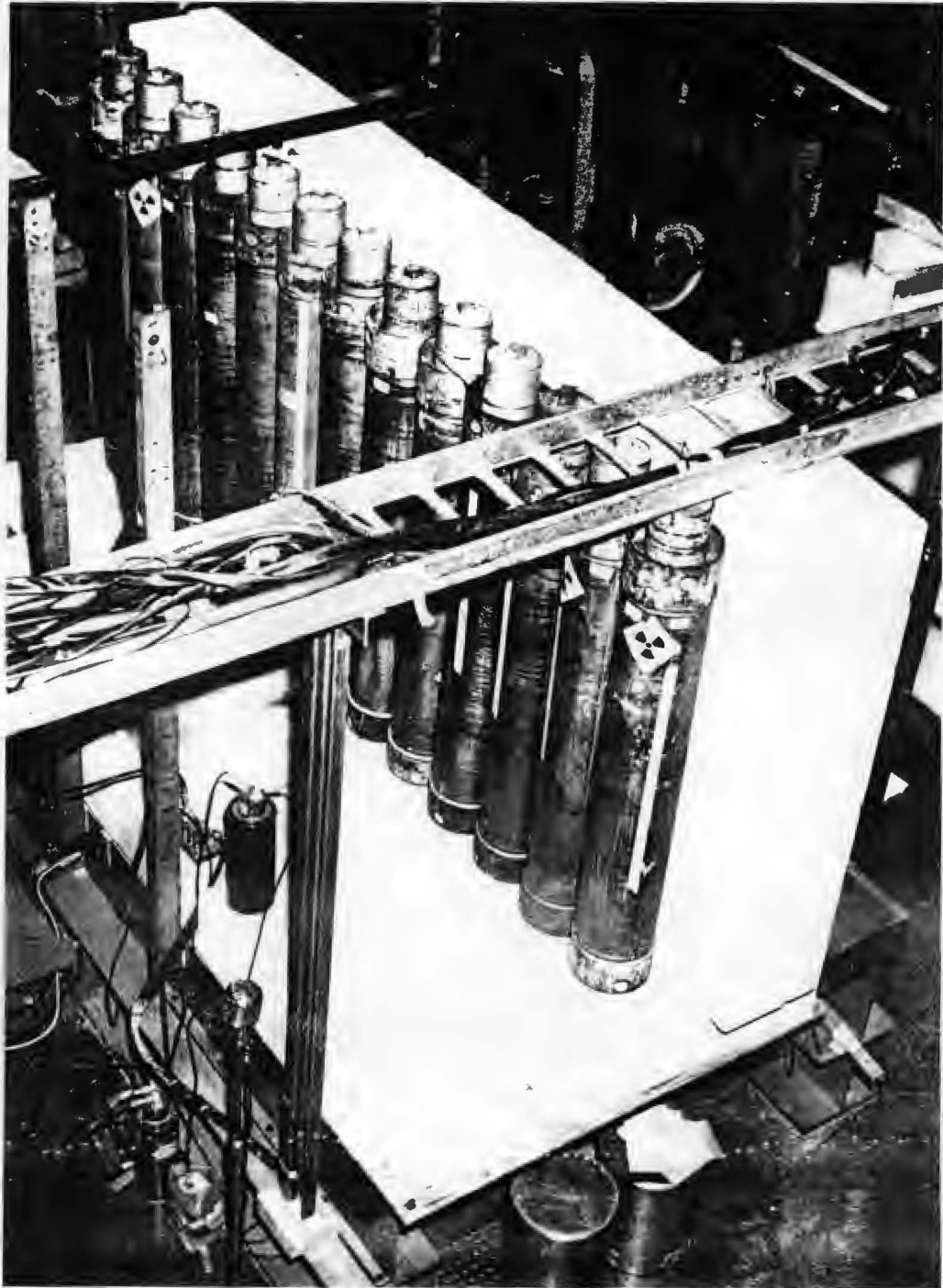
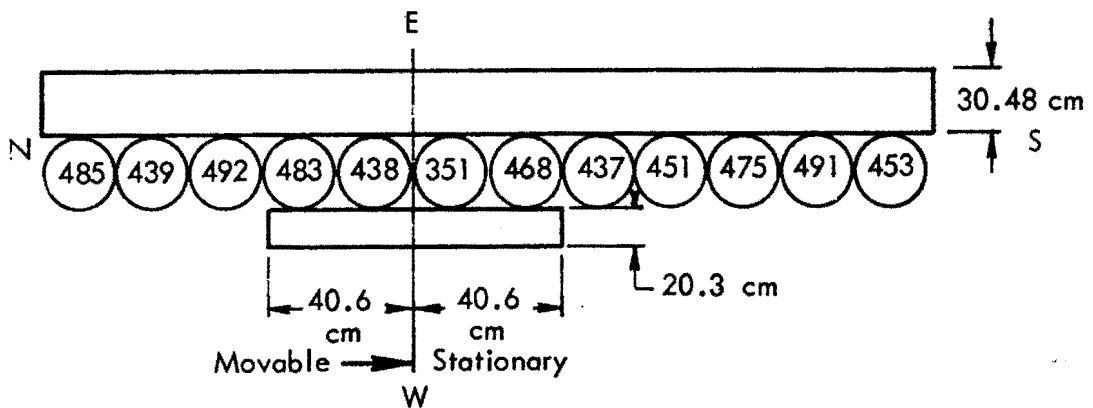


