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Critical Experiments with Interstitially-Moderated Arrays of Low-Enriched Uranium Oxide

Topical Report on
Reference Critical Experiments

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ABSTRACT

The critical separation between two tables supporting arrays of cans containing low-enriched uranium oxide has been measured for twenty-one (21) reflected configurations having interstitial layers of moderating material between cans. The critical separation varied between 0.23 and 1.84 cm. The uranium oxide (U_3O_8) is enriched to 4.46% ^{235}U, compacted to a density of 4.7 g/cm^3, and adjusted to an H/U atomic ratio of 0.77 by the addition of water. Each can weighs ~16 kg and is a 15.3 cm cube. Interstitial plastic moderator 1.0, 1.3, or 2.5 cm thick separates cans of the three-dimensional array. Some experiments include thin sheets of neutron absorbing materials, such as mild steel or polyvinyl chloride, surrounding each can. Arrays are closely reflected by thick cuboidal shells of plastic or concrete. The parameter varied to achieve criticality is the number of cans in the array. The smallest number of cans (40) occurs with 2.5-cm-thick moderator, no absorber, and concrete reflector. The largest (100) occurs for several combinations of absorber and moderator in both reflectors. For otherwise similar configurations, concrete is the better reflector in all cases.

SUMMARY

These critical experiments were sponsored by the Nuclear Regulatory Commission to extend the range of parameters for which accurate criticality data are published. Precise data are necessary to assure criticality safety in all phases of the nuclear industry. Critical parameters may be obtained either by experimental measurement or by computations; however, the latter cannot safely be used unless the computational methods used have first been verified by comparison with accurate experimental data.

Such data are necessary for many fissile materials in a wide variety of forms to serve the needs of the industry. The objective of this program is to provide accurate criticality data for one type of fissile material in one form: damp, compacted, low-enriched uranium oxide. This is the second program at this laboratory using this material and form. The first reported criticality data for ~ 2000 kg driven critical by high-enriched uranium "drivers". The present experiments used interstitial moderation between subunits of this material and did not require a driver. This paper reports twenty-one (21) critical configurations for which both geometry and material parameters are specified precisely.

The uranium was enriched to 4.46% ^{235}U, and the dampness of the oxide (U_3O_8) adjusted to yield an H/U atomic ratio of 0.77. The uranium oxide was compacted to 4.7 g/cm^3 and then packaged in aluminum cans, $\sim$ 15 kg of oxide per can. These were assembled in an array with methyl methacrylate plastic moderator (1.0, 1.3, or 2.5 cm thick) between cans. In some experiments, individual cans were also surrounded by thin sheets of neutron absorbing material such as mild steel or polyvinyl chloride (0.06 or 0.12 cm thick).

Two reflector materials were studied: methyl methacrylate plastic and concrete. For both, exterior dimensions of the thick-walled cubical shells were $\sim$ 130 cm, and reflector walls were always at least 25 cm thick. Interior dimensions of the reflector shell varied to suit each case individually, leaving only a small space between core and reflector.

The parameter varied to achieve criticality at small table separations was the number of cans in a nearly cubical array. This varied between 40 and 100 cans (about 600 to 1500 kg of oxide). In many cases, one layer of cans was incompletely filled, but the precise description of this layer is given in the text. For all combinations of these parameters, the number of cans was adjusted until criticality occurred with only a small separation between the two tables on which portions of the array were built. The separation ranged

between 0.23 and 1.84 cm, closely approximating a fissile core fully reflected in all directions by a large, thick-walled, cubical reflector shell.

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ACKNOWLEDGMENTS

The authors wish to thank G. Tuck, W. R. Sheets, and D. E. Payne for their assistance in data collection and equipment maintenance. D. Pecora performed many pre-experiment computations important to the design and safety of the experiment. The authors are grateful to her and G. Tuck for the many helpful discussions during the preparation of this paper.

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CRITICAL EXPERIMENTS WITH INTERSTITIALLY-MODERATED ARRAYS OF LOW-ENRICHED URANIUM OXIDE

INTRODUCTION

Critical parameters used in nuclear safety evaluations of plant operations involving fissile materials may be calculated by a number of computational techniques. Before applying these results to important matters involving the safety of people, a careful validation of the calculational method is essential. This criticality validation is accomplished by comparing calculated parameters with experimentally-measured data for systems similar to the plant operation being evaluated[1].

An important prerequisite of this validation is that geometry and material compositions of the experiment are so well known that no significant part of any discrepancy between calculated and experimental results can be laid to that information. The need for such data, especially for certain ranges of parameters, has been pointed out many times in the literature[1-5]. One area which has not previously been explored experimentally to any great extent concerns the criticality of under-moderated, low-enriched uranium. Some experimental data involving this fissile material are given in Reference 6.

The data reported here are the third from a series of programs at this laboratory designed to provide reference criticality data for computational validation over a wide variety of parameters of interest to the nuclear industry. The first reported criticality data for high-enriched uranyl nitrate solution systems under various conditions[7,8]. The second studied low-enriched uranium oxide at H/U = 0.77 in two reflectors. For these arrays, criticality could not be achieved without regions of high-enriched uranium serving as "drivers". The present program extends the second to include thicknesses of neutron moderating and absorbing materials between regions of uranium oxide. Future programs will expand further the broad parameter base so essential for testing calculational models against experimental evidence.

The present report provides criticality data for low-enriched, slightly damp, compacted uranium oxide. Three-dimensional arrays of cans of this fissile material, interspersed with layers of neutron moderating and absorbing materials, are reflected by thick cubical shells composed of methyl methacrylate plastic or concrete. The parameters varied include:

1. the thickness of methyl methacrylate plastic interstitial moderating material (1.0, 1.3, or 2.5 cm);

2. the composition (polyvinyl chloride and mild steel) and the thickness (0.06 and 0.12 cm) of neutron absorbing materials surrounding cans of fissile material;

3. the composition of the reflector (methyl methacrylate plastic or concrete); and

4. the size of the critical array (40 to 100 cans).

Fixed parameters are: an isotopic uranium enrichment of 4.46% ^{235}U, a compacted uranium oxide density of 4.7 g/cm^3, and an oxide dampness adjusted to produce a hydrogen-to-uranium (H/U) atomic ratio of 0.77.

Eight categories of experiments are identified in the next section of this report, and a brief justification for each in terms of industry needs presented. The equipment necessary to perform these experiments is described qualitatively in the following section, while the next four describe all aspects of the apparatus from the center of the experiment outward: fissile material, interstitial materials, the reflectors, and the immediate environment of the experiment. The procedure for a typical experiment is presented next, followed by a discussion of the experimental results for twenty-one critical configurations representing eight categories and two reflector materials. The paper concludes with a discussion of uncertainties.

CATEGORIES

Eight categories of interstitially moderated array experiments were studied, characterized by the material or combinations of materials interspersed between oxide cans and by the thickness of these materials. All eight were performed within the plastic cuboidal-shell reflector, and five were selected to be repeated with concrete reflection. A total of twenty-one critical configurations are reported, and the number assigned to each represents that experiment throughout this paper.

The only interstitial material serving primarily as a moderator was polymethyl methacrylate plastic called Plexiglas®*. All categories had some of this material present, although three different thicknesses were used on various experiments: 1.0, 1.3, and 2.5 cm.

Some categories of experiments used additional interstitial materials which were neutron absorbers. Mild steel of two thicknesses (0.060 and 0.117 cm) and 0.054-cm-thick polyvinyl chloride (PVC) were the two materials used. Whenever such absorbers were used, the material was cut into squares the same size as a can and each can surrounded

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* Trademark of Rohm and Haas Company, Philadelphia, Pennsylvania.

by six pieces. These were held in contact with the can during assembly by a small amount of ordinary office paper-mending (Scotch®)* tape. Precise dimensions and material compositions for these interstitial materials are given in later sections and tables.

The eight categories are designated by letters throughout this paper. Each category is described below in general along with a brief justification based on needs of the industry.

Category "O" - Optimum Moderation

Preliminary calculations indicated that criticality would occur for the smallest number of cans when the interstitial plastic thickness was about 2.5 cm; so the nearest commercially-available thickness (one inch) was selected for this category. Many subsequent categories retain this thickness of interstitial moderation, but include also the effects of neutron absorbing materials.

Category "U" - Undermoderated

A second plastic thickness, thinner than that used in Category O, was chosen to study the effect of moderator thickness on the critical number of cans. Preliminary

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* Trademark of Minnesota Mining and Manufacturing Company.

calculations revealed that the thinnest material for which criticality would occur within the existing reflector shells was ~ 1.0 cm. Consequently, the nearest commercially-available thickness material (3/8 inch) was selected for this category.

Category "S" - Supercans

Industrial operations with low-enriched uranium oxide occur in batch sizes larger than the 15.3 cm cube can used in these experiments. To study the effect of size on the criticality of interstitially-moderated arrays of cans, they were grouped into small subarrays, forming effectively larger cans. Then these larger "supercans" were separated from one another by the 2.5 cm optimum moderator thickness. An array of 2 x 1 x 2* "supercans" was critical in the plastic-reflected case. In the concrete reflector, an array of 2 x 2 x 2 "supercans" was built on one table with an array of 2 x 3 x 2 groupings on the other.

Category "P" - PVC Neutron Absorber

Certain industrial shipping containers for uranium oxide have a polyvinyl chloride packaging insert. Here, chlorine

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* Whenever an array is specified as "a x b x c", 'a' refers to the east/west measure of the array, 'b' to north/south, and 'c' to vertical. Whether a north/south entry refers to one table or to both tables will be clear from context. This nomenclature applies both to array dimensions in centimeters and to the number of elements in an array.

is a neutron absorber; so the effect of this material included in an array otherwise similar to Category O is expected to increase the critical number of cans. As stated earlier, each can was surrounded on every face by squares of the material, simulating the PVC packaging application.

Category "M" - Mild Steel Neutron Absorber

Iron is a fairly effective neutron poison, and many industrial operations involving uranium oxide use steel containers. The influence of this material, then, on arrays otherwise similar to Category O is of interest. For this category, mild steel plates were taped to the six faces of each aluminum can. This simulates a steel can because, although both metals were present, iron has a much greater influence on the reactivity of a fissile core than does aluminum.

Category "m" - Thin Mild Steel Neutron Absorber

The poisoning effect of steel varies with the thickness of the plates surrounding each can. This question was addressed by repeating the previous category (M) with thinner plates of the same material and size. The 0.060 cm mild steel thickness also allows a comparison between this material and PVC since Category P experiments had close to the same thickness absorber.

Category "T" - Thick Steel/Thin Moderator

The neutron absorbtion by the thick steel plates of Category M depends upon the energy spectrum of the neutrons in the critical array. The effect of steel on an under-moderated array will be very different from the effect on one having optimum moderation. This effect was studied by rebuilding the Category M array using 1.3-cm-thick interstitial plastic moderator in place of the 2.5-cm-thick material.

Category "E" - Expanded Array

The reactivity of an optimally-moderated array (2.5 cm total plastic thickness between adjacent cans) is expected to decrease if the space between cans is allowed to increase without changing the amount of plastic between them. This question was addressed by building an array similar to Category O but composed of two half-thickness plastic moderators in all directions. These half-thickness moderators were formed into close-fitting boxes surrounding each can. Boxes were then held apart by lightweight aluminum fixtures such that the expanded core filled the entire available space within the reflector shell.

EQUIPMENT

These experiments were performed on a heavy steel "split table" machine composed of movable "north" and "south" tables, both supported by a common framework. This machine is shown in Figure 1. Next, either the concrete or plastic reflector shell was assembled on the machine, and Figures 2 and 3 show these with both tables in the fully open position. Each reflector was composed of four pieces, two on each table; and a thick-walled, nearly-cubical shell was formed when the two tables closed on one another. Figure 2 identifies these four pieces as: ⓐ north reflector end panel, ⓑ north reflector frame, ⓒ south reflector frame, and ⓓ south reflector end panel.

The shell interior was large enough to accommodate a 5 x 5 x 5 array of cans, two columns (vertical layers) deep on the north table and three on the south. Interior dimensions were not, however, always large enough to accept a five-can array plus the desired interstitial moderator. In fact, all experiments had four cans in the east/west direction because of this limitation. Five cans could be assembled vertically with as much as 1.3 cm of interstitial materials, and this proved adequate for all cases studied. Five cans plus interstitial moderators exceeded the available depth in the north/south direction. This problem was solved by fabricating "reflector frame extensions" having the same

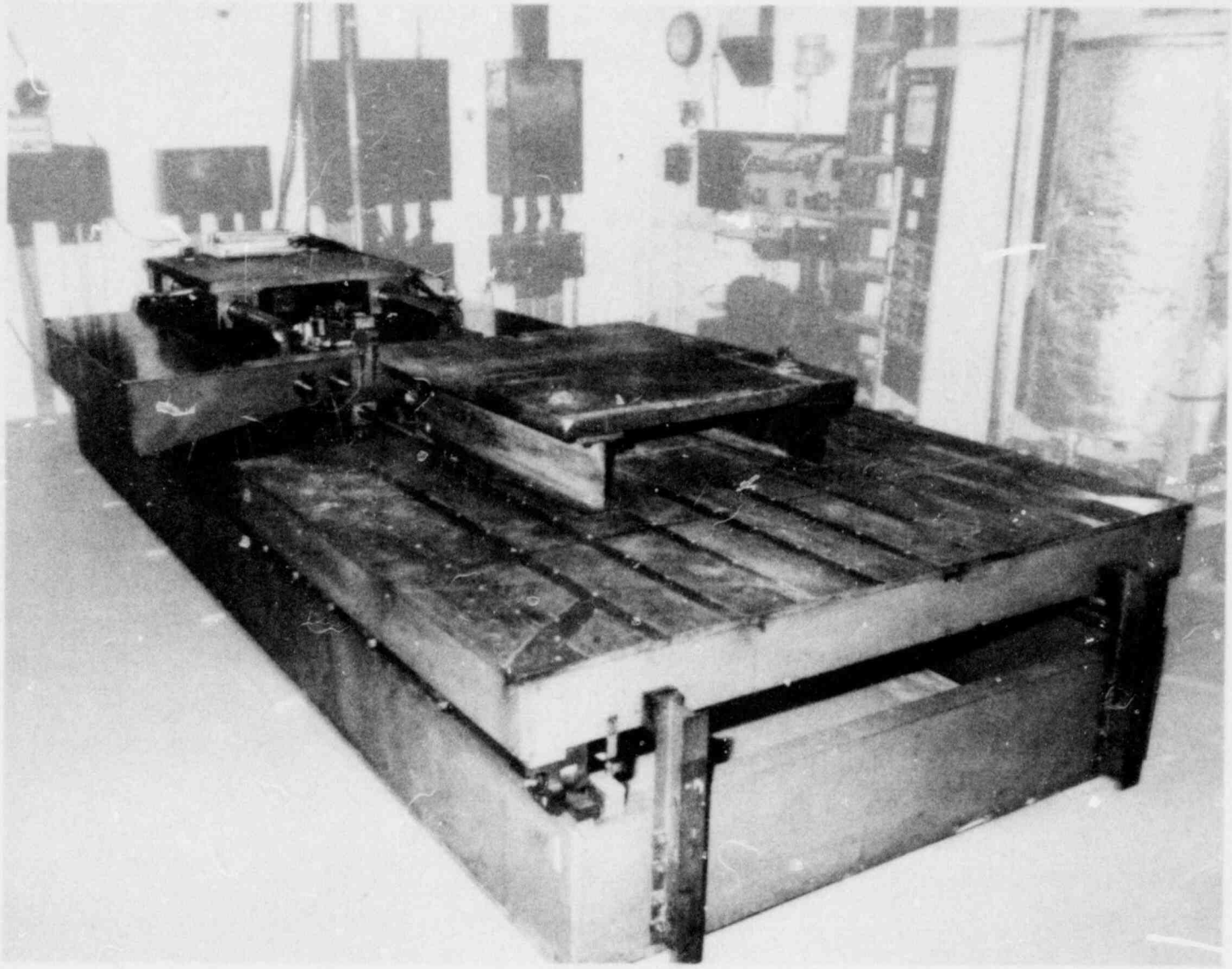

FIGURE 1

The horizontal split tables machine. Neutron detectors rest on the north table (away). The background has been suppressed to emphasize the machine.

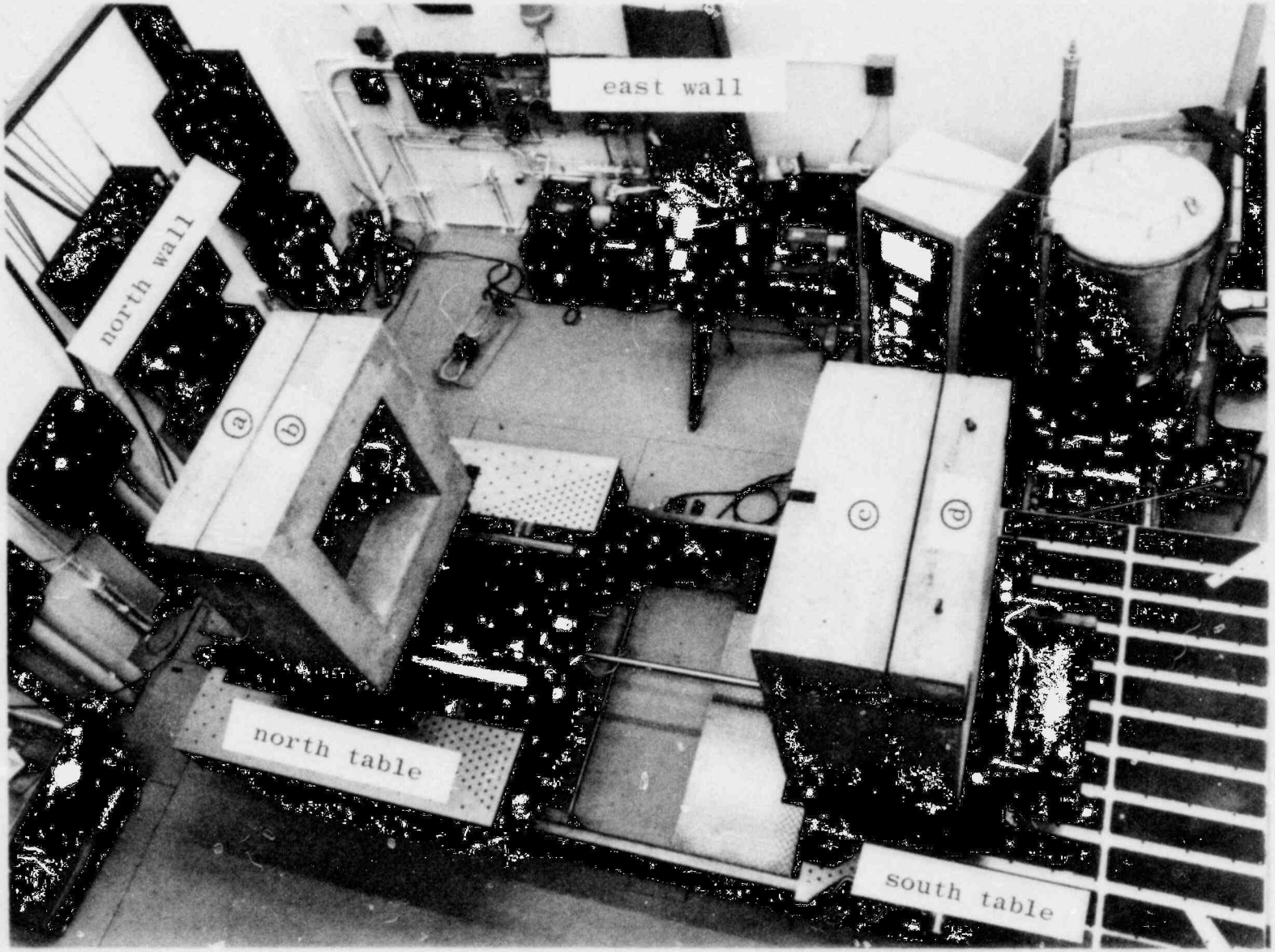

FIGURE 2

The concrete reflector shell. This figure may be used to orient references to compass directions. Parts lettered ⓐ and ⓓ are end reflector panels, ⓑ and ⓒ are reflector frames.