Fig. 5. A Subcritical Linear Arrangement of 13 Cylinders Reflected on the Bottom by 20.3-cm-thick Concrete and on One Side by 30.5-cm-thick Concrete.

Table 12. Critical Conditions for a 1 x 12 Array of U(97.7)F<sub>6</sub> Cylinders with Various Concrete Reflector Conditions.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
51	22.52	0.69	1
52	22.52	0.62	2
53	22.52	0.61	3
54	22.52	--	4

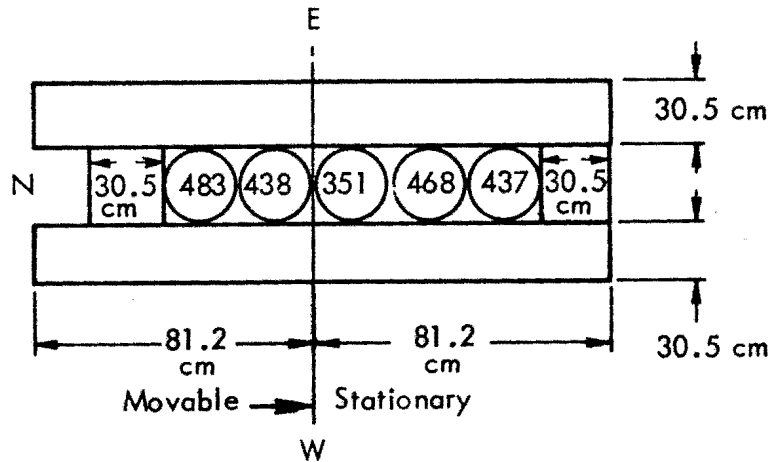


NOTES:

1. Assembly was subcritical reflected on one side by 30.5-cm-thick and by 20.3-cm thickness on bottom. Reflector height was 147.3 cm. Criticality achieved with reflector addition to west side as shown.
2. Removed Cylinder No. 485.  $\Delta k_{eff}$  of perturbation was -0.0006.
3. Removed cylinder No. 453.  $\Delta k_{eff}$  of perturbation was -0.0001.
4. Assembly subcritical upon removing cylinder Nos. 491, 475, 451, and 439. Six cylinders remain in assembly.

Table 13. Critical Conditions for a 1 x 5 Linear Array of U(97.7)F<sub>6</sub> Cylinders with Various Concrete Reflector Conditions.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
55	26.66	--	1
56	26.66	0.00	2
57	26.33	0.38	3
58	26.33	0.72	4
59	26.33	0.94	5
60	26.33	--	6
61	26.33	0.28	7
62	26.33	0.67	8



NOTES:

1. Assembly subcritical. Reflected on bottom and 4 sides; height of reflector 147.3 cm. Units in contact with reflector,  $k_{eff} = \approx 0.9997$ .
2. Added 20.3-cm-thick top reflector,  $k_{eff} = 0.9997$ .
3. Assembly supercritical.  $k_{eff} = 1.0018$  at table closure, top and bottom reflector 20.3-cm-thick concrete.
4. Increased reflector thickness on stationary table to 40.6 cm on East side.  $k_{eff}$  at closure  $\approx 1.0038$ .
5. Increased reflector thickness on movable table to 40.6 cm on East side.  $k_{eff}$  at closure  $\approx 1.0049$ .
6. Removed 30.5-cm-thick reflector from North side, i.e., unreflected North end. Assembly subcritical.
7. Added 10.16-cm thickness of concrete to North side of assembly.  $k_{eff}$  at closure  $\approx 1.0012$ .
8. Increase reflector thickness on North side to 20.3 cm.  $k_{eff}$  of assembly at closure  $\approx 1.0040$ .  
Comparison with configuration in Note 3 gives  $+0.0012$  as  $\Delta k_{eff}$  addition due to increasing East reflector thickness from 30.5 to 40.6 cm.



experiments examined variations of the side reflector thickness. A similar series of experiments, 63-65, reported in Table 14, examined the criticality of 4 cylinders.

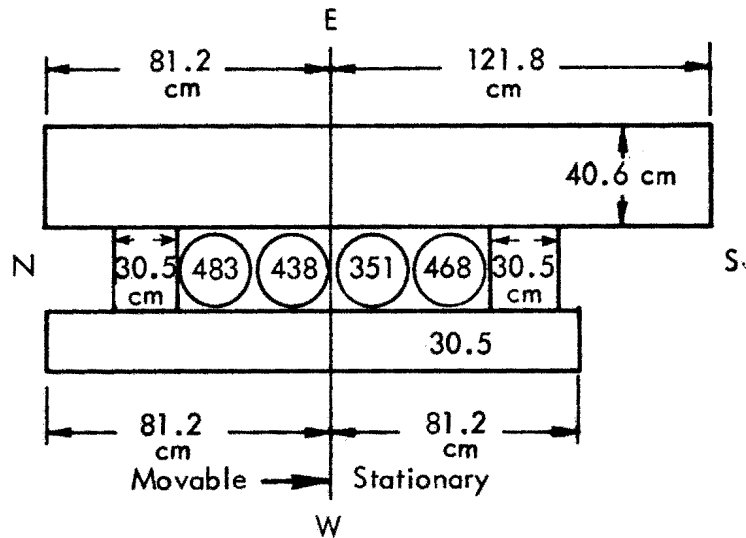
Criticality of a linear array of 3 cylinders was not possible and required the addition of Plexiglas between the cylinders. Various reflector thickness perturbations were also examined. These experiments, 66-70, are reported in Table 15.

Two subcritical 3-cylinder linear arrays were utilized to demonstrate neutron coupling through a 40.6-cm thickness of concrete. The assembly is described in Table 16 which also reports the influence on the assembly of reducing the amount of concrete between the arrays in increments of 10.2 cm. The reflector in these experiments was close fitting. In a variation of this experiment, the concrete was spaced from one of the arrays and close fitting in the second, as described in Table 17. The reactivity response of the assembly to displacements of the array within the cavity as well as displacement of one outside reflector wall was examined.

There was sufficient excess reactivity in the assembly with 40.6 cm separating the arrays to warrant examination of neutron coupling of the arrays through a 50.8-cm-concrete thickness. The experiments, 79-81, are reported in Table 18. The assembly was initially subcritical and required increases of the external reflector thickness to achieve criticality. A photograph of the assembly appears in Fig. 6 where the top reflector has been removed to expose the arrangement. The movable table is to the right of the photograph.

Table 14. Critical Conditions for a 1 x 4 Linear Array of U(97.7)F<sub>6</sub> Cylinders with Various Concrete Reflector Conditions.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
63	24.72	0.56	1
64	24.72	0.65	2
65	24.72	0.23	3



NOTES:

1. Assembly unreflected on top. Bottom reflector was 20.3-cm-thick concrete and height of reflector was 147.3 cm. Cylinders in contact with reflector.
2. Added top concrete reflector 20.3-cm thick.  $\Delta k_{\text{eff}}$  of addition was +0.0007.
3. Reduced reflector thickness on East side from 40.6 to 30.5 cm.  $k_{\text{eff}}$  of assembly at table closure was 1.0013.

Table 15. Critical Conditions for a 1 x 3 linear array of U(97.7)F<sub>6</sub> Cylinders with Various Reflector Conditions and with Plexiglas Separating the Cylinders.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
66	22.52	--	1
67	23.66	0.69	2
68	23.66	0.42	3
69	23.66	0.12	4
70	23.66	0.11	5

NOTES:

- Concrete reflector thickness was 40.6 cm on 4 sides and 20.3 cm on bottom. Cylinders in contact. Reflector was close fitting. Assembly subcritical.
- Top reflector 20.3-cm-thick concrete added. Two Plexiglas sheets 121.9 x 22.2 x 1.14 cm inserted between cylinders. Reflector in contact with cylinders.
- Reduced reflector thickness on West side to 30.5 cm.  $\Delta k_{\text{eff}}$  of perturbation was  $-0.0025$ .
- Reduced reflector thickness on East side to 30.5 cm.  $\Delta k_{\text{eff}}$  of perturbation was  $-0.0022$ .
- Removed top reflector.  $\Delta k_{\text{eff}}$  of perturbation was  $-0.0001$ .  $k_{\text{eff}}$  of assembly at table closure was 1.0008.

Table 16. Critical Conditions for Two Linear Three-Cylinder Arrays with Close Fitting Concrete Reflectors Neutron Coupled through a 40.6-cm Thickness of Concrete.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
71	22.52 E,W	2.49	1
72		3.54	2
73		5.17	3
74		1.06	4
75		2.47	5