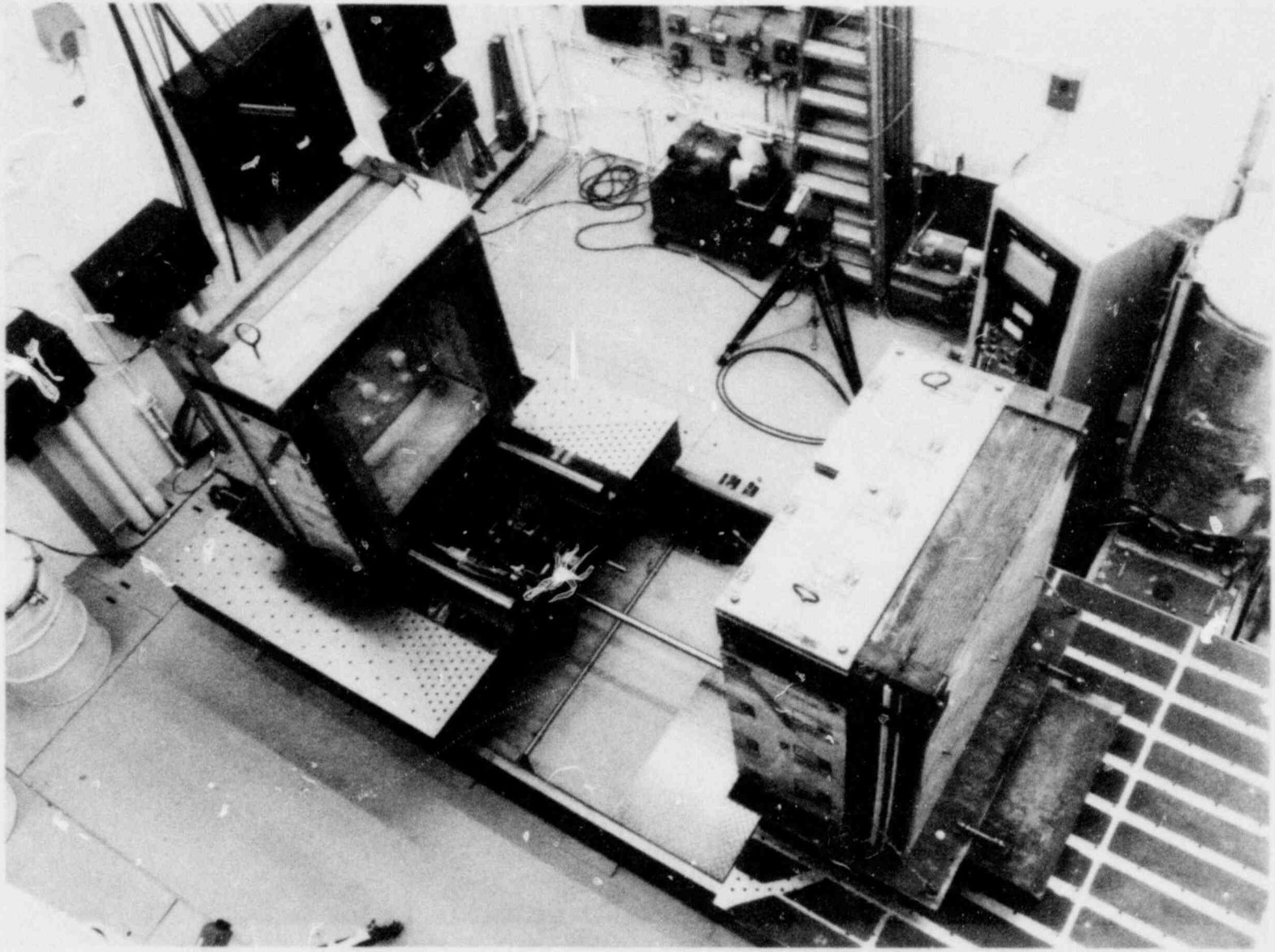

FIGURE 3

The plastic reflector shell. The holes partially through the north end panel received neutron detectors.

section dimensions as the frames themselves but suitable thickness to provide the needed depth. When used, these extensions were inserted between parts (a) and (b) and/or between parts (c) and (d) of Figure 2 with the corresponding end panels displaced back from center to accommodate the added pieces.

The several combinations of materials studied in this program lead to many different thicknesses of materials between adjacent cans. Consequently, dimensions of the fuel/moderator/absorber core region varied considerably. The inside cavity of the reflector shell (including frame extensions) necessarily exceeded all three of these core dimensions. Whenever practical to do so, this space between the core and reflector shell was filled with blocks of the same material as the reflector itself, thus effectively bringing the reflector as close as possible to the core region. One consequence of the use of these "fillers" is that the thickness of the reflector region is not constant in all directions. Such fillers were used above and (occasionally) below, to the east, and to the north and south of the core region.

Filler blocks were never used west of the core. Instead, cans were always stacked against the inside west wall of the reflector shell cavity, making this vertical surface a "key plane" common to all experiments. Two other key planes, also vertical but orthogonal to the first, are the approaching

faces of the two reflector frames. Cans were always stacked against these two planes; and, for most experiments, each was covered with a plastic "faceplate" screwed to the frame. These were half the thickness of the array's moderator plastic in anticipation of completing a uniform array across the two tables the moment they closed on one another. A few cases had one full-thickness faceplate screwed to one key plane only or other deviations from the above construction. Vertically, cans were stacked directly on the reflector floor, making this surface another key plane, unless the full height of the cavity was known to be not required for criticality. In these ten cases, the array was built on thick bottom filler pieces elevating the key plane by the thickness of these blocks. This was done to avoid placing a heavy weight on the top layer of cans. Both filler blocks and faceplates can be seen in many figures throughout this paper.

FISSILE MATERIAL

Oxide Can

The fissile material was primarily U_3O_8, although a small amount of $UO_{\sim 2.3}$ was detected. Initially, the very fine powder was spooned into polyethylene sandwich bags 0.018 mm thick weighing 1 g each (although ~ 10% of this was cut away before compaction), sealed with a twisted 0.06 g piece of paper-covered, soft-iron wire, and placed into a large-capacity press. There, each bag was compacted to a density of 4.7 ± 0.3 g/cm^3 (57% of the crystal density of U_3O_8). Each compacted block weighed ~ 540 g and measured 7.5 cm square with one corner rounded to match the can. The blocks were pressed to an average thickness of ~ 2.1 cm, although "spring back" after pressing caused the final thickness to vary. The plastic bags and wire seals were not removed for compaction, so this material is embedded in the oxide. A compacted block is shown in Figure 4.

The average isotopic enrichment of the uranium is given in Table I. The uranium oxide assayed 84.49 ± 0.08% uranium, averaged over 26 samples taken between 1976 and 1979. Qualitative x-ray diffraction studies revealed that ~ 95% of the oxide had an orthorhombic crystal structure at a lattice spacing associated with U_3O_8, while ~ 5% was cubic at a spacing characteristic of $UO_{\sim 2.3}$. The loose powder was analyzed for particulate size distribution before

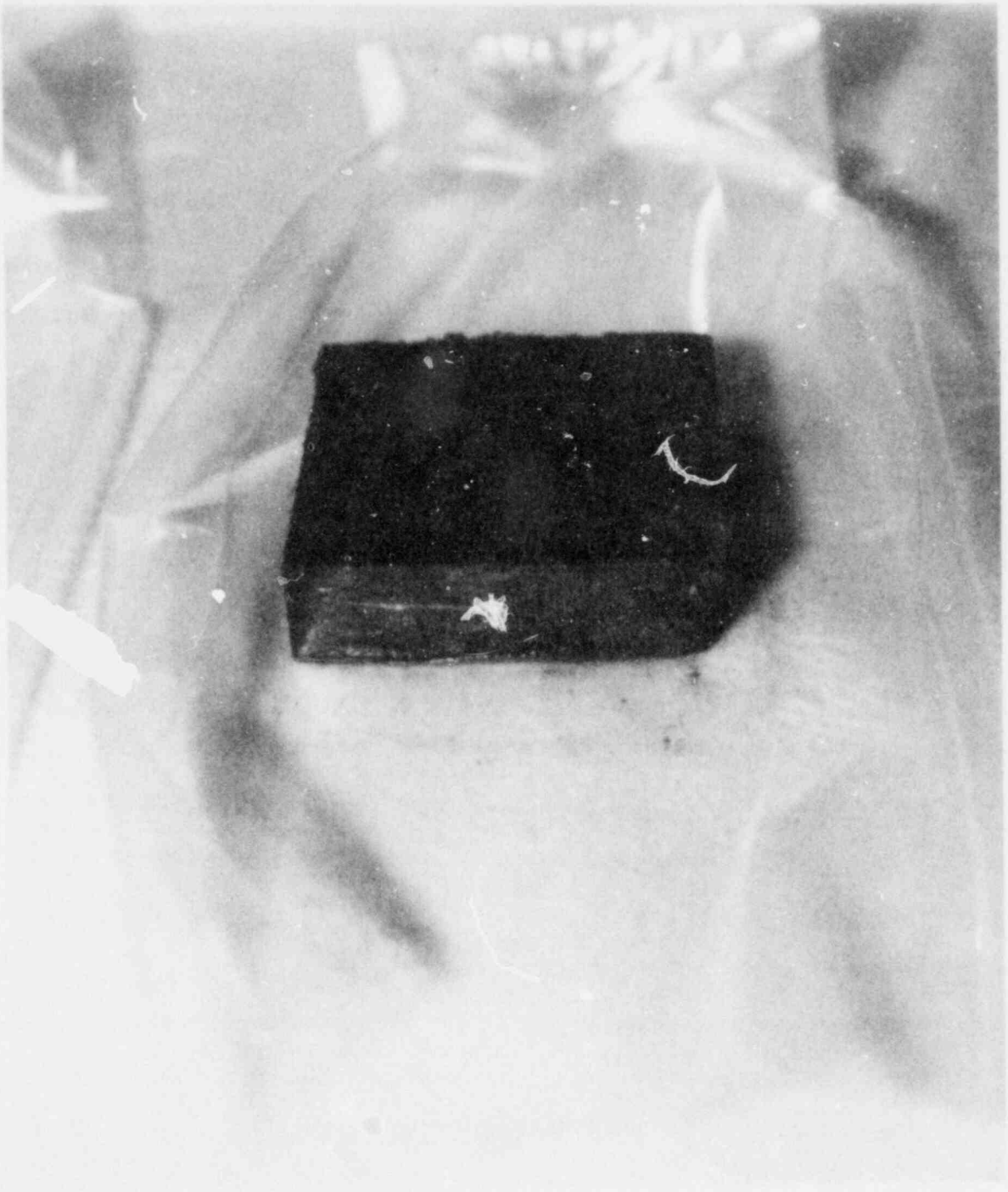

FIGURE 4

A finished block of uranium oxide. Four blocks per layer were packaged in an aluminum can. The rounded corner (lower right) matched the draw radius of the can. Seven layers filled a can.

TABLE I

Uranium Enrichment in Weight-Percent

^{234}U	^{235}U	^{236}U	^{238}U
0.03 ± 0.00	4.46 ± 0.02	0.08 ± 0.01	95.43 ± 0.02

compaction, and the results are expressed in number-percent within the micron ranges shown in parentheses: 1.0% (< 1), 93.0% (1 - 10), 4.5% (10 - 25), and 1.5% (> 25). Four impurity elements were analyzed by the atomic absorption method (± 5% accuracy, mg impurity per kg sample): Si(128), Cr(128), Fe(312), and Cu(185). Smaller impurities, determined by the less-precise emission spectroscopy method, were: Mg(13), Al(37), P(~50), K(25), Ca(~15), Ni(16), and Zn(~30), with all other elements detected less than 10 mg per kg each. Strong neutron absorbers boron and cadmium were found by atomic absorbtion to be less than 0.3 and 2.0 mg per kg, respectively.

Nearly cubical deep drawn type 1100 aluminum cans were used to contain the oxide blocks. Before packing, each can was prepared by drilling 28 holes on each of two opposite faces to facilitate later water additions. The prepared cans weighed 526 ± 3 g each, including type 1100 lid. The finished box with lid in place formed a cube (with rounded edges) 15.28 cm on a side and 0.15 cm thick. The draw radius between adjacent sides and between each side and the bottom was 0.79 cm. No such radius was necessary at the top as the flat lid rested directly on the square rim of the can. The 56 water-injection holes per can are each 0.6[illegible] cm diameter.

As blocks were loaded into cans, a second sandwich bag was placed around each and tucked neatly underneath. The purpose of this bag was to prevent migration of water

between blocks, assuring homogeneity at least to that degree. It was identical to the one imbedded during pressing except that no material was trimmed away. Thus, each can contained a total of 53 g of polyethylene bags.

Four blocks formed the bottom layer, and they were further seated by pounding on a ram which fit loosely inside the can. Seven layers of four blocks (28 total) were packaged in the can in this fashion. The last layer nearly filled the can, and swelling following water injection did cause the blocks to fill the can completely.

An aluminum lid was taped in place using one wrap of vinyl tape to assure sealing. This tape was 0.017 cm thick, 2.5 cm wide, ~64 cm long, and weighed 3 g per can.

Two holes were "drilled" into one side of each block through the predrilled holes in the aluminum cans. A non-fluted, pointed length of drill rod stock was used because no significant amount of oxide was drawn from the can during drilling. The purpose of these holes was to provide increased surface area for water to be absorbed into the oxide.

An amount of water necessary to produce the desired H/U atomic ratio (0.77) in a finished can was calculated, and half that measured out into a jar. Other sources of hydrogen (plastic bags, naturally-absorbed water, and two kinds of tape) were taken into account when calculating this amount: 273 ± 4 g distilled water per can. An equal share was then injected into each of 28 holes (two holes per block, 14

blocks exposed on one face) using a hypodermic syringe. Figure 5 shows this stage of the operation in progress. When all water had been injected into one side of the oxide, the holes were sealed with two layers of mylar tape (to prevent evaporation) over each of four vertical rows of seven holes. Next, the second half of the water was weighed out, and the above procedure repeated on the opposite face. The mylar tape was 0.005 cm thick by 2.5 cm wide. The 16 strips per can weighed 4 g (total) and were ~15 cm long each. The elemental composition of both kinds of tape and the plastic bags are given in Table II.

The end result was a cubical aluminum can containing compacted uranium oxide dampened as required to achieve the desired H/U ratio (0.77). Figure 6 shows trays of finished cans ready for assembly into an experimental array. A total of 125 cans were prepared in this fashion, and those used in this program were selected from that inventory.

The physical properties of an average finished can are given in Table III. Dimensions were measured on one can on two occasions to determine if sides were bowing due to handling. While the can remained fairly square (15.28 cm) for most of the height, a slight increase in can dimension was noted near the unsupported top. Three months into the program, the can measured 15.35 cm square there and stood 15.25 cm tall. These dimensions changed slightly to 15.45 cm and 15.30 cm, respectively, by the end of the study.

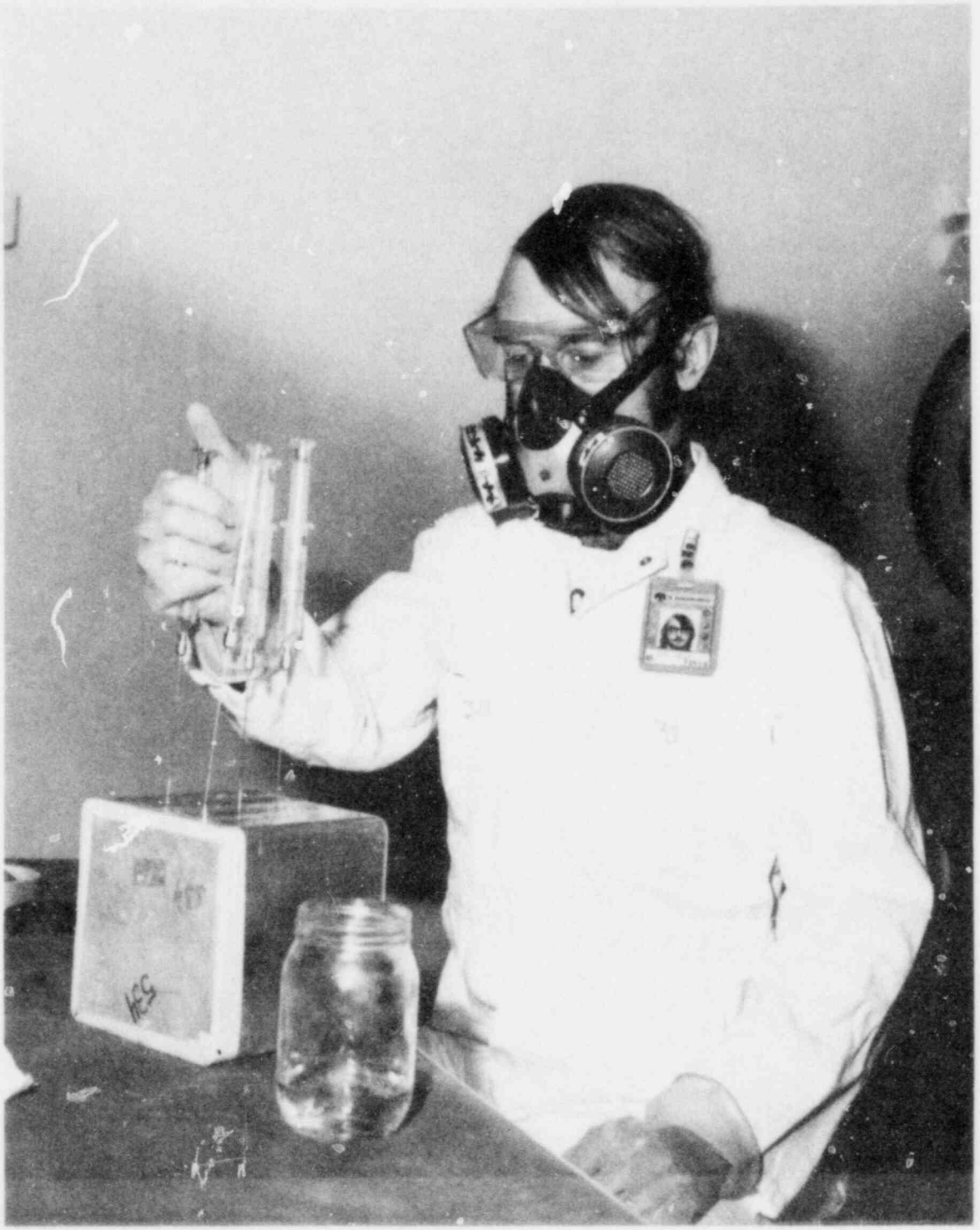

FIGURE 5

Water injection into uranium oxide. An amount of water necessary to achieve H/U = 0.77 was weighed into the jar with equal aliquots injected into every hole. Hydrogen in the mylar tape, used to seal the holes after injection, and the vinyl tape which sealed the lid to the can was included in the H/U calculation.

TABLE II

Elemental Analysis in Weight-Percent of Organic Materials

ELEMENT	CAN			CORE			REFLECTOR[a]			
							Methyl Methacrylate			
	Polyethylene Bag	Mylar Tape	Vinyl Tape	Methyl Methacrylate[b]	Polyvinyl Chloride	Office Tape	Ordinary[b] (19.38%)	Fire-Retardant (79.97%)	Paper (0.49%)	Glue (0.16%)
Hydrogen	14.01	6.83	5.92	7.83	5.25	6.92	7.84	7.16	6.48	11.67
Carbon	84.90	65.50	45.91	59.49	42.52	56.03	59.59	52.03	42.17	86.29
Nitrogen			0.16					0.16		
Oxygen	1.20	27.02	10.82	32.48	1.66	36.32	32.23	29.82	49.50	1.20
Phosphorus								1.02		
Chlorine			25.73		5 .14			1.84		
Calcium			6.9							
Bromine								7.10		
Aluminum			0.5							
Silicon			0.6							
Titanium			1.6							
Zinc			0.1							
Lead			1.1							
Total	100.11	99.35	99.34	99.80	99.57	99.27	99.66	99.10	98.15	99.16
Density (g/cm^3)	0.824 ± 0.004	1.110 ± 0.002	1.310 ± 0.006	1.185 ± 0.001	1.318 ± 0.008	1.189 ± 0.003	1.185 ± 0.001	1.284 ± 0.001	0.766 ± 0.001	0.728 ± 0.007

[a]Values in parentheses are weight-percent of the four components of the plastic basic reflector shell.

[b]Values under "Core" heading averaged over plastic < 3 cm thick, while "Reflector" data averaged over material > 3 cm.