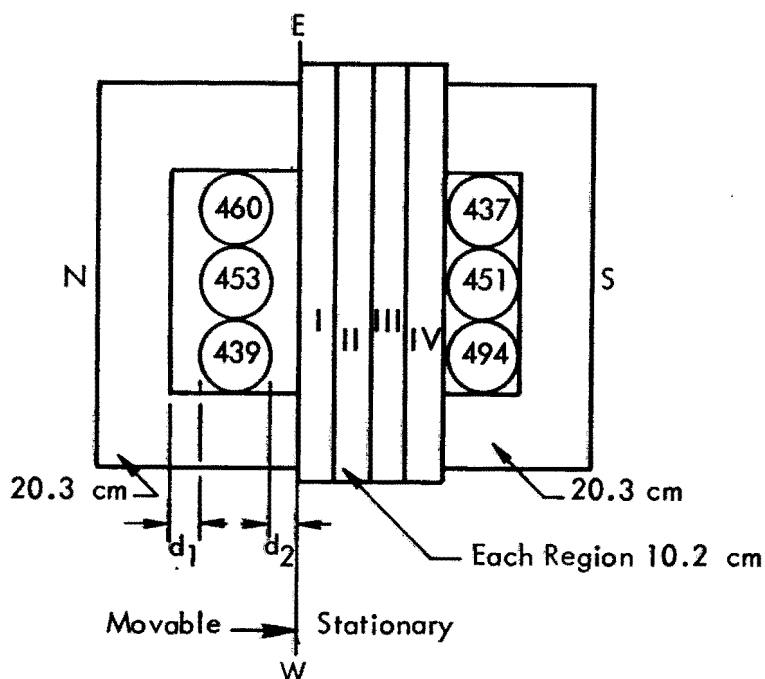
The diagram illustrates the experimental setup. It shows two vertical linear arrays of three cylinders each, labeled with numbers 439, 453, 460 on the left and 437, 451, 494 on the right. These arrays are separated by a central concrete reflector of total thickness 40.6 cm, divided into four regions (I, II, III, IV), each 10.2 cm thick. The entire assembly is enclosed in a concrete reflector that is 20.3 cm thick on the top, bottom, and three sides. The fourth side is neutron-coupled through a 40.6 cm thick concrete barrier. The diagram is oriented with North (N) on the left, South (S) on the right, East (E) at the top, and West (W) at the bottom. A 'Movable' arrow points to the left array, and a 'Stationary' arrow points to the right array.

NOTES:

1. Assembly consisted of 2 arrays each containing 3 cylinders in contact as linear array reflected by 20.3-cm-thick concrete on top, bottom, and 3 sides. The other (fourth) side of each array was neutron coupled through 40.6 cm of concrete as 4 regions, 10.2-cm-thick, as shown. Reflector height inside cavities was 147.3 cm. Center separation of the parallel arrays was 63.3 cm at table closure.
2. Concrete of Region I removed.
3. Concrete of Region II removed.
4. Concrete of Region III removed.
5. Replaced concrete in Regions I-III. Difference in table position at critical compared to Experiment 71 was  $7.1 \times 10^{-5}$  in  $\Delta k_{eff}$ .

Table 17. Critical Conditions for Two Linear Three-Cylinder Arrays with Concrete Reflectors Neutron Coupled Through a 40.6-cm Thickness of Concrete.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Reflector Cylinder Separation		Notes
			$d_1$ (cm)	$d_2$	
76	22.52 E,W	--	1.91	1.91	1
77		0.22	1.27	1.91	2
78		0.13	0.95	2.22	3

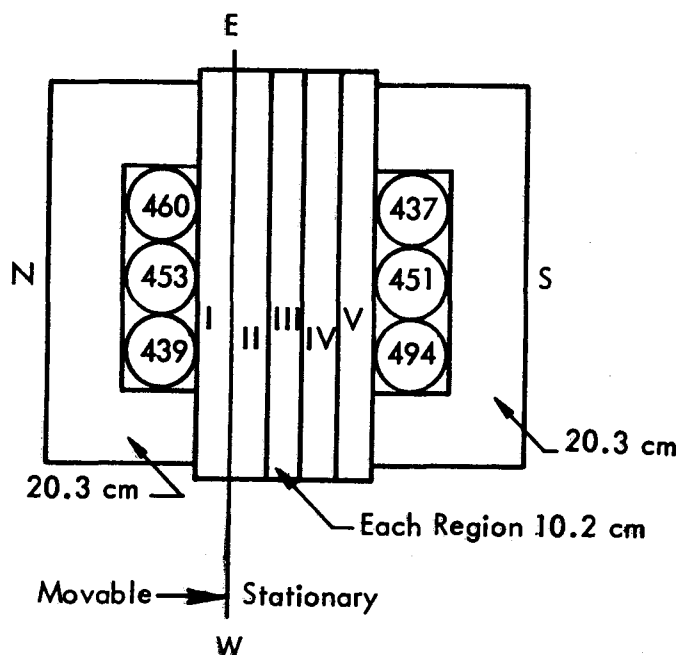


## NOTES:

1. Assembly consisted of two parallel linear arrays each containing 3 cylinders in contact. Cylinders in South array were in contact with concrete reflector on lateral sides. Cylinders in North array were in contact with concrete except for surface separations described by  $d_1$  and  $d_2$  shown in diagram. Reflector height inside cavities was 147.3 cm. Center separation of two parallel arrays at table closure was 65.2 cm. The assembly was subcritical but at a high source neutron multiplication.
2. North side reflector moved inward to decrease  $d_1$ .  $k_{eff}$  of assembly at table closure was 1.0005.
3. Cylinders moved in North direction to decrease  $d_1$  and increase  $d_2$ .  $k_{eff}$  of assembly at table closure was 1.0003.

Table 18. Critical Conditions for Two Linear Three-Cylinder Arrays of  $U(97.7)F_6$  with Various Reflector Conditions Neutron Coupled Through a 50.8-cm Thickness of Concrete.

Experiment No.	Cylinder Center Separation (cm)	Table Separation at Critical (cm)	Notes
79	22.52 E,W	--	1
80		0.39	2
81		7.36	3



NOTES:

1. Assembly consisted of two parallel linear arrays each containing 3 cylinders in contact. Concrete reflector is 20.3-cm thick and was in contact with lateral surfaces of cylinders. Arrays were reflected on six sides. Height of reflector cavities was 147.3 cm. Center separation of two parallel arrays at table closure was 73.3 cm. Assembly was subcritical with an apparent neutron source multiplication greater than 5.
2. Reflector thickness on North side increased to 30.5 cm.  $k_{eff}$  of assembly at table closure was 1.0007.
3. Reflector thickness on South side increased to 30.5 cm.

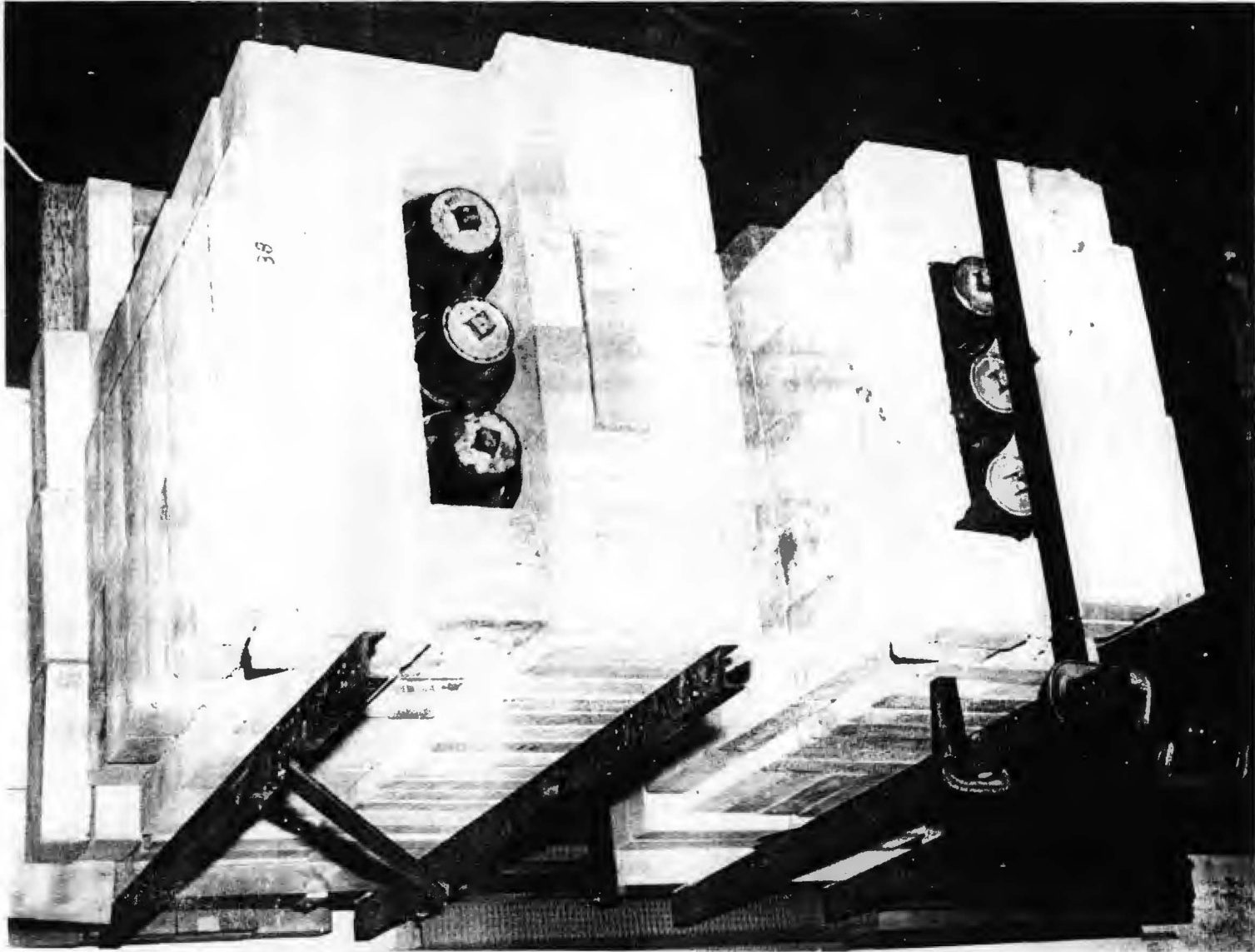


Fig. 6. View of the Assembly of Two Arrays Neutron Coupled Through a 50.8-cm Thickness of Concrete Shown with the 20.3-cm-thick Top Reflector Removed. The completed assembly would be supercritical at table closure.