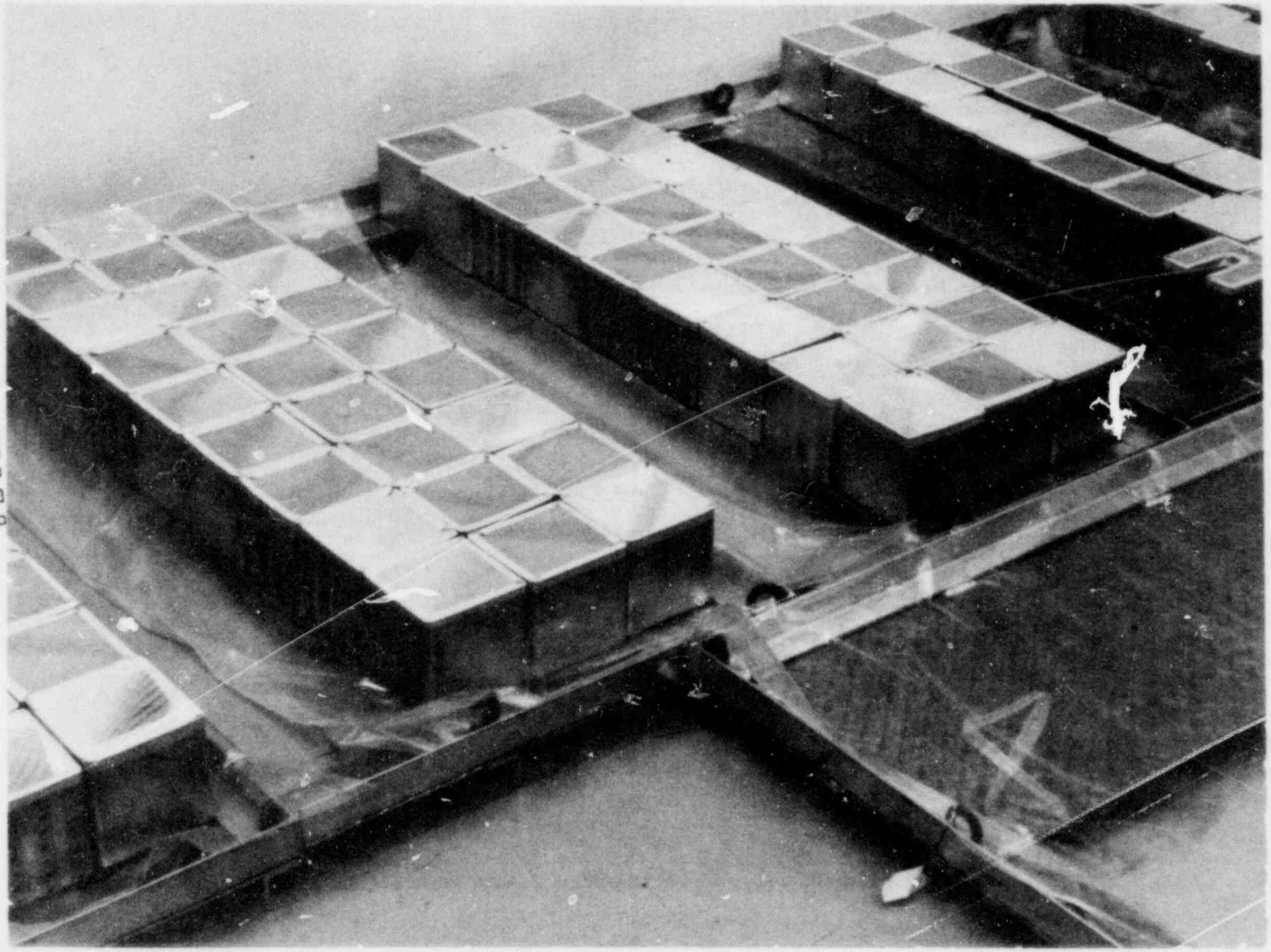

FIGURE 6

A partial collection of finished cans. The trays were used to facilitate loading.

TABLE III

Properties of an Average[a] Uranium Oxide Can

PROPERTY[b]	VALUE OR WEIGHT (g)	COMPOSITION See:	HYDROGEN OR [URANIUM]	
			Wt-%	Weight (g)
H/U Atomic Ratio	0.768 ± 0.005			
Uranium Oxide				
as received[c]	15129 ± 34	text		
uranium oxide	15088 ± 39	text	[84.49]	[12748 ± 33]
absorbed water	41 ± 20	nominal	11.19	4.6 ± 2.2
Water Injected	273 ± 4	nominal	11.19	30.5 ± 0.5
Total Water Content	314 ± 20	nominal	11.19	35.1 ± 2.3
Drilled Aluminum Can/Lid	526 ± 3	Table VII	0	0
Polyethylene Bags	53 ± 2	Table II	14.01	7.43 ± 0.28
Mylar Tape	4	Table II	6.83	0.27
Vinyl Tape	3	Table II	5.92	0.18

[a] Averaged over 125 cans. Important can parameters for critical experiments having fewer cans are given in Tables V and XIV for the specific cans used.

[b] See discussion in Uncertainties section for method of calculating standard deviations.

[c] The uranium oxide as received from the manufacturer contained 0.27 ± 0.13% moisture. The next two lines give the distribution.

Water Measurement

The amount of water contained in the uranium oxide is a very important parameter of this program because it forms the principal contributor of hydrogen in obtaining the desired H/U ratio. Most was intentionally injected into the oxide, but a smaller amount was absorbed from the atmosphere over the several months between calcination and injection, even though sealed in metal cans.

The water content was measured by two independent methods, and the H/U critical parameter of Table XIV was obtained by averaging both methods for each can and then averaging these data over the specific cans used. A method called "Thermogravimetric Analysis" (TGA) was one. A small sample of damp material is weighed initially and continuously as the sample is heated in a helium atmosphere up to $\sim 500^{o}$ C. The weight loss is primarily moisture. Up to $\sim 200^{o}$ C, it is presumed to be entirely the loss of absorbed water, while from there to $\sim 500^{o}$ C, 78 ± 15%* of the weight loss is attributed to the evolution of waters-of-hydration. The remainder of the weight loss in this second temperature interval is found to be the evolution of CO and CO_2 gases. The relatively large uncertainty (± 15%) in the water released between 200^{o} and 500^{o} C, coupled with the necessarily small-scale sampling of the damp oxide (not known

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* Determined by a method called dynamic mass spectrometry.

a priori to be homogeneous) yields a relatively large uncertainty in the moisture content by this method:

$$0.0186 \pm 0.0035 \text{ g } H_2O \text{ per g damp oxide} \qquad \text{(TGA)}$$

The second method of determining the water content used the oxide and injected-water weight data obtained during can preparation. The small amount of water absorbed into the oxide as received was measured by the TGA method (0.0027 ± 0.0013 g H_2O/g received oxide). Then these data were combined as follows:

$$\frac{\text{(g water injected)} + \text{(g absorbed water)}}{\text{(g received oxide)} + \text{(g water injected)}}$$

to yield another measure of the total water content of damp oxide (averaged over all 125 cans):

$$0.0204 \pm 0.0013 \text{ g } H_2O \text{ per g damp oxide} \qquad \text{(INJECTION)}$$

The H/U atomic ratio was calculated using an average of these two methods for the hydrogen contribution due to water.

One can was selected for destructive analysis thirteen months after injection to determine whether the water was distributed uniformly throughout a block and, also, throughout a can. Fifty samples were obtained from random locations within the can, with all seven layers sampled about equally. In addition, two blocks were sampled at four and nine places,

respectively. The TGA method of analysis was used. The standard deviation of all of these measurements was ~ 12% of the mean value, and no systematic bias was observed relative to a sample's proximity to a water injection hole.

Three other methods of measuring this important parameter were tried and rejected:

1. Karl-Fischer Titration - Titration continues until the affinity of the reagent for moisture is about the same as that of the oxide. The fraction of waters-of-hydration bound to the oxide reached by the reagent is uncertain. This method is presently being studied further, and improvements may make it viable.

2. Nuclear/Electronic Backscatter Device (frequently employed by paving companies) - Natural radiation from the uranium contributed a background indistinguishable from water. Also, the attainable geometry may have been unacceptable for this device.

3. Acetylene Gas Generation - The partial pressure of gas evolved in the interaction of calcium carbide and moisture was measured. The fraction of the total water actually reached by the calcium carbide is questionable.

Weight Gain

All cans were weighed periodically over the sixteen months of the experimental program, and a slow but continual increase in weight was noticed for almost every can.

At packaging, the 125-can inventory summed to 1,998,590 g. The total gain during the program was 3914 g, or 31.3 g per can (0.2%). Not all cans gained weight at the same rate. The largest gain was 51 g, the smallest 3 g. The weight gain for all 125 cans is shown in Figure 7. The standard deviation of this distribution is ± 8.2 g.

This gain is attributed to oxygen from the atmosphere reacting chemically with the uranium oxide, even though tape had been applied to the cans to seal them. Such a small increase, if due to oxygen absorption, causes no significant effect (worst case: $\Delta k = 0.001$) on critical parameters because oxygen is neither fissile nor an effective moderator or absorber. The belief that oxygen is responsible for the weight gain is based on a simple experiment and a literature search. In the experiment, four cans, selected at random, were sealed in separate containers to eliminate further contact with ambient atmosphere. One container was flushed with pure oxygen, while a second was given an atmosphere of argon gas. The third can was stored along with a desiccant, while the last shared the container with an open pan of water to create a very humid interior. The two containers with gases would test the hypothesis that the weight gain was caused by oxygen absorption. Those with dry and humid atmospheres would test an assumption that the weight gain was due to atmospheric moisture pickup. Over 53 days, the can in the oxygen atmosphere gained 16 g, strongly supporting

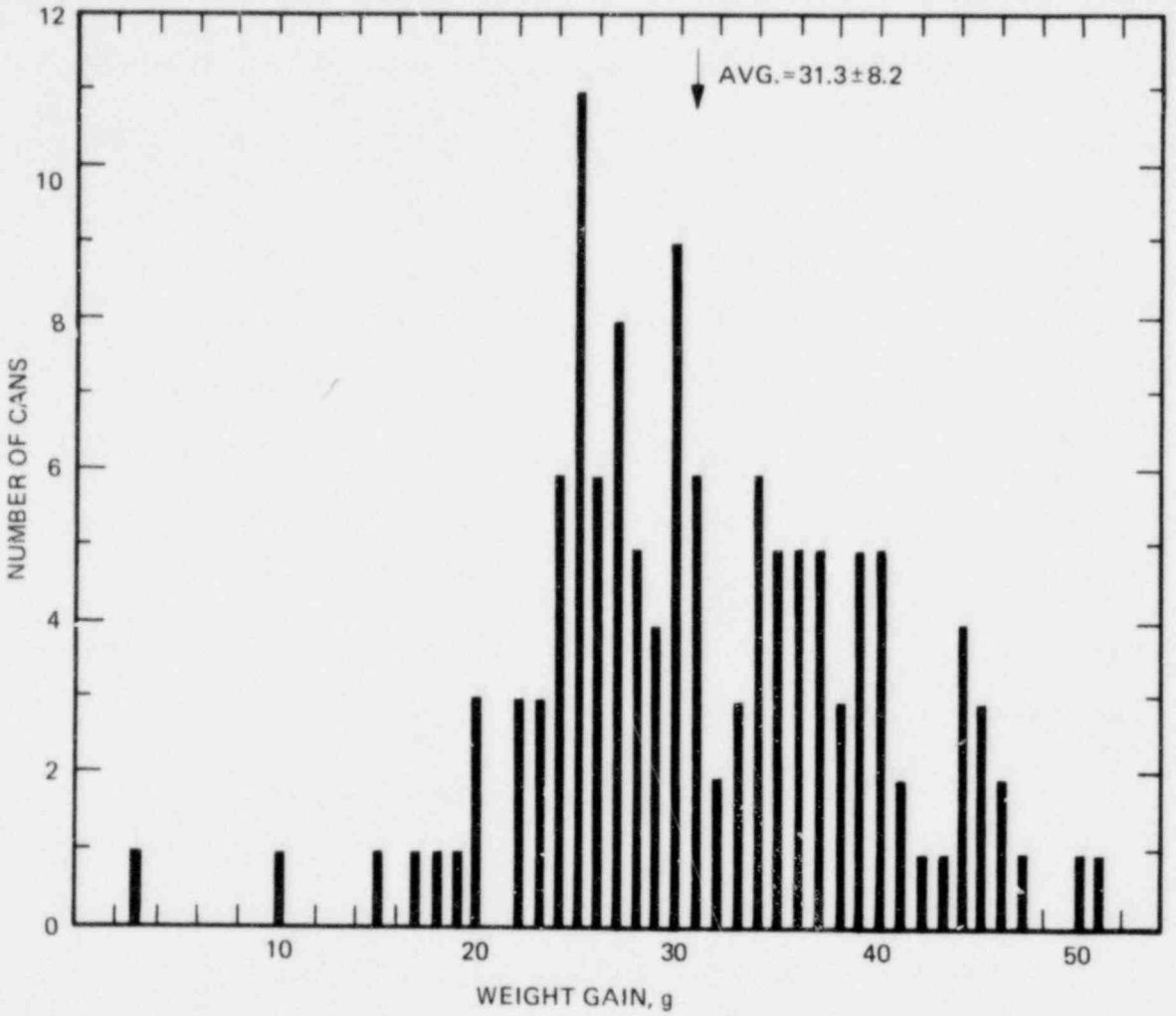

FIGURE 7

Oxide can weight gain over 16 months.

the contention that oxygen is being absorbed. The can in the argon atmosphere gained 2 g, just slightly greater than the readability of the scale. The can in the dry container lost 3 g, while the one in a humid atmosphere gained 4 g, both consistent with only a small mobility of moisture through the "sealed" oxide can.

A literature survey revealed that the stable oxide of uranium at room temperature is UO_3, but the stable form at elevated temperatures ($> 500^{o}$ C) is U_3O_8 (reference 9). The oxide used in this program was formed by calcination at temperatures considerably above this, so the material packaged is presumed to have been nearly all U_3O_8. As time passed, oxygen may have diffused through the tape, causing the following reaction:

$$2U_3O_8 + O_2 \rightarrow 6UO_3$$

Here, U_3O_8 may be viewed as $UO_2 \cdot 2(UO_3)$, and the first oxide is the one "burning" to the UO_3 state. This oxidation of UO_2 is enhanced for particle sizes on the order of 1 μ [9], and 93% of the oxide particles lie in the 1 to 10 μ range. These assumptions are consistent with x-ray diffraction findings for this oxide. Both U_3O_8 and UO_3 are orthorhombic [10], and this is found to be the major oxide present. A small portion of the oxide is found to be cubic with a nominal formula $UO_{\sim 2.3}$. This could be a small admixture of the oxide state U_4O_9.

INTERSTITIAL MATERIALS

Every core contained an array of oxide cans and some amount of plastic as interstitial moderator. Thin plates of neutron absorbing material surrounded cans for category P, M, m, and T experiments, while those of category E contained aluminum spacer bars. The construction and composition of the cans was given in the preceding section. This section will provide the same detail for all other core materials.

Moderator

All interstitial moderator material was methyl methacrylate plastic. Its elemental composition is given in the "CORE" portion of Table II. The weight-percents given are simply the average of three samples, one from sheet stock of each nominal thicknesses studied in this program.

The weights and dimensions of all 377 flat pieces of moderating plastic and the 64 boxes used in category E experiments are given in Table IV. All this material was cut from commerical plastic sheet which varies considerably in thickness from sheet to sheet and even across a given sheet. Consequently, some variation in weight among pieces of the same nominal size was observed. Not all pieces in a given category were used on any one experiment, and those used were selected at random from all items of the same

TABLE IV

Average Dimensions in cm and Weights in g
of the Complete Inventory of Moderator Plastic

CATEGORY	LENGTH x WIDTH	THICKNESS	WEIGHT	PRIMARILY USED BETWEEN	NUMBER ON INVENTORY[a]
U	64.0 x 31.7	0.916 ± 0.015	2186	layers	10
	64.1 x 15.3	0.916 ± 0.018	1066	rows	12
	15.3 x 15.3	0.935 ± 0.020	252.7	cans	60
	15.2 x 15.2	0.932 ± 0.023	252.9	cans[d]	15
	81.1 x 76.1	0.938 ± 0.034	6703	columns[d]	1
	64.1 x 15.2	0.945 ± 0.019	1082	layers[d]	4
	132.3 x 121.9	0.924 ± 0.022	17513	tables[c]	1
average thickness of above material: 0.929 ± 0.011					
T	65.4 x 32.2	1.23 ± 0.03	3035	layers	8
	65.3 x 15.2	1.24 ± 0.03	1438	rows	10
	15.2 x 15.2	1.22 ± 0.02	332.1	cans	50
	15.1 x 15.1	1.23 ± 0.02	346.8	cans[d]	64
	81.1 x 76.0	1.24 ± 0.07	8946	columns[d]	1
	65.4 x 15.2	1.22 ± 0.04	1412	layers[d]	4
	132.3 x 127.3	1.23 ± 0.03	24173	tables[c]	1
	132.3 x 127.3	1.23 ± 0.02	24214	tables[c]	1
average thickness of above material: 1.23 ± 0.01					
O, P, M, m	69.7 x 33.5	2.42 ± 0.04	6681	layers	9
	69.8 x 15.1	2.45 ± 0.06	3046	rows	10
	15.3 x 15.3	2.41 ± 0.06	671	cans	50
	132.3 x 127.3	1.23 ± 0.03	24173	tables[c]	1
	132.3 x 127.3	1.23 ± 0.02	24214	tables[c]	1
S[b]	63.4 x 30.4	2.47 ± 0.05	5506	layers	2
	63.5 x 30.1	2.50 ± 0.07	5581	layers	2
	30.4 x 30.4	2.44 ± 0.05	2636	supercans	4
	15.3 x 15.3	2.41 ± 0.06	671	supercan edges	50
	81.2 x 76.4	2.47 ± 0.08	17881	columns[d]	4
	132.3 x 127.3	1.23 ± 0.03	24173	tables[c]	1
	132.3 x 127.3	1.23 ± 0.02	24214	tables[c]	1
average thickness of 2.5 cm material: 2.44 ± 0.03					
F	weight of box, less top		1988 ± 19		64
	weight of box top		471 ± 6		64
	weight of complete box		2459 ± 20		64
	weight of acetone (glue)[e]		0.5 ± 0.3		
	thickness of walls		1.238 ± 0.013		

[a] Not all pieces on inventory within a category used on any one experiment.

[b] Used some material from the O, P, M, m block of this table.

[c] These are the faceplates.

[d] Pieces fabricated separately from above because of the need to build arrays larger than 64 cans. These pieces used in conjunction with the 5th vertical face of cans on the south side of the array.

[e] Weight of finished box (less top) minus weight of five pieces used to make that box.

nominal size. Usually, the weight of specific moderator pieces in each experiment was obtained by weighing those used after an array was disassembled.

On a few early runs, these weights were obtained by multiplying the number of pieces of each size used by the average weight of the entire inventory of that size. The difference between the two methods is negligibly small.

The total weight of plastic moderator within the core cuboid is given in Table V for each of the 21 critical configurations reported. Two weights are shown, but only one - the "Interstitial Weight" - would have been necessary had every cuboidal array been fully-packed* with cans. Unfortunately, 15 experiments (of the 19 using flat plastic pieces as moderator, which excludes the two category E experiments) had one plane of cans incompletely filled, resulting in some kind of departure from the moderator/oxide can assembly procedure found elsewhere in the core. The second plastic moderator weight of Table V, labeled "Non-Interstitial Weight", gives the weight of plastic within the core cuboid which had at least one of its faces not in contact with a can of oxide**. Whenever one piece of plastic spanned both descriptions, its weight was properly apportioned

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*Such as 100 cans (4 x 5 x 5), 80 cans (4 x 4 x 5), 64 cans (4 x 4 x 4), and 48 cans (4 x 4 x 3).

**For the immediate discussion, any separation between two approaching faceplates is ignored, and two faceplates are assumed to constitute one moderator thickness.

TABLE V

Critical Data: Core Weights in kg and Thicknesses in cm

Experiment Number	Oxide Can		Plastic Moderator			Absorber/(Aluminum)		
	Total Weight as Packaged[a]	Weight Gain to Date[b]	Thickness	Interstitial Weight	Noninterstitial Weight	Thickness	In-Core Weight	Core-to-Reflector Weight
PLASTIC REFLECTOR								
1	671.59	0.95	2.43	65.17	6.01	--	--	--
2	687.61	1.26	2.43	66.85	5.47	--	--	--
3	1599.16	2.81	0.93	70.94	0.0	--	--	--
4	1599.16	2.81	0.93	72.74	0.0	--	--	--
5	1183.49	1.97	2.43	66.46	6.39	--	--	--
6	895.62	1.36	2.43	92.86	7.02	0.054	5.44	--
7	959.56	1.40	2.43	101.77	7.10	0.117	78.05	--
8	991.56	1.44	2.43	106.53	3.86	0.117	80.65	--
9	815.52	1.24	2.43	83.05	10.94	0.060	34.15	--
10	1599.12	2.62	1.23	93.11	0.0	0.117	119.14	--
11	991.57	1.75	1.24	152.47	0.0	--	(12.48)	(3.84)
12	1023.57	1.84	1.24	157.37	0.0	--	(13.02)	(7.44)
CONCRETE REFLECTOR								
13	639.59	1.20	2.43	62.34	12.83	--	--	--
14	639.59	1.20	2.43	62.34	12.83	--	--	--
15	1567.27	3.04	0.92	60.86	1.82	--	--	--
16	1599.16	3.10	0.92	62.68	0.0	--	--	--
17	1535.37	3.00	2.45	55.96	2.79	--	--	--
18	831.64	1.56	2.43	85.35	11.76	0.054	4.97	--
19	847.65	1.59	2.43	86.85	10.93	0.054	5.20	--
20	927.59	1.76	2.43	96.68	6.79	0.117	74.35	--
21	943.60	1.80	2.43	99.11	5.05	0.117	75.62	--

[a] Based on initial weight of each can at the time of packaging (Nov/Dec 1977), summed over actual cans used, not just the average weight of the entire inventory times the critical number of cans.