## CONCLUSIONS

The experiments described, as well as the data obtained, have been reviewed with representatives of the U.S. AEC, Goodyear Atomic, and UCC-Nuclear Division groups who perform nuclear safety calculations. The group concluded that experiments described together with the data presented would serve to validate nuclear criticality safety calculations involving storage and handling of  $U(97)F_6$ .

Much of relevance to nuclear criticality evaluations in the handling of these  $UF_6$  cylinders may be derived from this series of experiments. The experiments are described in sufficient detail to be applied directly for the establishment of safety specifications and to be considered of benchmark caliber for calculational validations. Many of the perturbations to regular configurations are particularly meaningful to the evaluation of reactivity effects on storage arrangements arising in everyday operations.

The following is presented as a suitable list of benchmark experiments because of their geometric simplicity, well defined reactivity, and significance to nuclear criticality safety.

1. Unreflected arrays: Experiments 4, 5, 14, and 16.
2. Polyethylene reflected arrays: Experiments 26 and 29.
3. Polyethylene reflected arrays with interspersed plexiglas: Experiment 22.
4. Concrete reflected arrays: Experiments 45, 46, 48, 56, 57, 61, 62, and 65.
5. Concrete reflected arrays with interspersed plexiglas: Experiments 69 and 70.
6. Concrete reflected arrays with interspersed concrete: Experiments 77, 78, and 80.

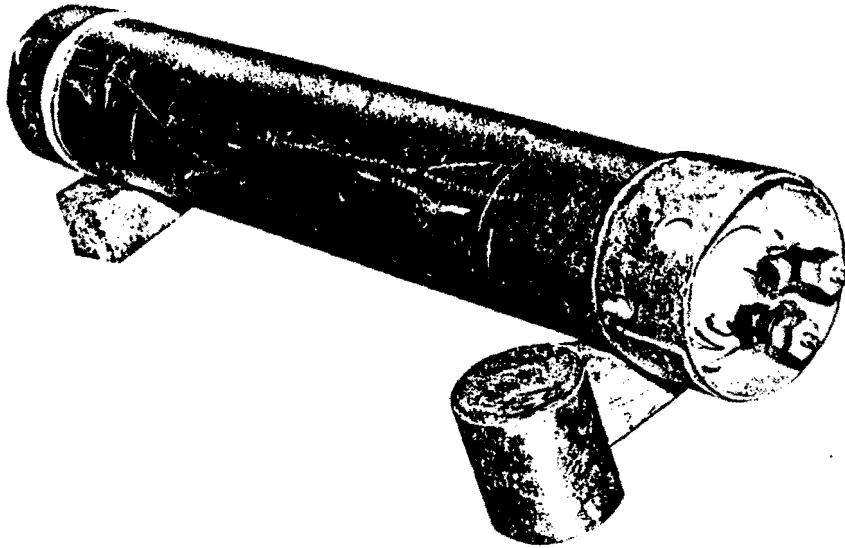
The influence of the steel table top supporting the assemblies may be neglected in those experiments having the polyethylene reflector but should be considered in any calculations of other configurations.



## ACKNOWLEDGEMENTS

The experiments recorded represent about one third the number of approaches to critical. This is a crude but effective measure of the effort required and put forth by an experimental team. This series of experiments was performed by Messers C. Cross, J. J. Lynn, and J. R. Taylor of the Oak Ridge Critical Experiments Facility.

## APPENDIX

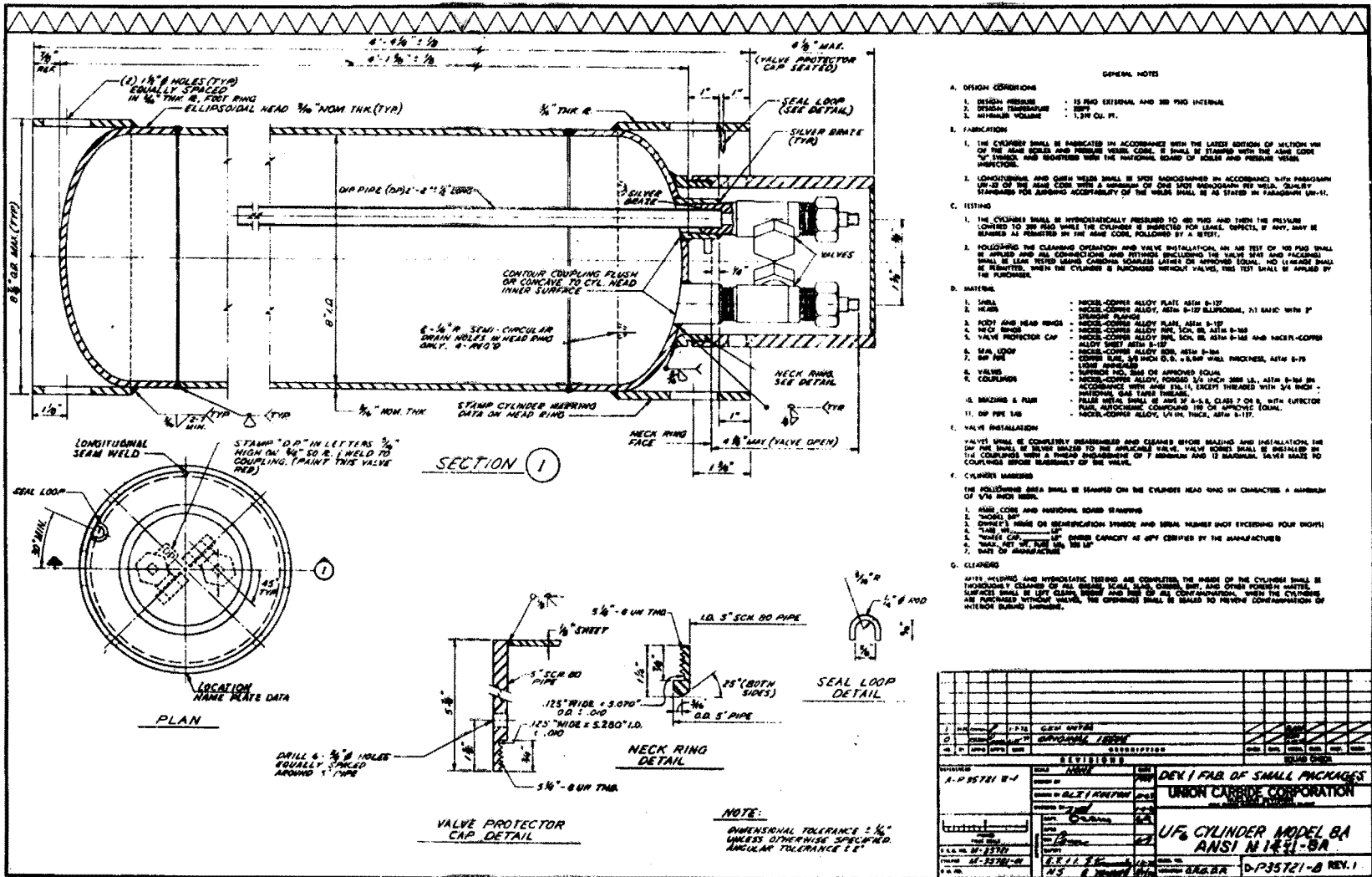
DESCRIPTION<sup>(1)</sup> OF UF<sub>6</sub> CYLINDER MODEL 8A

## GENERAL DATA

Other Descriptive Terminology Used - 8-inch

ENGINEERING DRAWING REFERENCE	UNION CARBIDE CORPORATION, ORGDP: D-P 35721-B, REV. 1
Nominal Diameter	8 in.
Nominal Length	56 in.
Wall Thickness	3/16 in.
Nominal Tare Weight	120 lb
Maximum Net Weight	255 lb
Nominal Gross Weight	375 lb (without cap)
Minimum Volume	1.319 cu ft
Basic Material of Construction	Monel
Service Pressure	200 psig
Hydrostatic Test Pressure	400 psig
Isotopic Content Limit	12.5% <sup>235</sup> U max

Valve Used - Superior No. 5665, or equal.