[b] Increase in weight to the approximate date of the experiment, summed over actual cans used.

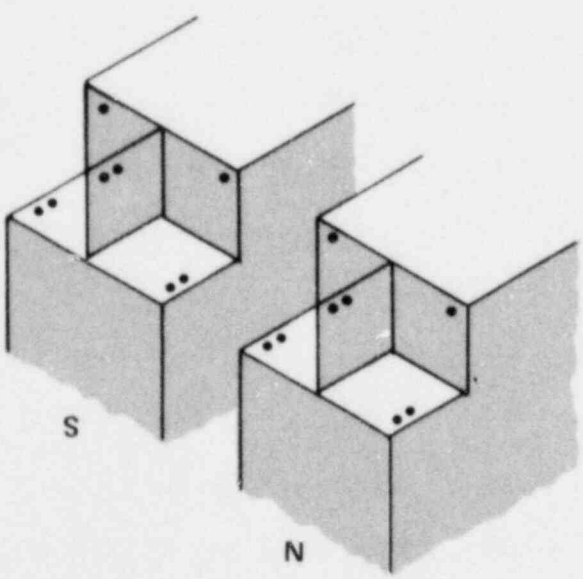
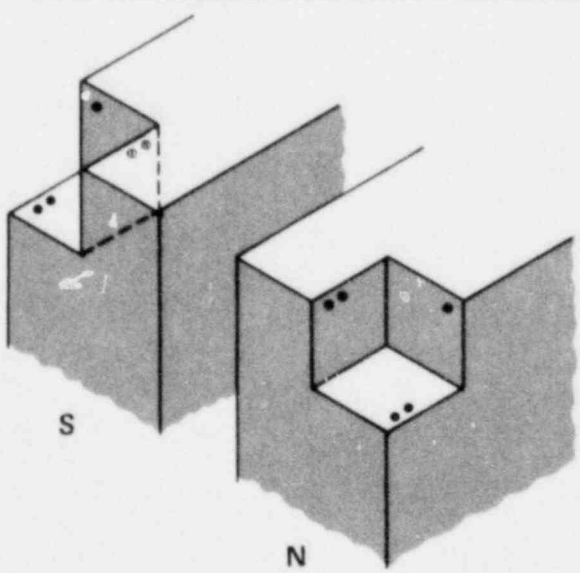
as "interstitial" and "noninterstitial" and included in the respective sums. A detailed knowledge of the location of such noninterstitial material is essential to a complete specification of these fifteen cases. To illustrate its importance, criticality would not occur for one particular array (#13), even with the table closed, until two pieces of noninterstitial moderator were added. Table VI describes the noninterstitial moderator for all cases, although the definition breaks down for category E experiments where a box would be absent only when its associated can was also absent.

The faceplates on the closing faces of the two tables served as interstitial moderator, but part of them always extended into the reflector region since they were screwed to the reflector shell. This was a greater perturbation to concrete-reflected cases than to plastic-reflected ones because the faceplate composition was nearly identical to that of the plastic reflector. The full weight of any faceplates used, however, was always properly apportioned as "interstitial moderator", "noninterstitial moderator", or "reflector". Faceplates contributed noninterstitial moderator in six of the twenty-one cases. Experiments #7, #18, and #21 had one, two, and one can vacancies, respectively, symmetrically located on <u>both</u> sides of faceplate

TABLE VI

Specification of Noninterstitial Plastic Moderator Within the Core Cuboid (Excluding Faceplates)

Experiments 3*, 4*, 10*, 11+, 12 and 16
FULL ARRAY - No deviation from interstitial moderation. *Experiments #3, #4, and #10 (categories U and T) had additional faceplate material between the two tables but no other perturbations. +Experiment #11 (category E) had two cans missing from a full array; but their associated plastic boxes were also absent.
Experiments 1, 2, 6 and 9
ONE-HALF THE MODERATOR THICKNESS, characteristic of the remainder of the core, touched each face of every present can when that face was exposed to a vacancy.
Experiments 5*, 13, 14 and 15
THE FULL MODERATOR THICKNESS, characteristic of the remainder of the core, touched each face of every present can when that face was exposed to a vacancy. *Experiment #5 (category S) satisfied these conditions in terms of the 2 x 1 x 2 supercan unit, except that the top surface of the sole partial supercan [refer to Figure 13 (n)] had no moderator at all.
Experiments 17, 18, 19, 20 and 21
THE FULL MODERATOR THICKNESS, characteristic of the remainder of the core, separated present cans of the next-to-top layer from vacancies in the top layer; but no plastic was present on vertical surfaces in the top layer which faced a vacancy.

Experiment 7	Experiment 8
	

These are portions of Figures 13, (j) and (k) but viewed southwest and down. Surfaces shown with a single or double dot are covered with 1.3-cm and 2.5-cm-thick plastic, respectively. One surface, (..), is still hidden from view. The shaded regions represent 2.5-cm-thick moderator having cans on neither side.

material*. Experiments #9, #19, and #20 had two, one, and one, respectively, vacancies symmetrically on both sides* plus one can contacting a faceplate with a vacancy in the corresponding position on the other table*.

Because commercial plastic sheet varies considerably in thickness, the separation between layers could differ from that between cans in a layer. Average thicknesses for the 377 pieces used as moderating plastic on one experiment or another are given in Table IV. The data cover the complete inventory, and no distinction between two pieces of the same nominal size was made in any experiment.

The plastic moderator thickness, also given in Table V for each of the 21 critical configurations, is the average for all three directions of the core. The thickness in each direction is obtained from Table IV, averaged over the appropriate number of pieces of each size in that direction. Consider a Category U experiment as a clarifying example. If a typical north/south line through the core encountered two pieces described by the second line of Table IV, one piece described by the fifth, and one faceplate (Line 7), then the average moderator thickness in the north/south direction would be:

$$1/4\ [2(0.916) + 0.938 + 0.924] = 0.924 \text{ cm}$$

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* For the immediate discussion, any separation between two approaching faceplates is ignored, and two faceplates are assumed to constitute one moderator thickness.

Category E experiments differed from all others. Plastic sheet 1.24 cm thick was cut into pieces and glued together to form a five-sided box. Acetone was used to weld the the joints: 0.5 ± 0.3 g per box. Next, a can was placed inside the box and a top was held in place with ordinary tape. Figure 8 shows a typical oxide can boxed in this fashion. About 5 g of tape was used to box all 64 units. The completed box (including lid) formed a 18.1 cm cube (outside dimension) with 1.238-cm-thick walls. The interior cavity was ~ 0.3 cm larger than a can, providing clearance for each assembly and disassembly.

Absorber

Both polyvinyl chloride and mild steel were used as neutron absorbing material in conjunction with plastic moderator. These absorbers were sheared into 15.3-cm-square plates, with six surrounding each can in contact with the aluminum. This construction approximates cans fabricated of the absorber material because aluminum is relatively ineffective at moderating or absorbing neutrons. During assembly, some plates were held in place with short lengths of ordinary office tape. About 16 g of tape were required in constructing a 64-can array. The composition of the tape is given in Table II.

The polyvinyl chloride was 0.054 ± 0.001 cm thick, and its elemental composition is also given in Table II. Each

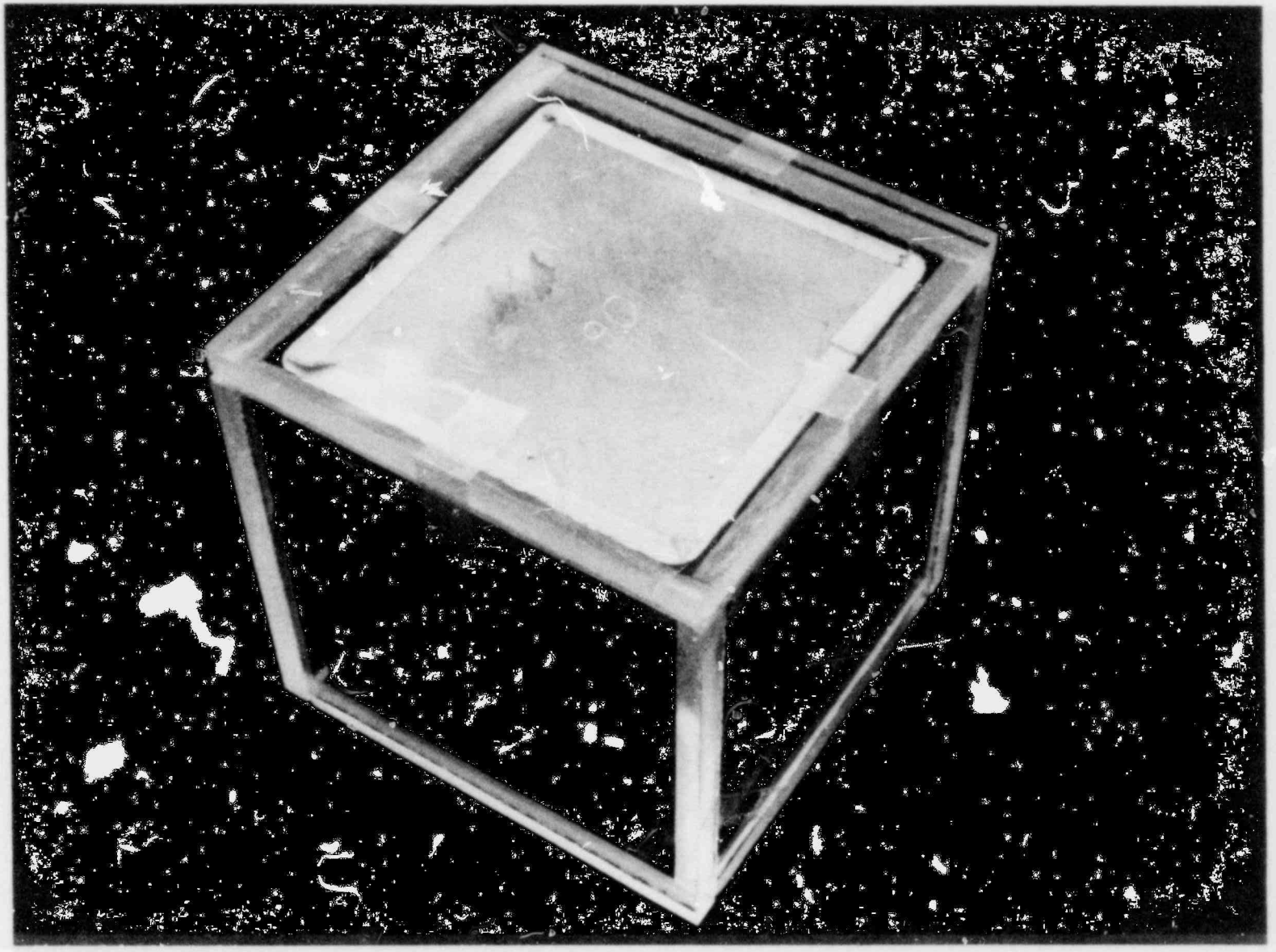

FIGURE 8

An oxide can enclosed in plastic box for Category "E" experiments. Ordinary office tape held the lid onto the box.

plate weighed 16.3 g. Three of twenty-one cases contained this material. One (#18) had eight pieces inadvertently omitted during assembly. Those missing were the top plates on the bottom layer of cans on the south table.

Two thicknesses of mild steel were used: 0.060 ± 0.004 cm (Category m) and 0.117 ± 0.002 cm (Categories M and T). The thinner steel plates weighed 111.6 g each. Each thick plate weighed 217 g, although a few dozen additional plates had to be fabricated for the larger array of Experiment #10, and they turned out somewhat lighter (210 g). No distinction between the two slightly different plates is made, although the absorber weights given in Table V for the experimental assemblies are the actual measured weight of the plates used. The elemental composition of both mild steels is given in Table VII. Five cases included the thicker mild steel as neutron absorber, with only one thin-absorber case reported.

Criticality did not occur even with 100 cans for the Category T experiment (#10). To increase reactivity, twenty steel plates were intentionally deleted from each of the two closing faces (just behind the faceplates) on the two tables. With this modification and the increased reactivity of a second faceplate (double moderator thickness), criticality did occur.

TABLE VII

Elemental Analysis[a] in Weight-Percent of Metals

ELEMENT	CAN Including Lid[b]	WITHIN THE CORE			BETWEEN CORE AND REFLECTOR		BEYOND REFLECTOR		
		Thick Absorber	Thin Absorber	Spacer	Spacers Expt #11	Spacers Expt #12	Table Tops	See Fig.1[d]	Table Bottom
	1100 Aluminum	Carbon Steel			Several Types of Aluminum[c]		304L Stainless	Several Types of Mild Steels	
Carbon		0.065	0.034				0.024	0.267	0.25
Magnesium	< 0.01			1.16	1.01	0.87		< 0.001*	< 0.001*
Aluminum	(99.33)	0.07*	0.015*	(97.23)	(97.41)	(98.44)		0.006*	< 0.001*
Silicon	0.10			0.56	0.18	0.18		0.211*	0.1*
Chromium	< 0.01	0.08*	0.04*	0.08	0.05	0.06	19.7	0.084*	0.1*
Manganese	0.007	0.34	0.33	0.065	0.12	0.01		1.1	0.7
Iron	0.42	(99.27)	(99.50)	0.24	0.2	0.20	(70.0)	(98.24)	(98.73)
Nickel		0.07*	0.05*				10.3	0.034*	< 0.001*
Copper	0.12	0.06*	0.02*	0.65	0.99	0.20		0.037*	0.1*
Zinc	0.005			0.02	0.04	0.04		0.01*	0.01*
Molybdenum		0.05*	0.01*					0.010*	0.01*
Density (g/cm^3)	2.713 ± 0.002	7.863 ± 0.005			2.709 ± 0.002		7.93[e]	7.84[e]	
Categories	All	M, T	m	E	E (#11)	E (#12)	All		

[a] Analytical methods used: ordinary type (except carbon) - atomic absorption (± 5%); all five carbon entries - Leco combustion (± 10%); asterisked - emission spectroscopy (± factor of 2); parentheses - major elements, determined "by difference" from 100%.

[b] Can and lid analyzed separately. Average weighted according to number of sides.

[c] Average weighted over several types and shapes used. See text for details.

[d] Average weighted over all steel slabs, round bars, and I-beams seen on or above the two stainless steel tables shown in the figure or screwed to bottom of reflector panel.

[e] Nominal density.

Spacers

The plastic-boxed oxide cans of Category E experiments were held in their "expanded" configuration by aluminum pieces. Examples of all such pieces are visible in Figure 9. Layers were separated by "trays" consisting of eight 1.27 x 1.91 cm bars strung on two 0.64-cm-diameter rods. In Experiment #11, the bars were as shown in Figure 10; the larger vertical separation of Experiment #12 was achieved by rotating the eight bars 90°. Boxes were spaced 1.27 cm in an east/west direction for both experiments because of limited space within the reflector. Short lengths of square bar stock provided this separation for two layers at a time. The north/south separation between boxes was achieved in a similar fashion using short lengths of other bar stock (0.64 cm x 1.27 cm for Experiment #11, and 0.64 cm x 1.91 cm for Experiment #12) strung on a length of aluminum welding rod. Where possible, the plastic boxes were spaced from the plastic reflector shell by one-half the spacing between boxes. Again, lengths of aluminum bar and rod stock were used for this purpose.

The total weights of all aluminum used in the two Category E critical experiments are given in Table V enclosed in parentheses to distinguish them from PVC or steel weights. The incomplete rectangular array of Experiment #11 (62 cans) had 511 g of "noninterstitial aluminum" in the same sense that plastic moderator was sometimes

regarded as noninterstitial. The weight of aluminum used to hold the array away from the reflector walls is also given in the last column of Table V. The elemental composition of aluminum both in the core and that holding the core away from the reflector shell is given in Table VII. Several aluminum types were used in this application, but only the average, weighted in proportion to the abundance of each type used, is given because the total amount of aluminum used is so small. The trays were fabricated of type 6061 bar stock on type 2011 rods. The east/west spacers were type 2017, and north/south spacers were about half type 2024 and half type 6063.

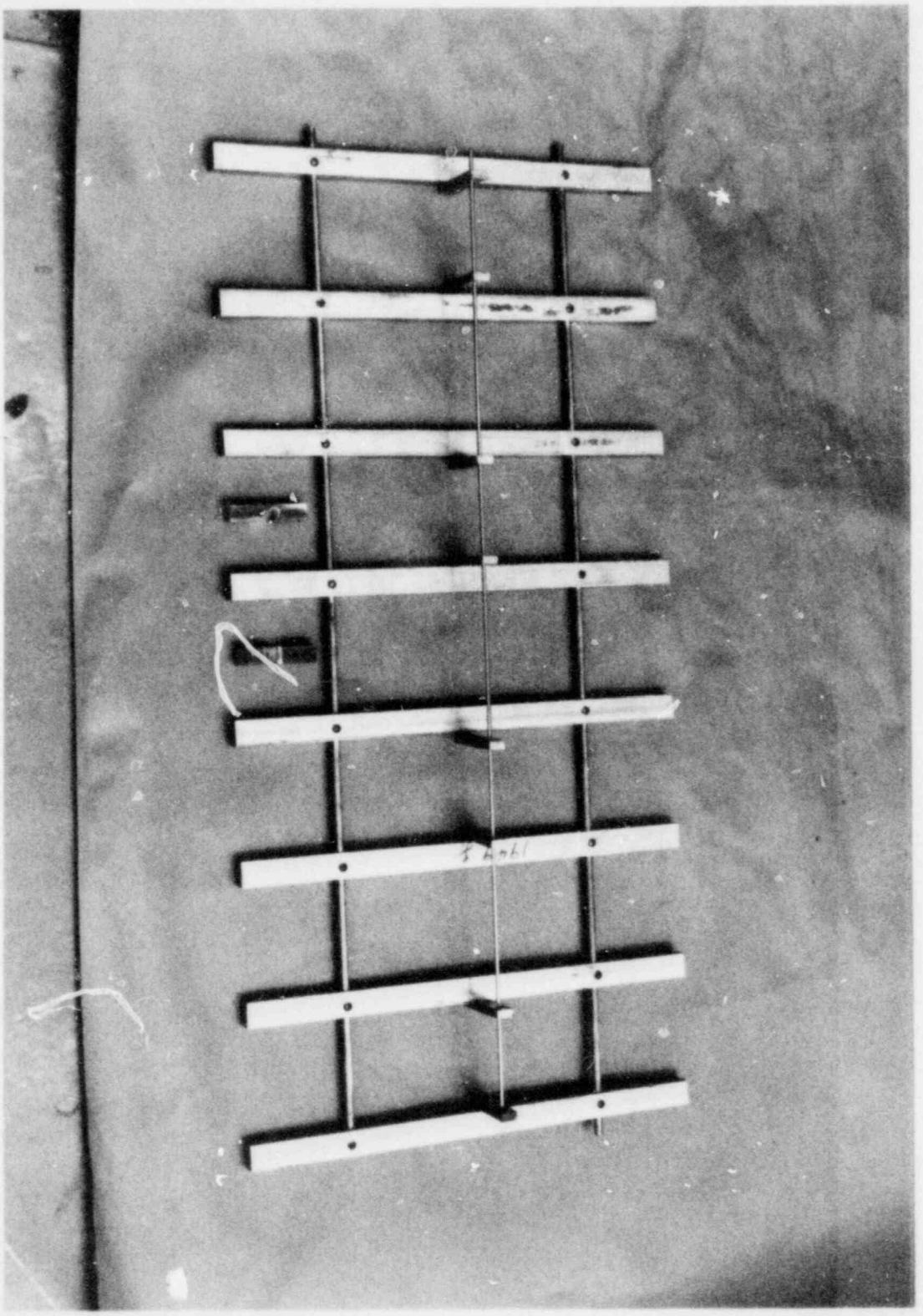

FIGURE 9

The aluminum bars and rods for Category E experiments.

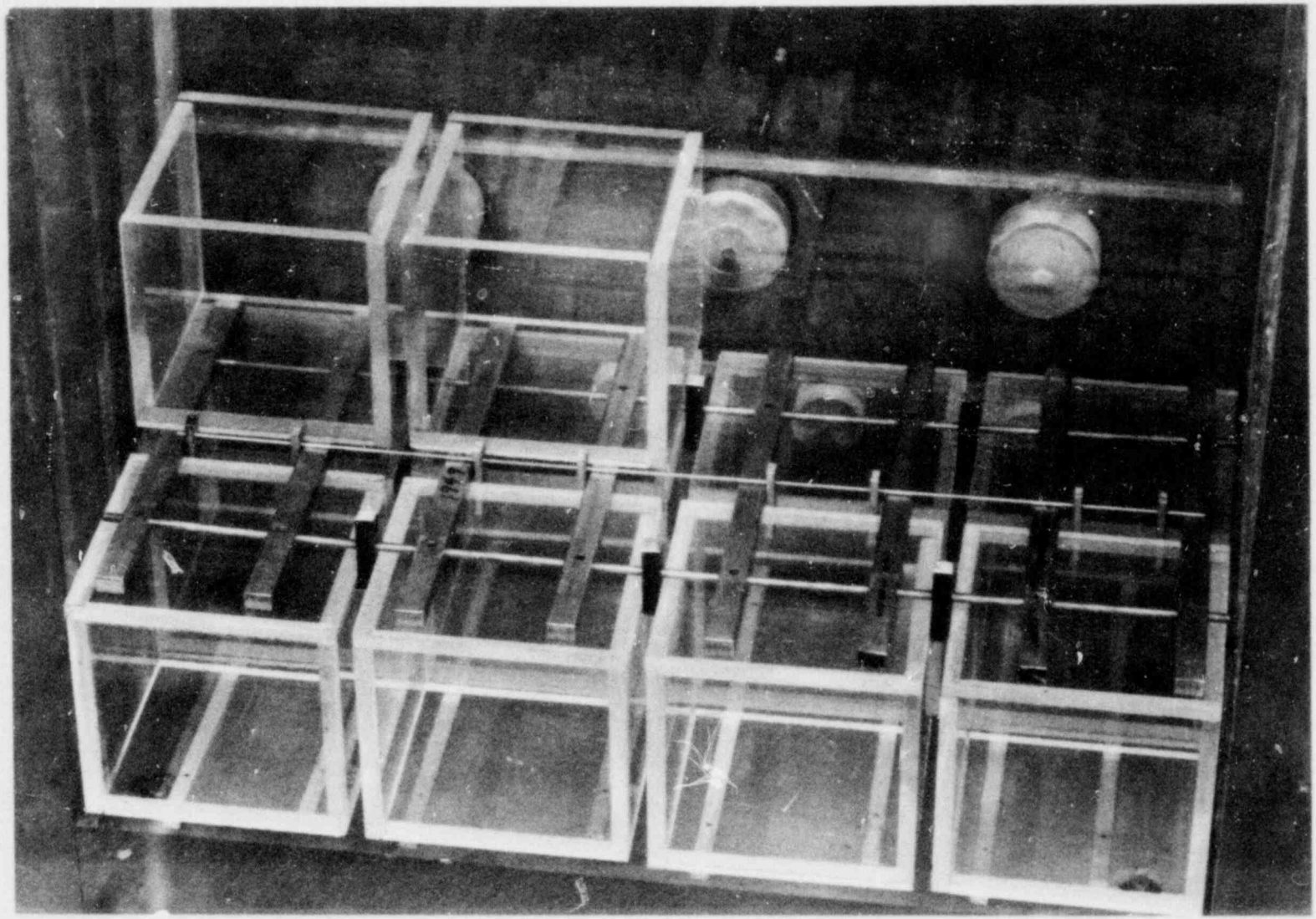

FIGURE 10

A mock array (no oxide) for Category E experiments. The figure illustrates how aluminum bars and rods held the plastic boxes apart from one another and half that distance from the walls of the reflector shell. Neutron detectors were located in the partial holes visible in the end panel behind the array.

REFLECTOR

The plastic reflector was used for Experiments #1 through #12, the concrete for #13 through #21. Whenever either was being installed, the two frame sections were aligned relative to one another until their west interior walls and bottom interior surfaces were coplanar on the two tables. These were defined earlier to be "key planes". The pitch and yaw of the two tables relative to one another was also shimmed until the facing surfaces of the two frames were as nearly parallel as possible. These surfaces formed two other "key planes", as defined earlier.

This multidimensional alignment proved difficult. The faces of the two frames were not perfectly flat, so a small gap existed at one place when they touched at another. Sometimes this problem was accentuated by a small bowing near the center of the faceplates resulting from slight can movement during normal operations. The addition of weight (the array and end reflector panels) sometimes altered the alignment slig v. Imperfectly cast end panels left slight gaps to the corresponding frame section. Sometimes this gap exposed oxide cans, and other times it merely looked upon reflector material in the form of a back filler piece. None of these perturbations was large but simply the consequence of working with large, massive blocks of plastic and concrete.

Nevertheless, their magnitude is evaluated in later tables (see RESULTS section).

Most arrays proved too large in the north/south direction for the cavities formed within the reflector shells, so frame extenders were used as described in the EQUIPMENT section. Plastic-reflected experiments employed plastic extenders of three thicknesses (1.2, 7.4, and 8.6 cm) on the north table and one (2.4 cm) on the south. Concrete-reflected experiments had only two thicknesses (1.3 and 1.9 cm) used on the north table only. Such thin sections of concrete could not be handled safely, so a concrete/asbestos composition material called Transite®* was used instead.

Some metal was unavoidable in fabricating these assemblies. Threaded tie bolts held together the laminated plastic reflector pieces, while the concrete had rebar embedded for strength. Other metal facilitated handling and assembly. The weights of plastic, concrete, and steel in the various reflector pieces and frame extenders are given in Table VIII. The table also gives dimensions for each piece. The metal weight does not include the steel plate immediately below the reflector shell, visible in Figures 2 and 3, nor any metal of the split table machine. These are discussed separately in the next section.

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* Trademark of Johns-Manville Corp., Denver, Colorado.

TABLE VIII

Reflector Shell Weights in kg and Dimensions in cm[a]

	East/West		North/South	Vertical		Total Weight (± 1.0)	Steel Weight[b] (± 0.2)	Experiments Used
	Outside	Inside		Outside	Inside			
PLASTIC REFLECTOR								
North Table								
frame	128.3	77.7 ± 0.3	31.6 ± 0.1	132.5	83.3 ± 0.4	425	9.1	#1 - #12
end panel	128.6 ± 0.4	---	25.6 ± 0.4	134.3 ± 0.4	---	497	7.1	#1 - #12
8.6-cm extension	129.1	78.3	8.6	133.7	83.6	110	2.1	#11
7.4-cm extension	129.1	78.3	7.4	133.7	83.6	94	2.1	#1, #2, #6 - #10, #12
1.2-cm extension	129.1	78.3	1.2	133.7	83.6	15.7 ± 0.1	0	#5
South Table								
frame	128.4	77.3	47.0 ± 0.3	134.6	83.4 ± 0.4	651	10.5	#1 - #12
end panel	128.5 ± 0.5	---	26.5	134.5 ± 0.4	---	564	8.0	#1 - #12
2.4-cm extension	128.3	78.1	2.4	134.0	83.8	30.6 ± 0.2	0	#3, #4, #5, #10
CONCRETE REFLECTOR								
North Table								
frame	128.5	77.5 ± 0.1	32.3	134.1	83.2 ± 0.1	792	5.5	#13 - #21
end panel	128.0 ± 0.3	---	25.6 ± 0.3	134.3 ± 0.4	---	1014	6.2	#13 - #21
1.9-cm extension[c]	128.5	77.5	1.9	134.1	83.2	37.5 ± 0.1	0	#20, #21
1.3-cm extension[c]	128.5	77.5	1.3	134.1	83.2	25.0 ± 0.2	0	#13, #14, #18, #19
South Table								
frame	128.5	77.1 ± 0.4	47.5 ± 0.1	134.3	82.6	1166	10.0	#13 - #21
end panel	128.0 ± 0.3	---	25.6 ± 0.3	134.3 ± 0.4	---	1097	6.2	#13 - #21

[a] Uncertainties in dimension are ± 0.2 cm unless otherwise noted.

[b] The total weight of four "L"-shaped brackets and bolts (visible in Figures 2 and 3) which hold end panel to frame is 11.4 kg (plastic) and 14.4 kg (concrete). These weights are not included in the weight of embedded steel given in this column.

[c] Transite, not concrete.

Geometrical Concept

The reflector shell, with or without frame extensions, formed a cavity within which arrays of oxide cans were assembled. Filler blocks of the same material as the reflector were necessary to occupy space within the cavity but outside the core.

It is convenient to describe each critical configuration by three pairs of nested cuboids, as shown in Figure 11. The three are called (smallest to largest) the "core", "reflector interior", and "reflector exterior" cuboids. One set of three rests on the north table, while the other is mounted on the south. Each set has one coplanar face, and these two planes represent the closing surfaces of the two tables. When the two tables touch, the three pair become one set of three.

The core cuboid for categories O, U, and S includes the outside aluminum surfaces of extreme oxide cans in a row. For Categories P, M, m, and T, this measure includes the neutron absorber sheets to the outside of extreme cans. The core cuboid for Category E experiments is defined to include the 1.2-cm-thick plastic pieces forming the outside walls of boxes for extreme cans and aluminum spacer material holding these boxes away from reflector shell surfaces. The physically-measured core dimensions are listed in Table IX for the twenty-one critical configurations, with the table's lettered dimensions defined in Figure 12. Table IX also

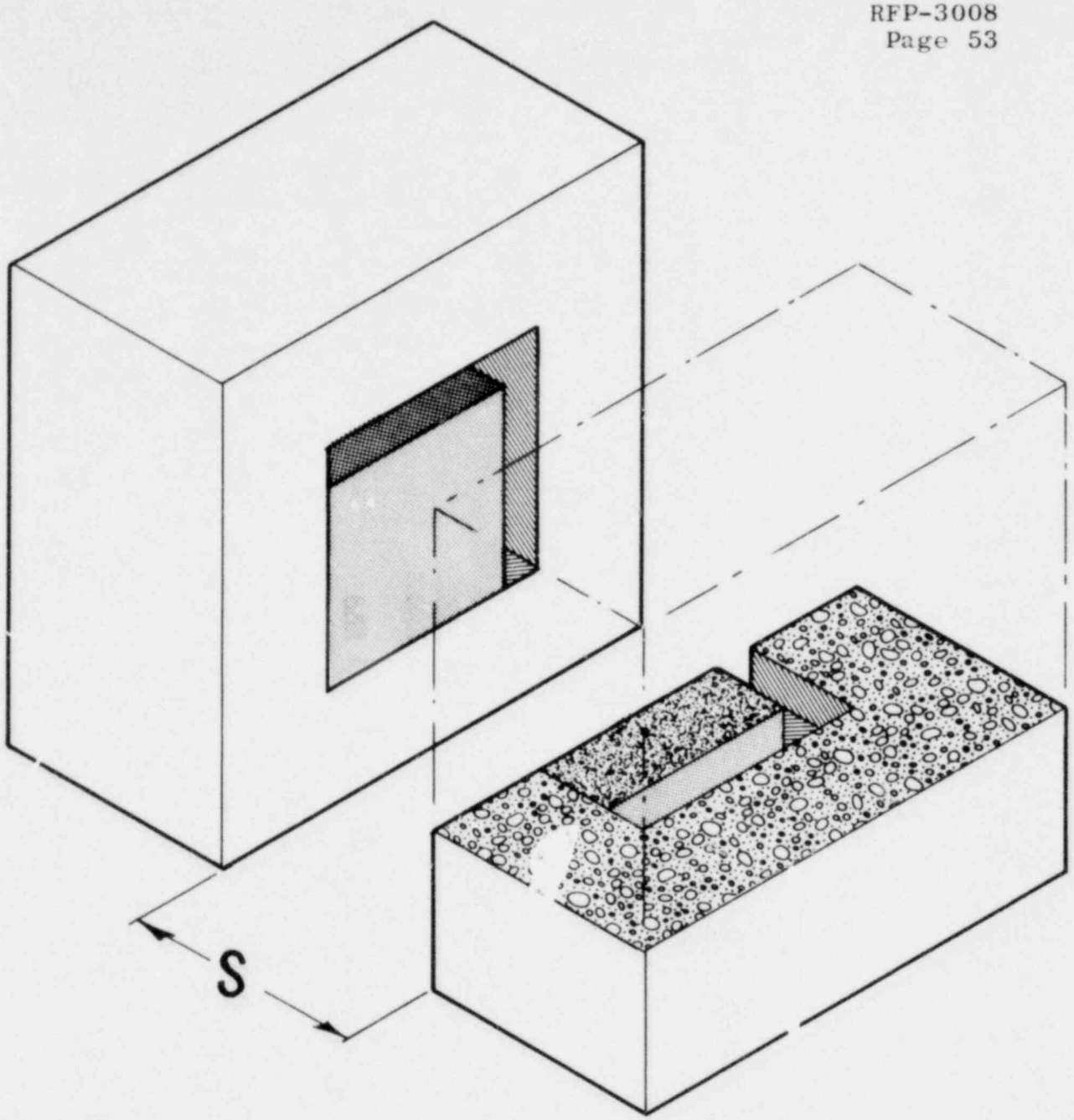

FIGURE 11

Geometrical concept of three pairs of nested cuboids. The smallest, the "core cuboid", is shown by two degrees of solid shading. Portions of floor and wall planes of the "reflector interior" cuboid are shown by cross-hatching. One set of three cuboids has been sectioned by a horizontal plane and then the "reflector exterior" cuboid (only) completed in phantom lines. The three pair of cuboids become one set of three as the separation, S, becomes zero.

TABLE IX

Critical Data: Cuboid Dimensions[a] in cm

EXPERIMENT NUMBER	CORE				REFLECTOR INTERIOR				REFLECTOR EXTERIOR			
	East/West	North/South		Vertical	East/West	North/South		Vertical	East/West	North/South		Vertical
	both	north	south	both	both	north	south	both	both	north	south	both
	A	B	C	D	E	F	G	H	I	J	K	L
PLASTIC REFLECTOR												
1[b]	68.0	34.4	34.4	50.6	68.0	34.7	34.7	50.6	128.4	65.3	74.5	133.6
2	68.8	34.5	34.6	50.8	68.8	35.4	35.2	50.8	128.4	65.8	75.6	133.6
3	63.7	33.4	50.0	80.2	64.5	33.4	50.0	80.2	128.4	58.2	77.6	133.6
4	63.7	33.4	50.3	80.2	64.5	33.4	50.3	80.2	128.4	58.2	77.9	133.6
5	63.9	35.1	52.6	63.6	63.9	35.1	52.6	63.6	128.4	59.2	78.7	133.6
6	69.8	35.2	35.6	68.6	69.8	35.2	35.6	68.6	128.4	65.3	74.5	133.6
7	69.7	34.9	34.9	69.2	69.7	34.9	34.9	69.2	128.4	65.3	74.5	133.6
8	69.7	34.9	34.9	69.2	69.7	34.9	34.9	69.2	128.4	65.3	74.5	133.6
9	69.6	35.0	35.0	69.1	70.0	36.2	36.2	69.1	128.4	65.3	74.5	133.6
10	66.4	33.8	51.0	82.7	66.4	33.8	51.0	82.7	128.4	66.0	77.6	133.6
11	76.4	37.9	38.5	76.4	77.5	38.6	39.1	77.6	128.4	66.1	73.9	133.6
12	76.3	37.9	38.2	78.3	77.5	39.8	39.2	80.2	128.4	64.7	73.9	133.6
CONCRETE REFLECTOR												
13	68.8	34.7	34.7	50.8	70.3	35.0	35.4	52.4	128.5	60.9	74.8	134.2
14	68.8	34.5	34.7	50.8	70.0	34.9	35.4	52.4	128.5	60.9	74.8	134.2
15	64.3	31.8	48.3	80.2	64.4	32.6	48.3	83.0	128.5	58.4	74.9	134.2
16	64.3	31.8	48.3	80.2	64.4	32.6	48.3	83.0	128.5	58.4	74.9	134.2
17	64.0	32.2	47.6	81.2	64.0	34.0	49.0	83.0	128.5	59.6	74.5	134.2
18	69.4	31.8	35.0	68.8	70.1	35.0	35.6	70.3	128.5	60.8	74.7	134.2
19	69.3	34.9	34.9	68.8	70.2	35.1	35.7	70.3	128.5	60.8	74.7	134.2
20	69.8	35.0	35.0	69.4	69.8	36.1	35.0	83.0	128.5	61.8	74.5	134.2
21	69.8	35.0	35.0	69.4	69.8	36.1	35.0	83.0	128.5	61.8	74.5	134.2

TABLE IX (cont'd)

Experiment Number	ADDITIONAL DIMENSIONS														
	Faceplate Thickness		Frame Extender Thickness		Gap[d]		East Side		Filler Thickness					Mass of Other Fillers (grams)	Filler Volume Achieved (%)
									Back		Top		Bottom		
	north	south	north	south	north	south	north	south	north	south	north	south	both		
	M	N	O	P	Q	R	S	T	U	V	W	X	Y		
PLASTIC REFLECTOR															
1	1.23	1.23	7.4	--	--	--	8.5	8.5	4.9	12.2	7.3	7.3	26.1	--	88
2	1.23	1.23	7.4	--	(0.4)	(0.6)	8.5	8.5	4.9	12.2	7.3	7.3	26.1	--	89
3	1.23	0.924	--	2.4	0.5	0.6	13.4	12.5	--	--	3.4	2.5	--	4450	70
4	1.23	1.23	--	2.4	0.5	0.6	13.4	12.5	--	--	3.4	2.5	--	4450	70
5	1.23	1.23	1.2	2.4	--	1.8	13.9	13.9	--	--	19.8	19.8	--	--	79
6	1.23	1.23	7.4	--	--	--	7.4	7.4	4.9	12.2	4.9	3.6	10.1	210	90
7	1.23	1.23	7.4	--	--	--	6.4	6.4	4.9	12.2	3.7	3.3	10.1	--	88
8	1.23	1.23	7.4	--	--	--	6.6	6.4	4.9	12.2	3.7	3.3	10.1	--	88
9	1.23	1.23	7.4	--	(1.2)	(1.2)	7.3	7.3	4.9	12.2	3.7	3.6	10.1	--	86
10	1.23	1.23	7.4	2.4	(0.7)	0.6	11.3	11.3	7.1	0.6	0.9	--	--	4450	84
11	--	--	8.6	--	--	(0.6)	--	--	2.5	7.3	6.1	4.9	--	--	86
12	--	--	7.4	--	0.5	(0.7)	--	--	--	7.3	3.4	2.5	--	--	81
CONCRETE REFLECTOR															
13	1.23	1.23	1.3[c]	--	0.8	(0.8)	6.4	6.4	--	11.4	--	--	30.5		85
14	1.23	1.23	1.3[c]	--	0.8	(0.8)	6.4	6.4	--	11.4	--	--	30.5		85
15	--	0.924	--	--	(0.9)	1.3	12.1	12.1	--	--	--	--	--		81
16	--	0.924	--	--	(0.9)	1.3	12.1	12.1	--	--	--	--	--	none	81
17	1.23	1.23	--	--	0.6	0.6	12.1	12.1	--	--	--	--	--		87
18	1.23	1.23	1.3[c]	--	0.7	(0.8)	6.4	6.4	--	11.4	--	--	12.7	used	79
19	1.23	1.23	1.3[c]	--	0.7	(0.8)	6.4	6.4	--	11.4	--	--	12.7		80
20	1.23	1.23	1.9[c]	--	0.8	(0.5)	6.4	6.4	--	11.4	--	--	--		69
21	1.23	1.23	1.9[c]	--	0.8	(0.5)	6.4	6.4	--	11.4	--	--	--		69

[a] The capital letters A through Y refer to Figure 12, and the words "north", "south", and "both" just above these letters refer to the side(s) of the split table machine to which the dimensions in that column pertain.

[b] These dimensions were not directly measured but were calculated from a photograph.

[c] Transite thickness.

[d] The space between the frame or frame extender and the end reflector panel. Gaps enclosed in parentheses did not provide a neutron leakage path directly from oxide cans and, so, are less important.