- GENERAL NOTES**
- A. DESIGN CONDITIONS**
- DESIGN PRESSURE: 15 PSIG EXTERNAL AND 300 PSIG INTERNAL
  - DESIGN TEMPERATURE: 250° F
  - INTERNAL VOLUME: 1.59 CU. FT.
- B. FABRICATION**
- THE CYLINDER SHALL BE FABRICATED IN ACCORDANCE WITH THE LATEST EDITION OF MILITARY SPECIFICATION OF THE MAIN METALS AND RESISTANCE WELDING CODE. IT SHALL BE STAMPED WITH THE ASME CODE "U" SYMBOL AND INSPECTED WITH THE PREVIOUS BOARD OF QUALITY AND PRESSURE VESSEL INSPECTION.
  - CONTOURING AND QUOTE WELD SHALL BE SPECIFIED IN ACCORDANCE WITH PARAGRAPH 4.1.2 OF THE ASME CODE WITH A MINIMUM OF ONE VOLT HOMOGENEOUS PER WELD. QUALITY STANDARDS FOR ASSESSING ACCEPTABILITY OF THE WELD SHALL BE AS STATED IN PARAGRAPH 4.1.1.
- C. TESTING**
- THE CYLINDER SHALL BE HYDROSTATICALLY PRESSURED TO 400 PSIG AND THEN THE PRESSURE LOWERED TO 200 PSIG WHILE THE CYLINDER IS INSPECTED FOR LEAKS. DEFECTS, IF ANY, SHALL BE REPAIRED AS PERMITTED BY THE ASME CODE, FOLLOWED BY A RE-TEST.
  - FOLLOWING THE CLEANING OPERATION AND VALVE INSTALLATION, AN AIR TEST OF 100 PSIG SHALL BE APPLIED AND THE CONNECTIONS AND FITTINGS INCLUDING THE VALVE SEAT AND PACKING SHALL BE LEAK TESTED USING CARBON DIOXIDE LEAK DETECTION EQUIPMENT. NO LEAKAGE SHALL BE PERMITTED. WHEN THE CYLINDER IS PURCHASED WITHOUT VALVES, THIS TEST SHALL BE APPLIED BY THE PURCHASER.
- D. MATERIALS**
- SEAL: NICKEL-COPPER ALLOY PLATE ASTM B-117
  - HEAD: NICKEL-COPPER ALLOY, WITH 9-1/2" ELLIPTICAL, 71 SAUC WITH 1/4" DRUMMING FLANGE
  - HEAD AND HEAD RINGS: NICKEL-COPPER ALLOY PLATE, ASTM B-117
  - HEAD RINGS: NICKEL-COPPER ALLOY PIPE, SCH. 80, ASTM B-168
  - VALVE PROTECTOR CAP: NICKEL-COPPER ALLOY PIPE, SCH. 80, ASTM B-168 AND NICKEL-COPPER ALLOY SHEET ASTM B-117
  - DRY PIPE: NICKEL-COPPER ALLOY PIPE, ASTM B-168
  - DRY PIPE JOINT: COPPER BULK, 2.0 INCH O.D. X 1/4 INCH WALL THICKNESS, ASTM B-75
  - VALVES: 1/2 INCH NIPPLES AND AS APPROVED EQUAL
  - COLUMNS: NICKEL-COPPER ALLOY, FORMED 3/4 INCH DIA. 1/2 INCH B-168 IN ACCORDANCE WITH ASME SECTION VIII, EXCEPT THREADED WITH 1/4 INCH - 20 NIPPLES GAS TIGHT TUBING.
  - PACKING & FLUID: PAIR METAL WITH SEALS OF A-S-E, CLASS 7 OR 8, WITH EXTRACTOR PAUL AUTOGENIC COMPOUND 110 OR APPROXIMATE EQUAL.
  - DRY PIPE TAG: NICKEL-COPPER ALLOY, 1/4 IN. THICK, ASTM B-117.
- E. VALVE INSTALLATION**
- VALVES SHALL BE COMPLETELY DISASSEMBLED AND CLEANED BEFORE INSTALLATION. THE DRY PIPE SHALL BE SILVER BRAZED TO THE APPLICABLE VALVE. VALVE SEALS SHALL BE INSTALLED IN THE CYLINDER WITH A MINIMUM OVERLAP OF 1/8 INCH AND 1/2 INCH MINIMUM. VALVE SEALS TO COUPLINGS BEFORE REASSEMBLY OF THE VALVE.
- F. CYLINDER MARKING**
- THE FOLLOWING DATA SHALL BE STAMPED ON THE CYLINDER HEAD AND IN CONTACTS A MINIMUM OF 1/4 INCH HIGH.
- ASME CODE AND NATIONAL BOARD SYMBOLS
  - "MODEL 8A"
  - OWNER'S NAME OR IDENTIFICATION SYMBOLS AND SERIAL NUMBER NOT EXCEEDING FOUR DIGITS
  - DATE
  - MANUFACTURER'S NAME
  - DESIGN CAPACITY AS SHOWN ON ANY CERTIFIED BY THE MANUFACTURER
  - DATE OF MANUFACTURE
- G. CLEANING**
- AFTER APPROVED AND HYDROSTATIC TESTING AND COMPLETION THE INSIDE OF THE CYLINDER SHALL BE THOROUGHLY CLEANED OF ALL BRINE, SCALE, SLUDG, OIL, AND OTHER FOREIGN MATTER. SURFACES SHALL BE LEFT CLEAN, DRY, AND FREE OF ALL CONTAMINATION. WHEN THE CYLINDER IS PURCHASED WITHOUT VALVES, THE PURCHASER SHALL BE RESPONSIBLE FOR CONTAMINATION OF INTERIOR SURFACES.

REVISIONS		DATE		BY	
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UF<sub>6</sub> CYLINDER MODEL 8A

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