FIGURE 12

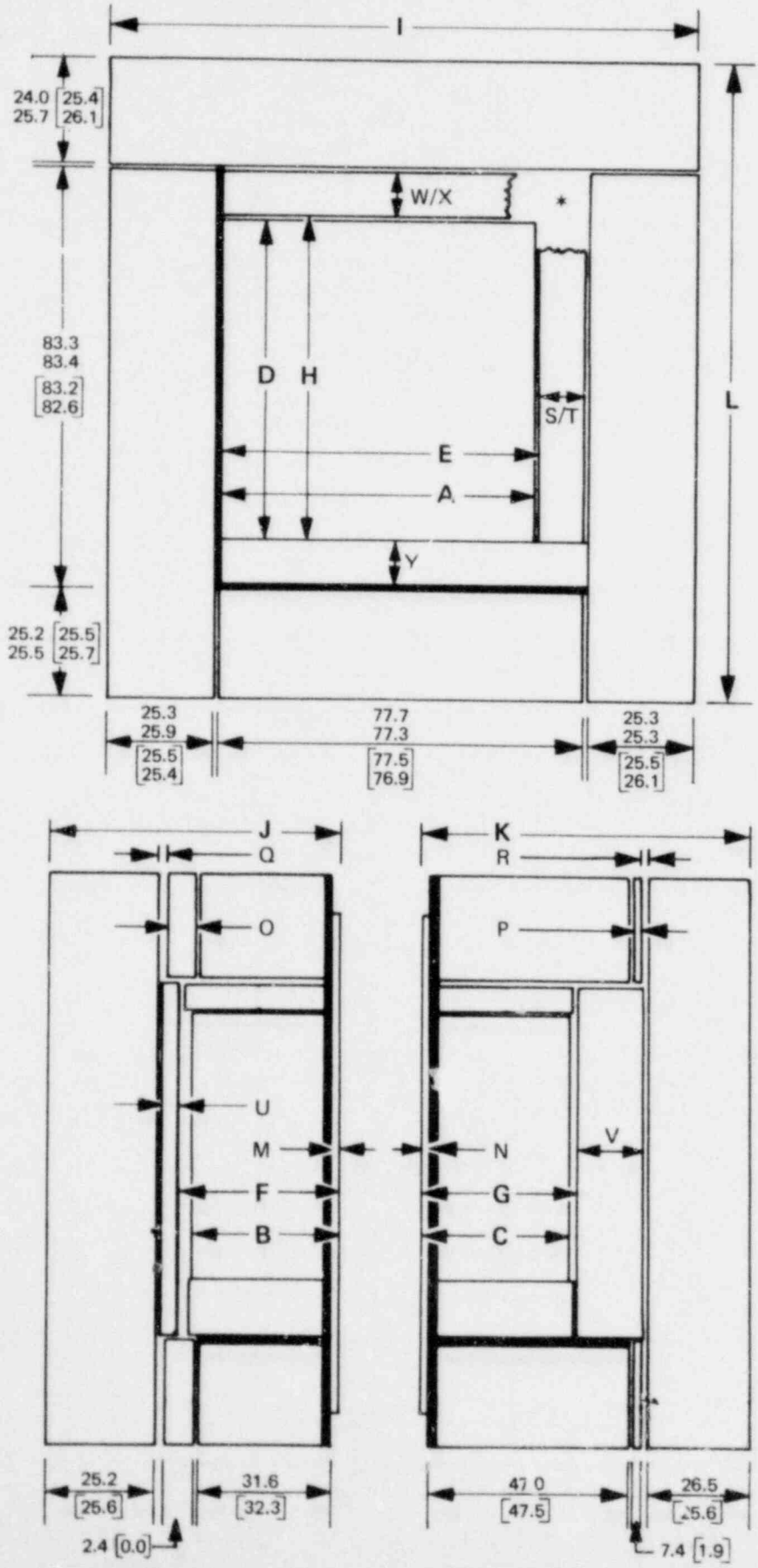

FIGURE 12

Dimensions of a typical experiment. This example was selected to define graphically the dimensions of Table IX. Double entries refer to dimensions on the north and south tables, respectively. Pairs of numerical dimensions without square brackets refer to plastic-reflected experiments, those in brackets to concrete cases. The region containing an asterisk was often filled with miscellaneous pieces of filler material, and the total weight is given in the penultimate column of Table IX.

contains the thickness of faceplates and frame extenders used on each table, and the thickness of filler pieces used in several locations. Although filler blocks were fabricated of full-density plastic or concrete, their effective density was reduced slightly because not all space could be filled completely by the limited number of pieces available. The last column of Table IX gives the fraction of space between the inner reflector cuboid and the interior of the reflector shell which was filled with full-density filler material. Where possible, gaps resulting from the use of these fillers were moved as far away from the core as possible.

Plastic Reflector

The several rectangular blocks which formed the frames and end relfector panels were laminated from many sheets of plastic of various thicknesses. Subsequent analyses revealed that two types of plastic had, unfortunately, been used in fabrication. One of these was ordinary methyl methacrylate plastic, while the other was similar but contained a fire-retardant additive known as "Tris". The additive increased the density $\sim 8\%$ and introduced measurable quantities of four additional elements. The composition of both kinds of plastic is given in Table II, along with the abundance of each. Nearly 80% of the plastic reflector shell was composed of fire-retardant plastic. A good approximation would be to describe the north frame, south frame, and south end panel

as composed entirely of fire-retardant material, while the north end reflector panel, all frame extensions, and all filler blocks were composed of ordinary plastic.

The plastic used for the reflector shell had been in the company's warehouse for a number of years. As a result, most of the protective paper covering could not be removed. About 91% of the original paper remained, so both the paper and glue were analyzed and their weight fractions estimated. These data are included in Table II. No paper adhered to any other plastic.

Plastic frame extenders were not laminated but cut from sheet stock; these are detailed in Table VIII. Filler plastic came from sheet stock of the following thickness: 10.2 ± 0.1, 7.4 ± 0.1, 5.0 ± 0.1, and 2.4 ± 0.0 cm. In addition, thinner pieces designed for use as core moderator material were sometimes used to fill a thinner gap when not needed within the core.

Concrete Reflector

The concrete cast for this program was designed to be the same composition as that poured for a previous benchmark criticality experiment[7] (high carbon content). To achieve this, dolomite limestone, high in carbonates of calcium and magnesium, served as the aggregate. The concrete was poured on three occasions. The four pieces comprising the reflector shell were cast twenty months prior to the first concrete-

reflected experiment of this program. They were made for another criticality study involving larger arrays of these same oxide cans[6]. Filler blocks were necessary for the present program because that shell had not been designed with these smaller arrays in mind. Nine fillers were cast eight months prior to use; and a tenth, a smaller piece necessary because an additional vertical layer of cans was required for criticality, was cast just the day before its use.

The time between pouring and use of concrete is important in criticality considerations because concrete loses water as it cures. This loss is rapid for the first day or two but decreases over the next several months. One test block has been weighed periodically for over a year, losing $\sim 2/3$ of its moisture in that time[7]. Larger concrete pieces such as the reflector shell lose water much more slowly. For example, one large, thick-walled concrete structure built for another experiment lost only 29% of its moisture in sixteen month's time.

The elemental composition of concrete was determined by two methods. In one, an ~ 10 kg piece was broken from a large sample block which had been cast at the same time as other pieces and kept in the same environment. This piece was analyzed by a private laboratory. They used a variety of laboratory techniques to evaluate different elements*:

*An estimate of the uncertainty for each method is given in parentheses.

atomic absorbtion, most metals (± 0.2%); calorimetric, silicon and aluminum (± 0.5%); CH analyzer, carbon (± 0.2%) and hydrogen (± 0.1%); Kjeldahl, nitrogen (± 0.5%); high temperature combustion, sulfur (± 0.1%); and spark source spectrometry, impurity elements (± 40%). The second method utilized separate analyses of the sand, cement, and limestone (given in Table X) used in making the concrete. The amount of each element in the overall composition was calculated by multiplying the weight fraction of the element in each ingredient by the weight fraction of the ingredient within the concrete and summing these products over all ingredients having that element.

Both the cement and the limestone aggregate (average chip size: 1.3 cm) were assumed to contain no absorbed water because considerable effort was expended to keep them dry. The sand, however, did contain moisture. This was measured and that amount included with the amount of water put into the mix at the cement plant when calculating the initial wetness. The wet sand used in making the basic reflector shell contained 5.0% water; that for the filler pieces, 3.3%.

The elimination of water during curing is assumed the only change in the concrete throughout the entire experiment. This is the least well known parameter in an analysis by the second method because of the strong dependence of water

TABLE X

Composition of Concrete Ingredients in Weight-Percent

Element	Portland Cement	Ordinary Sand	Limestone Aggregate	Water[a]
Hydrogen				11.19
Carbon			11.9	
Oxygen[b]	38.41	48.63	48.88	88.81
Sodium		0.62		
Magnesium	3.6	0.17	2.51	
Aluminum	1.75	5.1	0.03	
Silicon	9.9	42.5	0.99	
Sulfur	1.1			
Potassium		0.38		
Calcium	44.5	1.1	35.6	
Titanium			0.01	
Iron	0.74	1.5	0.08	
Totals	100.0	100.0	100.0	100.0

[a] Not analyzed.

[b] Oxygen determined "by difference".

retention on size and shape. Still, the hydrogen content is known to ~ ± 5% (see Uncertainties section).

The elemental composition of all concrete used in this program is presented in Table XI. Results are given for both methods of analysis for the larger, more important, pieces; and an unweighted average of the two is suggested as the best elemental composition to assume for these several concrete pieces. Densities are included here also, and they ranged from 2.30 g/cm^3 to 2.44 g/cm^3 for the concrete substitute material Transite. Results presume to represent the water content at the time the experiments were performed. The composition of Transite, used as north table frame extenders on six concrete-reflected experiments, is also given in Table XI.

Ten filler blocks were used in the nine concrete-reflected experiments. Their weights and dimensions are given in Table XII, along with a specification of which category employed which piece. The last line of Table XII describes the one cast just the day before its first use.

All concrete pieces except three filler blocks contained some form of steel reinforcement. The two frame sections contained 464 cm (north table) and 927 cm (south table) of 1.3-cm-diameter rebar material welded in a single rectangular loop (north table) and two loops (south table). The steel was buried in the concrete during pouring and kept at least 15 cm from any interior surface. The end panels each had

TABLE XI

Elemental Analysis in Weight-Percent of Concrete

ELEMENT	REFLECTOR SHELL			FILLER BLOCKS				ROOM WALLS	TRANSITE FRAME EXTENSION
	Total: Two Frames and Two End Panels			Total: Ten Pieces			Special Piece[a]		
	Cured Concrete[b]	By Ingredient[c]	Average	Cured Concrete[b]	By Ingredient	Average	By Ingredient	Cured Concrete[b]	Analysis of Material Used
Hydrogen	0.57	0.59	0.58	1.21	0.55	0.88	0.8	0.5	1.0
Carbon	5.30	5.50	5.40	5.22	5.28	5.25		0.5	0.6
Nitrogen	< 0.05	0.00	0.00	0.50	0.00	0.25		0.0	0.0
Oxygen[d]	(49.09)	49.54	49.32	(60.54)	49.40	54.97	49.5	(56.1)	(45.2)
Sodium	0.68	0.22	0.45	0.78	0.23	0.51	1.6	1.5	0.3
Magnesium	1.40	1.69	1.54	1.24	1.64	1.44	1.5	0.4	4.6
Aluminum	2.37	2.05	2.21	2.86	2.18	2.52	5.7	5.5	1.7
Silicon	17.20	16.81	17.00	15.20	17.84	16.52	29.2	30.0	9.5
Sulfur	0.12	0.14	0.13	0.28	0.14	0.21		0.1	0.0
Potassium	1.42	0.13	0.78	0.91	0.14	0.53		1.1	0.2
Calcium	20.80	22.65	21.73	9.75	21.90	15.82	6.5	2.5	35.0
Iron	1.05	0.67	0.86	1.51	0.70	1.10	4.8	1.8	1.9
Total	100.00	99.99	100.00	100.00	100.00	100.00	99.6	100.0	100.0
Average Density (g/cm^3)	2.297 ± 0.013			2.35			2.368	2.32	2.44

[a]Cast later than other pieces for use on experiments #15 to #17 only. Common gravel used as aggregate.

[b]Analysis by private laboratory of representative fragment.

[c]Assumes 71% water retention at time of use.

[d]Oxygen values in parentheses calculated "by difference".

TABLE XII

Average Dimensions in cm and Weights in kg of the Complete Inventory of Concrete Filler Pieces

Category	Dimensions E/W x N/S x Vertical	Total Weight	Weight of Steel	Location Used Relative to Core	Number on Inventory
O, P, M	76.2 x 11.3 x 81.3	161.5	0.21	back, south table only	1
O	76.2 x 31.1 x 17.8	96.3	0.14	below	2
O, P	76.2 x 31.1 x 12.7	68.3	0.14	below	2
U, S	12.1 x 31.8 x 81.3	70.8	0.14	east	2
O, P, M	6.35 x 33.7 x 50.8	24.4	0.0	east	2
U[a], S	12.7 x 15.2 x 81.3	37.3	0.0	corner[b]	1

[a] Experiment #15 only.

[b] Cast only the day before use.

610 cm of the same rebar welded in a square mesh pattern and roughly centered in each panel (~ 13 cm from an interior face). Reinforced filler blocks had a square mesh of #9 wire (0.29 cm dia) with 15 cm between wires. This mesh was roughly centered in the concrete during pouring. All concrete except a few smaller pieces had steel anchors set into the concrete during casting. These were used later to facilitate handling. The total weight of steel in each concrete piece is given in Tables VIII and XII.

ENVIRONMENTAL REFLECTION

This section describes conditions external to the outside reflector cuboid. Less detail is supplied because of the decreased importance to system reactivity of these more remote reflectors.

The reflector frames for both reflectors were screwed to 1.3-cm-thick steel "baseplates" large enough to support also the end reflector panel. The plate under each frame was mounted flush to the closing face of the frame, but extended beyond the reflector to the rear and sides. These plates are clearly visible immediately below the reflector in both Figures 2 and 3. The plates measure 149 cm (east/west) x 91.5 cm (north/south) and weigh $\sim$ 140 kg each.

Between these plates and the steel tops of the two tables, materials differ on the north and south portions of the split table machine. These were common to the previous experimental program and are illustrated by Figures 11, 12, and 13 of Reference 6, but the following narrative description may aid one in visualizing the split table machine. The north reflector and baseplate rest on a 5-cm-thick steel subtable which forms one of the two movable components of the machine. This subtable measures 102 cm (east/west) by 122 cm (north/south). It also is flush with the closing face of the reflector frame. The subtable moves on two 10-cm-diameter polished steel rails, in turn bolted to a

2.5-cm-thick steel slab. The rails and this slab are bolted to the north table top, flush with the south edge. When the north table is closed to its operational position, all these flush mountings fall roughly into the same plane. The slab measures 116 cm (east/west) x 186 cm (north/south), and the ~ 2-cm-thick perforated steel table top measures 216 cm (east/west) by 188 cm (north/south). This table top is supported, in turn, by a heavy honeycomb steel substructure.

The south reflector and baseplate also rest on a 5-cm-thick steel subtable supported by two 24-cm-high steel I-beams. The subtable measures 102 cm (east/west) by 91 cm (north/south). The web of the I-beam is 0.5 cm thick and both top and bottom flanges are ~ 2 cm thick. The I-beams bolt to a ~ 2-cm-thick perforated steel table top the same size as on the north table. The south table top is also supported by a heavy honeycomb substructure, which forms the second movable component of the machine. The baseplate, subtables, and I-beams are flush with the closing face of the south frame but project 9.5 cm north of the table's edge. This is readily apparent in Figure 2.

Both honeycomb substructures (fixed and movable) are supported by the heavy-duty, steel-channel rectangular base of the split table machines. The combined weight of this base and the two steel substructures is estimated at ~ 5,000 kg.

The split table machine was located in a concrete room 1128 cm (east/west) by 1067 cm (north/south) x 975 cm high. The bottom surface of the outside reflector cuboid stood ~ 108 cm above the 20-cm-thick floor. With the north table closed to its operational position, the south face of that table was ~ 245 cm from the 152-cm-thick north wall, and the centerline of the reflector shell was ~ 350 cm west of the east wall. East, west, and south walls of the concrete room were 122 cm thick; the ceiling was 61 cm. The elemental composition of the concrete room is included in Table XI.

PROCEDURE

Core Assembly

Each experiment began by loading the desired configuration of uranium oxide cans into the aligned frames of the reflector shell with the two tables fully separated. Loading was accomplished from between the two tables. Interstitial moderator of the appropriate size and shape was added as rows and layers were built. Cans were separated from one another in east/west rows by square plastic blocks of the desired thickness but the same size as a can otherwise. Such rows were separated by blocks as tall as a can of the same thickness plastic, but extending the full length of a row. This formed a planar array (layer) of oxide-cans-plus-moderator, and such a layer was separated from another above it by large plates of the same thickness plastic. The length and width of these plates closely matched the size of a layer on one table. The result of this procedure was a cuboidal array of spaced cans containing uranium oxide with all space within that cuboid filled with plastic of the desired thickness. If an absorber was used for the category being built, each can was surrounded by this material as it was added to the array. Upon completion of the core, east and top filler pieces (if any) were inserted and gently pressed against the array. (Any back or bottom filler pieces would have been installed prior to the first can.)

As layers were built, they were pulled forward to compact the core as much as possible. Then each layer was tapped back flush with the face of the frame. This construction assured a tightly-packed array with a minimal gap between tables when closed.

This procedure was performed first on one table and then repeated on the second. Next, a large plastic sheet (faceplate) of one-half the plastic thickness between cans was screwed to each table along the eventually mating faces such that if the two tables were completely closed on one another, the array geometry would be preserved across the two tables. The reciprocal multiplication technique for critical-approach experiments assured criticality safety during assembly of the core.

The above procedures were followed in most cases, but a few exceptions should be noted. Experiment #15 (category U) had only one full-thickness faceplate on one table. This preserved the moderator geometry across the table in this case. Experiments #3, #4, and #10 had a thickness of faceplate material in excess of that required to preserve geometry. This was necessary because additional reactivity was needed to achieve criticality. Category S experiments did not have moderation between all cans but only between supercan subarrays. Finally, experiments #10 and #18 had some of their absorber plates absent.

A small ^{252}Cf neutron source (2.3×10^6 n/s) was positioned within the core. This assured that all reactivity additions resulting from table closure would be properly detected by the battery of radiation sensing instruments. Seven neutron detectors and one gamma device were used on all critical-approach experiments. The neutron detectors were located just outside the outer reflector cuboid on the north table for all concrete-reflected experiments. Neutron absorption in the plastic reflector proved too great, so all seven detectors were placed in holes drilled into the north end reflector panel. These holes are visible from inside the reflector shell in Figures 3 and 10. Holes stopped 3.6 cm short of penetrating that reflector panel.

Critical Approach

The first remote operation was to close and latch the north table in its operational position. This placed the faceplate of the north table in roughly the same plane as the south edge of the north table. Then, closure of the south table began, again using the reciprocal multiplication technique to assure safety. When criticality appeared imminent within the next few incremental movements of the south table, the neutron source was removed in alternating incremental steps with small incremental table closures. Eventually, the source was withdrawn ~ 2 m above the outer reflector cuboid as the table separation was adjusted to

achieve a long, positive reactor period, usually ranging between 5 and 15 minutes. At this moment, the assembly was slightly above delayed critical. Then the south table was moved slightly away from the north until a negative reactor period of about the same magnitude as the positive was achieved. Both positive and negative reactor periods and their corresponding table separations were recorded.

The critical separation was obtained by linearly interpolating between the reciprocal positive and negative reactor periods at their associated table separations. Criticality corresponds to a reciprocal reactor period of zero. This interpolation method has been discussed in the literature [7].

The neutron source was removed and the time spent at or near criticality kept as low as practical to minimize the amount of radioactive fission products formed. Typically, the time between source removal and the subsequent full opening (reactor shutdown) of the two tables was about ten minutes. Combining this short duration with the low power level achieved by source removal assures that the fissionable material will not become perceptibly radioactive even over several hundred experiments.

Table Separation

The separation between the two tables was the parameter varied to attain criticality. This separation was sensed by an electrical/mechanical device and read out (in arbitrary

units) on an electrical meter in the reactor control room. Two parameters are necessary to relate data from this linear but arbitrary system to an actual table separation in centimeters: a slope and an intercept.

The slope was determined on a number of occasions by measuring the change in table separation using machinist's gauges as a function of meter readout. This calibration remained constant and linear at 0.2294 ± 0.0008 cm per one major division throughout the full range of the meter. The intercept was measured using a soft putty called Duxseal®*. Several pea-sized mounds were pinched onto one of the two closing faces of the array. Usually five or six were distributed over the array of oxide cans and eight around the perimeter of the reflector area. Then the two tables were closed until the other face flattened the mounds. Small tabs of vinyl plastic prevented the mounds from sticking to the second face and distorting as the tables separated. The meter reading, M', corresponding to this closest approach, S', was carefully noted. Combining these data, the following formula was used to calculate all table separations, S, from meter readings, M:

$$S = S' + 0.2294\ (M - M')\ \text{cm}$$

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* Trademark of Johns-Manville Corp., Denver, Colorado.

In all applications of the putty mound data, a simple average thickness over the face of the array (core and reflector) was used. This assumes that the two converging faces of the north and south tables are parallel planes. A careful examination of the putty mound data reveals that this was not always the case. Sometimes one region between the two faces would be slightly closer together than another, suggesting that one face was "pitched" and/or "yawed" with respect to the other. This deviation from ideal experimental conditions is estimated for each experiment in Table XIII in terms of the increase in separation across the height or breadth of the core cuboid. Furthermore, the putty mound data sometimes showed that the average core separation was somewhat smaller than the reflector separation (averaged all around), and this is also estimated in Table XIII. The cause of this small departure from two truly parallel planes is the massive weight of large and bulky reflector pieces and the tendency for these to shift some as still more weight is added via core materials. These perturbations are assumed negligibly small in affecting the critical configurations described in this paper.

TABLE XIII

Estimated Deviations from the Assumption that the Closing Faces on the Two Tables are Parallel

Experiment Number	Increase in Core Separation		Reflector Minus Core[c] (cm)
	Vertical[a] (cm)	East/West[b] (cm)	
PLASTIC-REFLECTED			
1	+ 0.10	+ 0.02	0.00
2	d	d	d
3	- 0.32	+ 0.07	+ 0.05
4	- 0.32	+ 0.07	+ 0.05
5	- 0.02	+ 0.04	+ 0.09
6	- 0.17	+ 0.02	+ 0.12
7	+ 0.09	+ 0.26	+ 0.26
8	+ 0.09	+ 0.26	+ 0.26
9	+ 0.09	+ 0.26	+ 0.26
10	- 0.13	+ 0.05	+ 0.05
11	- 0.05	+ 0.37	- 0.02
12	- 0.05	+ 0.37	0.00
CONCRETE-REFLECTED			
13	- 0.02	+ 0.03	+ 0.21
14	- 0.02	+ 0.03	+ 0.21
15	- 0.04	+ 0.15	+ 0.01
16	- 0.04	+ 0.15	+ 0.01
17	+ 0.03	+ 0.02	+ 0.23
18	- 0.23	- 0.02	- 0.03
19	- 0.20	+ 0.04	- 0.03
20	- 0.27	- 0.04	+ 0.18
21	- 0.27	- 0.04	+ 0.18

[a]Core separation at top less that at bottom.

[b]Core separation at west less that at east.

[c]Average separation between reflector less average separation between core.

[d]No such data available.

EXPERIMENTAL RESULTS

Twenty-one critical configurations are described in sufficient detail to permit an accurate validation of appropriate calculational methods for each. The principal experimental result is the separation between two tables containing arrays of fissile and other materials for which criticality occurred. The number of cans in the array was adjusted in each case until the critical separation was as small as practical. This critical spacing varied between 0.2 and 1.5 cm for the twenty-one configurations.

Table XIV describes each critical core: the number of cans used, their precise configuration (shown in Figure 13), and the critical separation between tables. This last parameter is the one recommended for use in computer simulations of these experiments; however, table separations associated with both positive and negative reactor periods are also provided because of a possible alternative comparison between experimental and calculated results. In the more common method, the critical separation is interpolated from the above data and compared with the calculated value anticipated to be precisely unity. The alternative method is to determine the neutron reproduction factor ($\neq 1.0$) corresponding to the positive (or negative) reactor period, and compare that with the factor calculated for the measured table separation associated with that period. The former assumes the linear

TABLE XIV

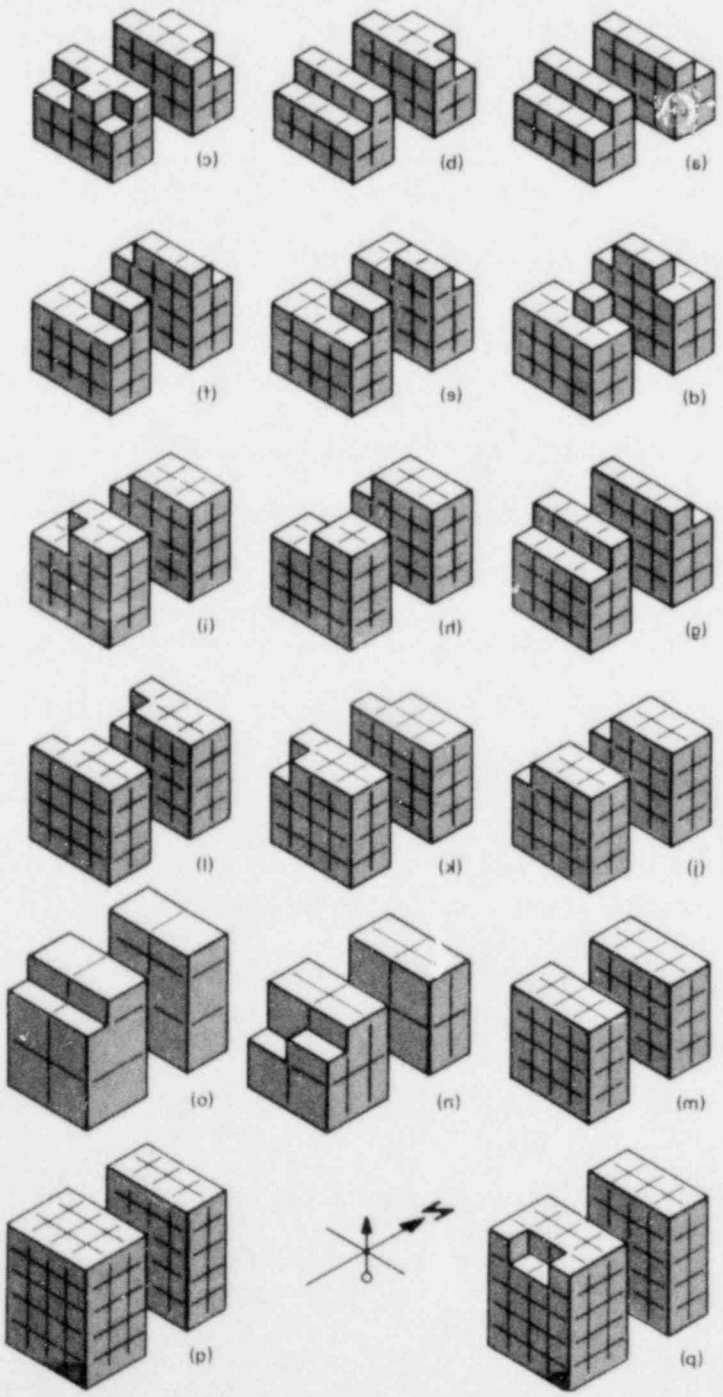
Critical Data: Core

Experiment Number	Category	Number of Cans	Configuration Shown in Figure 13	H/U ± 0.005	Separation Between Tables				
					Critical (cm)	+ Period (min)	at (cm)	- Period (min)	at (cm)
PLASTIC REFLECTOR									
1	O	42	b	0.770	0.31	7.1	0.28	6.2	0.34
2	O	43	c	0.769	1.52	13.4	1.55	8.3	1.52
3	U	100	q	0.768	1.05	7.5	1.05	19.0	1.05
4	U	100	q	0.768	1.54	26.6	1.83	9.7	1.86
5	S	74	n	0.768	0.68	8.1	0.65	23.6	0.69
6	P	56	g	0.768	0.42	15.0	0.41	9.4	0.45
7	M	60	j	0.768	0.23	9.4	0.21	16.5	0.25
8	M	62	k	0.768	1.28	7.4	1.26	7.6	1.31
9	m	51	d	0.769	0.24	33.0	0.22	168.0	0.24
10	T	100	q	0.768	0.70	4.9	0.66	4.3	0.76
11	E	62	l	0.768	0.53	21.0	0.52	9.8	0.56
12	E	64	m	0.768	1.13	11.2	1.11	16.7	1.14
CONCRETE REFLECTOR									
13	O	40	a	0.769	0.57	7.9	0.54	18.0	0.58
14	O	40*	a	0.769	0.62	10.1	0.60	8.6	0.64
15	U	98	p	0.768	0.48	8.6	0.46	7.9	0.51
16	U	100	q	0.768	1.19	9.6	1.16	7.4	1.23
17	S	96	o	0.768	0.58	13.0	0.56	6.8	0.63
18	P	52	e	0.768	0.40	9.4	0.38	20.6	0.41
19	P	53	f	0.768	1.05	3.2	0.97	5.1	1.10
20	M	58	h	0.768	0.25	no + period		164.4	0.25
21	M	59	i	0.768	1.18	5.6	1.15	7.2	1.21

*Same cans but ordered differently in array.

FIGURE 13

Isometric representation of seventeen different critical core configurations. Table XIV associates each of the twenty-one experiments to one of these configurations. Configurations (n) and (o) are shown subdivided according to their respective "supercan" arrangements; all other subdivisions show individual cans.



interpolation between reciprocal periods valid; the latter assumes conversion from period data to reactivity is correct. Neither is strictly true, but both are reasonable approximations. The conversion is accomplished using the curves of Figure 14, drawn from data taken directly from Reference 11, pages 370 and 371.

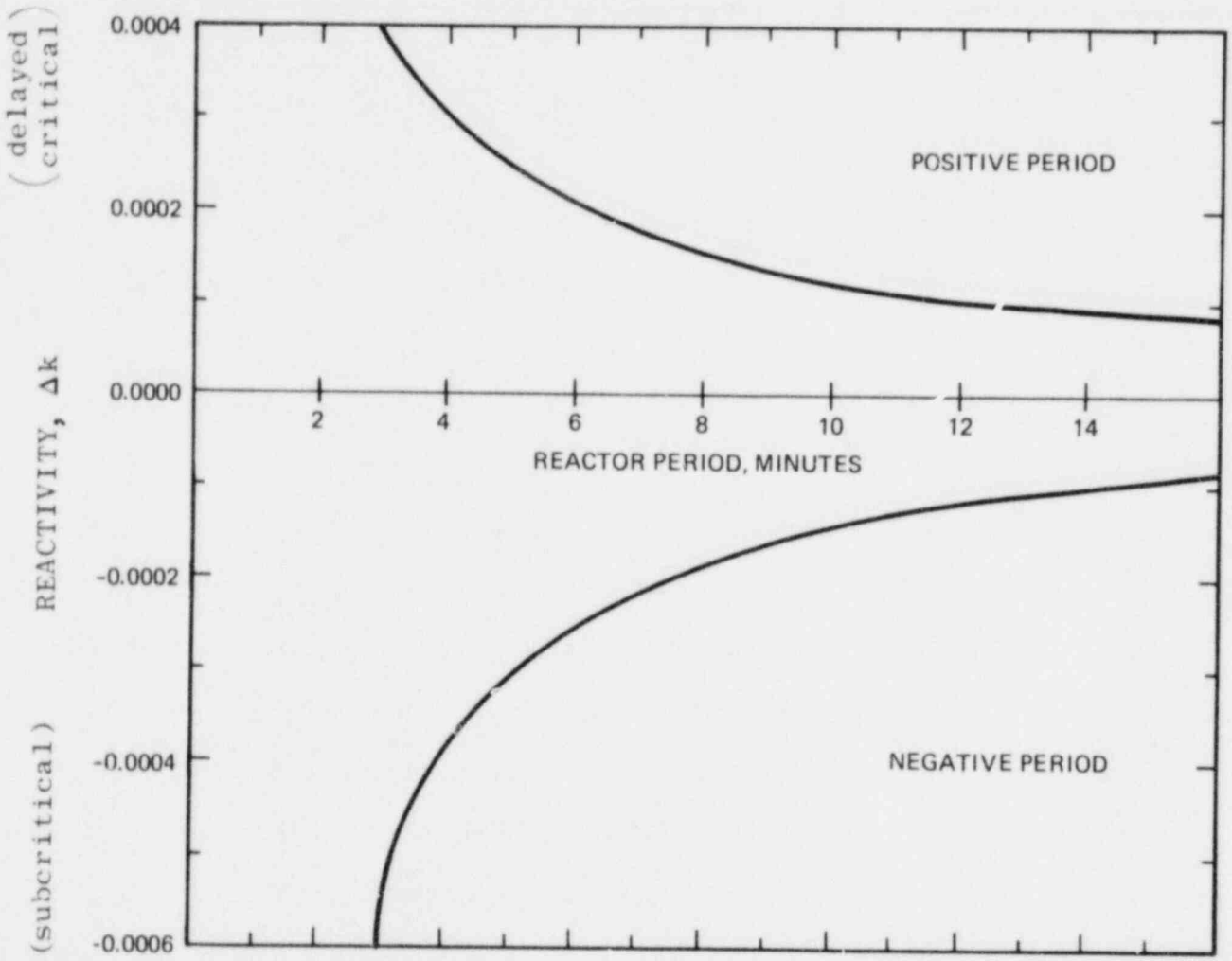
Results by Category

Criticality was achieved with only three layers of cans for the optimally-moderated experiments of category O. Two critical configurations are reported for each reflector. Comparing experiments #1 and #2 (plastic reflector), one oxide can is evidently worth 1.2 cm of table separation in this case. Extrapolating these two experiments to zero table separation suggests that this hypothetical situation would occur for 41.75 cans. Experiment #14 (concrete reflector) is a repeat of #13 but with all cans shuffled* to new locations, although the same forty cans and moderator pieces were used. Concrete is evidently a better reflector than plastic since fewer cans were required to attain criticality at a small table separation. This may be made more quantitative by interpolating between the separations of

* Except for this one experiment, all experiments in all categories used the same cans in the same locations. Arrays of fewer than 100 cans merely deleted cans not needed for a particular configuration.

FIGURE 14

Reactor period vs reactivity. These curves are generated from the data of Table A-1, Reference 11.



experiments #1 and #2 to the average separation of #13 and #14 (0.592 cm). This separation would have occurred in the plastic reflector for 42.24 cans, about $2\frac{1}{4}$ cans more than required in the concrete reflector. Figure 15 shows one view of the plastic-reflected case for this category, Figure 16 the concrete-reflected one.

When the moderator thickness was reduced to ~ 0.9 cm for category U experiments, criticality was barely possible even for the largest possible array of 100 cans (4 x 5 x 5 array). Again, two critical configurations are reported for each reflector and concrete was still the better reflector material. For plastic-reflected experiments, criticality could not be achieved as hoped using only one faceplate of the same thickness (not half) as that elsewhere in the core. Instead, additional reactivity was required, and this was accomplished by using a greater total faceplate thickness than would be required to preserve geometry across the two tables (0.924 cm). Two experiments having different total faceplate thicknesses (#3, 2.15 cm, and #4, 2.46 cm) are reported for the 100-can array. Comparing the critical table separations for these two experiments, an increase of 0.31 cm in faceplate thickness caused an increase in critical table separation of 0.79 cm. Now, comparing the two experiments in the concrete reflector, <u>two</u> cans are evidently

worth ~ 0.7 cm in table separation, 3.4 times* smaller than that for category O. Combining these two comparisons, a crude estimate may be derived for the number of cans for which criticality would occur in the plastic reflector with only the desired 0.924 cm faceplate thickness and zero separation between tables: ~ 106 cans. Extrapolating experiments #15 and #16 to zero table separation suggests that this hypothetical situation would occur for 96.6 cans. One photograph of this category in each of the two reflectors is shown in Figures 17 and 18.

Only one supercan experiment (category S) is reported for each reflector; and even the size of the supercans differed so no comparison between the two reflectors was possible. The supercan for the plastic-reflected case was a 2 x 1 x 2 subarray of cans without moderator between. Two vertical layers of these, each composed of four supercans, filled out the north table. Two more vertical layers of four supercans each were built on the south table; but then $2\frac{1}{2}$ more supercans were required on a third vertical layer to achieve criticality. Figure 19 shows this layer and a portion of the complete vertical layer of cans behind it for this experiment (#5). The supercan arrangement for the concrete-reflected case (#17) was even more complicated.

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* Experiment #16 had a 12.7 x 15.2 x 81.3 cm void in the reflector at one corner of the array. No other configuration reported had this void.

The supercan on the north table was constructed of 2 x 2 x 2 subarrays of cans. Four of these full supercans plus an additional layer of cans on top forming two "half-high supercans" was built on the north table. An identical array was built on the south table, but this proved insufficient for criticality to occur. So, the core was extended south with sixteen more cans resulting in four full 2 x 3 x 2 supercans plus a layer of eight cans on top of this array. The total on both tables was 96 cans. The vacancy formed by the absence of four cans from a full 100-can array can be seen in Figure 20.

Thin polyvinyl chloride (PVC) squares surrounded each can in the category P experiments. Otherwise, the array was built similar to that of category O. The squares were only 0.054 cm thick, but even this amount of absorber increased considerably the number of cans necessary for criticality to occur. In the plastic-reflected case (#6), 33% more cans were required with absorber than without it (#1). As with previous categories, concrete proved to be a better reflector than plastic. Compared to its plastic counterpart, experiment #19 required three fewer cans to achieve criticality; this can difference would have been slightly greater had the table separations been the same. A second concrete-reflected category P experiment is reported: #18. This case was discovered during disassembly to have eight pieces of PVC inadvertently omitted

from the core. The eight missing squares were those covering the top of the bottom layer of cans on the south table. The 336 squares used on experiment #6 increased the number of cans required for criticality by 14, making each piece worth about 0.04 can. In this approximation, the eight missing squares would have been worth ~ 1/3 can, and the critical data for line 18 of Table XIV would have read: 52.3 cans (at a separation of 0.4 cm). Extrapolating this derived critical number of cans to zero table separation with the aid of experiment #19 suggests that the critical number of cans with zero separation would be ~ 51.9 cans. The plastic-reflected experiment is illustrated in Figure 21, and experiment #18 in the concrete reflector is shown in Figure 22.

Another neutron absorber used around each can was 0.117-cm-thick mild steel sheets (category M). Two experiments are reported in the plastic reflector because the first one done (experiment #8) had a relatively large separation between tables; and criticality was possible for fewer cans at a much smaller table separation. Extrapolating data from these two experiments suggests that 59.6 cans would have been critical at zero table separation. In configuration #7, 43% more cans were required with absorber than without it (#1). Comparing this with the 33% found in the PVC case demonstrates that this thick steel is a much better absorber than the thinner PVC. Two experiments are also reported in the concrete reflector. For experiment

#20, some portion of the two tables came into contact*, preventing further closure, before a positive reactor period could be achieved in accordance with the critical approach procedure described earlier. A long negative period, however, was obtained in the absence of an external neutron source, indicating the system was extremely close to criticality and worthy of reporting. Extrapolating configurations #20 and #21 to zero table separation suggests that this would occur for ~ 57.7 cans. Configurations #8 and #20 are illustrated by Figures 23 and 24, respectively.

Mild steel squares, close to the same thickness as the PVC squares, were used in one category m experiment (#9). In this plastic-reflected case, only 21% more cans were required with absorber than without it (#1). Comparing mild steel and PVC (#6), the latter is a much better neutron absorber for the same thickness. The critical number of cans may be graphed against neutron absorber thickness using the data from experiments #1, #7, and #9. The resulting curve is linear, suggesting that the influence of other thicknesses of mild steel may be interpolated with confidence. The slope of this line is 15.4 cans per millimeter of mild steel thickness. This is equivalent to a 37% increase in core

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* Even though contact occurred, the average table separation was still ~ $\frac{1}{4}$ cm. This case illustrates the difficulty of trying to align large, massive pieces such as these reflector shells.

size (number of cans) per mm steel. This category is shown in Figure 25, and it was not repeated in the concrete reflector.

The same thick steel plates used in category M experiments were used again in one category T experiment. In this plastic-reflected case (#10), the interstitial moderator was only half the thickness of the former category. Because of the decreased moderation and the significant absorption, criticality could not quite be achieved even with the largest possible array (100 cans). Two perturbations were effected which did permit criticality to occur for an array close to the desired one: [1] faceplates 1.3-cm-thick were used on both tables instead of only the one which would have preserved the geometry across the two tables, and [2] the absorbing steel plates just behind both faceplates were removed. A total of 40 plates were removed from the 600 plates used on a 100-can experiment. Since two perturbations were applied, the impact of neither can be estimated with confidence. The only conclusion to be drawn is that the critical number of cans without perturbations would have been several more than 100. Figure 26 illustrates this experiment, which was not repeated in the concrete reflector.

Two critical experiments are reported for category E, both performed in the plastic reflector. About 50% more cans are required for these expanded-array experiments than for the compact arrays of category O having the same total

plastic thickness between adjacent cans. In configuration #11, a 1.27-cm expansion gap existed between adjacent plastic box moderators in all three directions. Boxes were inset from the face of both reflector frames by half that amount such as to obtain this same gap across the two tables the moment they touched. In this experiment only, then, the critical separation of Table XIV represents the average separation between reflector frames; the average separation between facing columns of boxed cans would be 1.27 + 0.53 = 1.80 cm. The second configuration (#12) had larger expansion gaps; but, because of reflector shell size limitations, they could not be equal in all three dimensions. The expansion gap in the horizontal direction at right angles to the direction of table motion (east/west) was 1.27 cm, as in the first case. The vertical separation between layers of plastic-enclosed cans was 1.90 cm. The horizontal gap in the direction of table closure was also 1.90 cm except that arrays on both table halves were built flush with the mating surfaces of the reflector, such that the separation between second and third vertical columns of cans would be zero <u>if</u> the table were to close completely. This compromise was necessary because criticality would not occur with properly inset cans even for a full 64-can array. In this experiment only, then, a table separation of 1.90 cm would have had the same expansion gap <u>across</u> the two tables as within <u>each</u> table

(in the north/south direction). Unfortunately, this separation was not critical and the tables had to be brought 0.77 cm closer together (to 1.13 cm separation) for criticality to occur. For both experiments in this category, the boxed cans of oxide were spaced from the interior walls of the reflector by half the expansion gap in that direction found between boxes of the array. Assembly limitations did not permit this criterion to be satisfied everywhere in the array, as evidenced to the left of Figure 27. This perturbation is described in detail in Table IX, which gives cuboid dimensions.

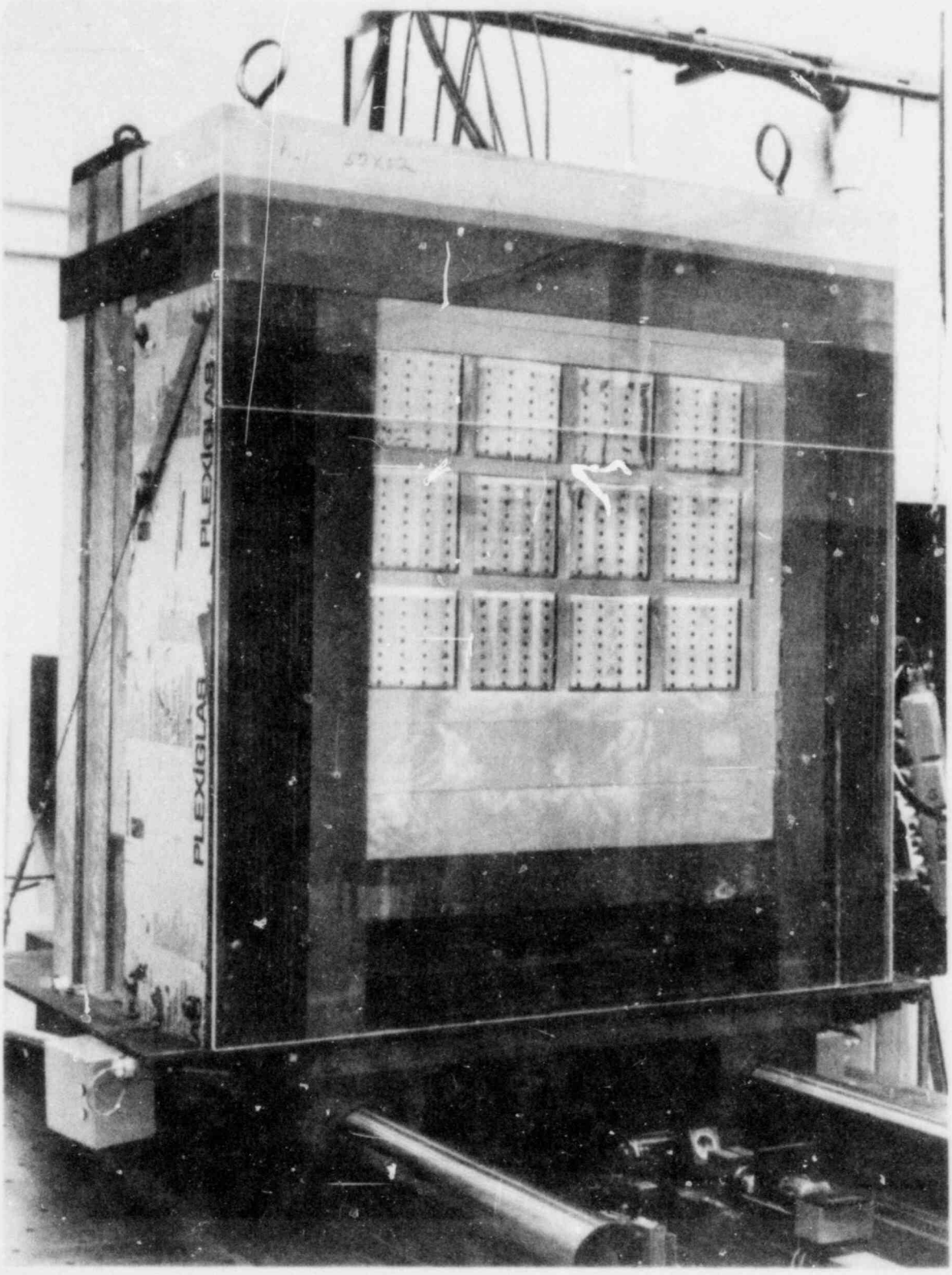

FIGURE 15

Category O experiment, plastic reflector. A two-piece face-plate is screwed to the face (key plane) of the north table reflector frame.

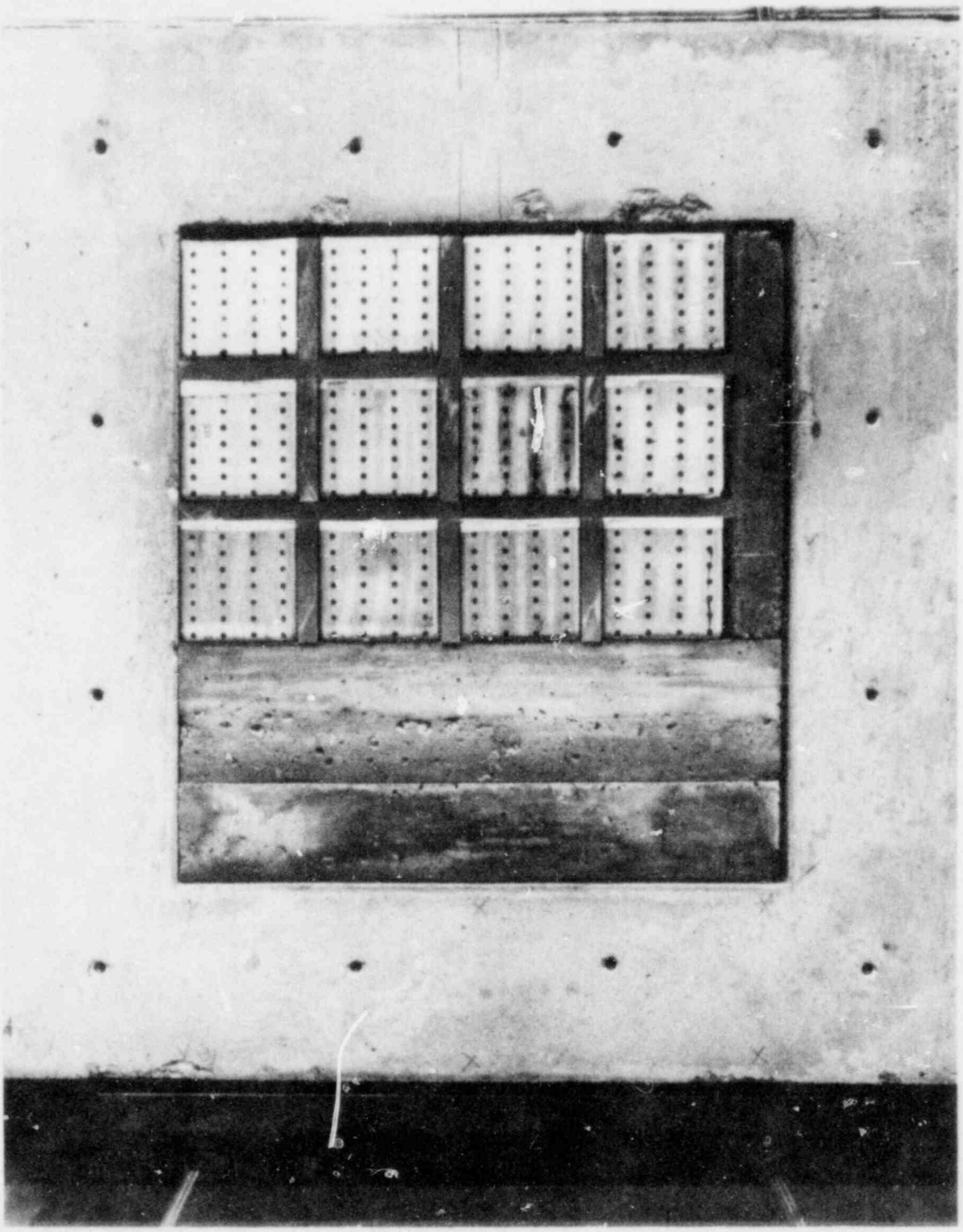

FIGURE 16

Category O experiment, concrete reflector. The faceplate has been removed for this photograph of a north table key plane. The three-layer core rests on a pair of thick bottom filler pieces.

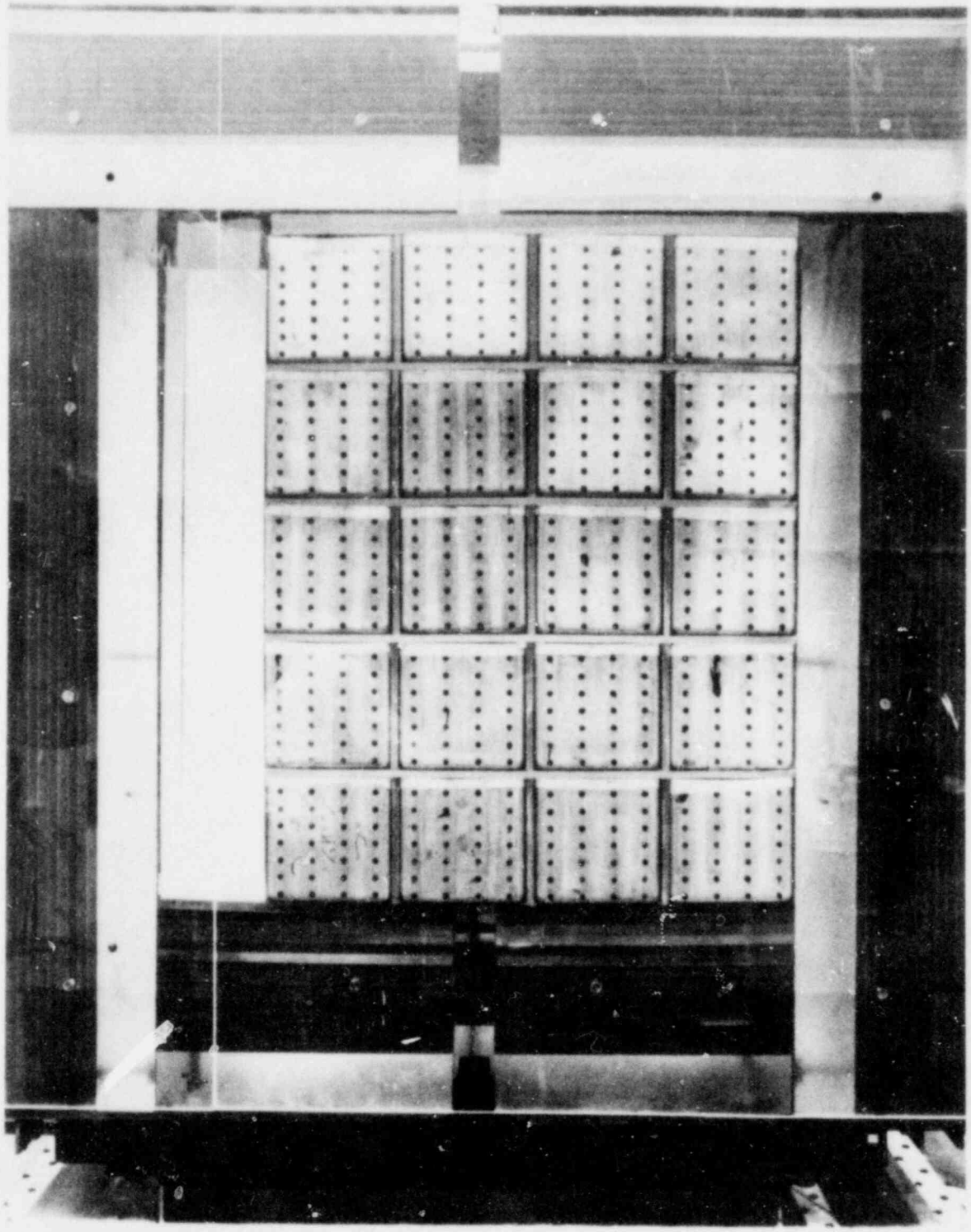

FIGURE 17

Category U experiment, plastic reflector.

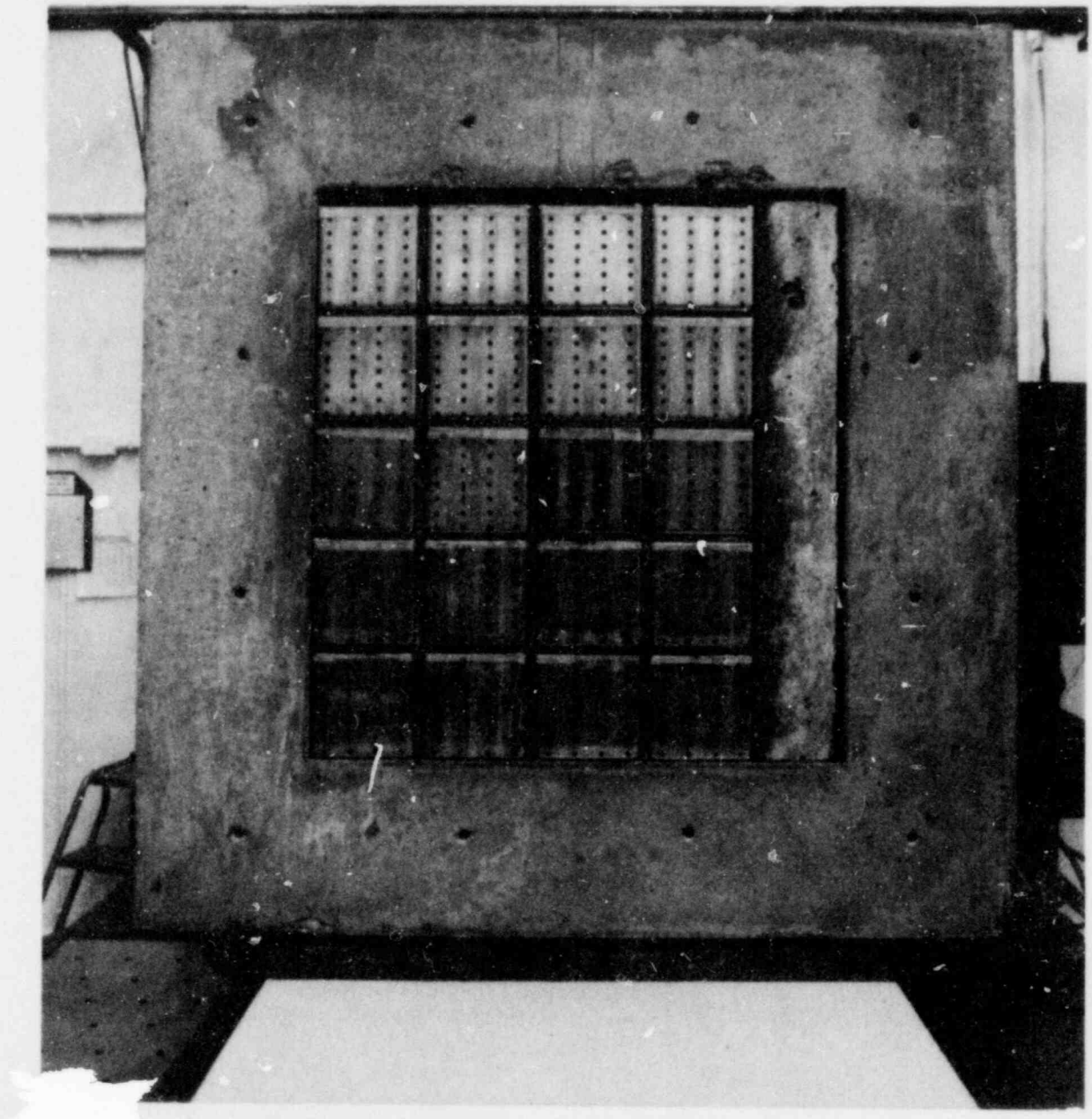

FIGURE 18

Category U experiment, concrete reflector. Space between core and reflector tended to be larger in concrete-reflected experiments because thin sections of concrete were not available.

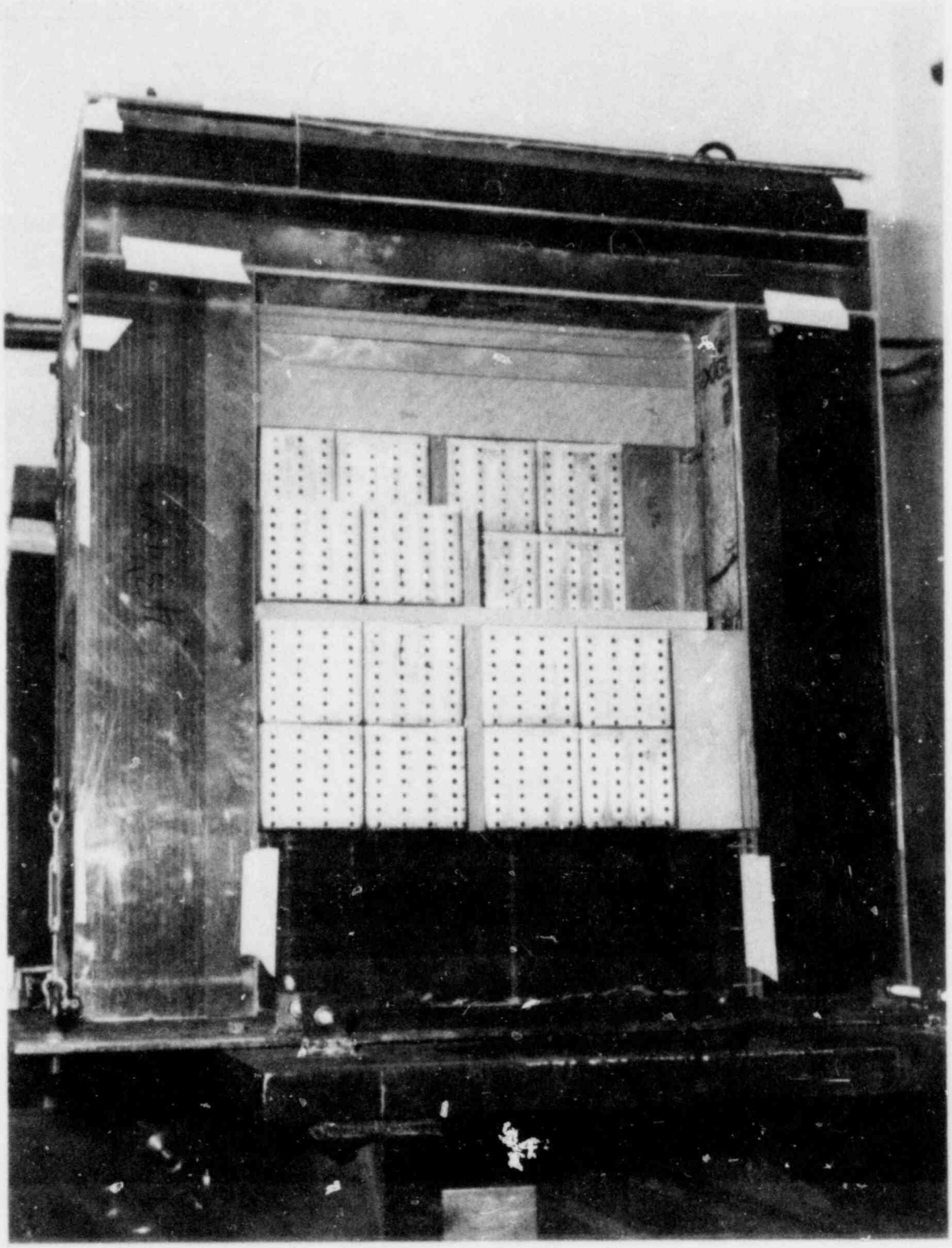

FIGURE 19

Category S experiment, plastic reflector. The south end reflector panel has been removed; the four rectangular pieces of plastic held by tape form the 2.5-cm-thick frame extension. The most southerly column of cans contains $2\frac{1}{2}$ 2 x 1 x 2 "supercans".

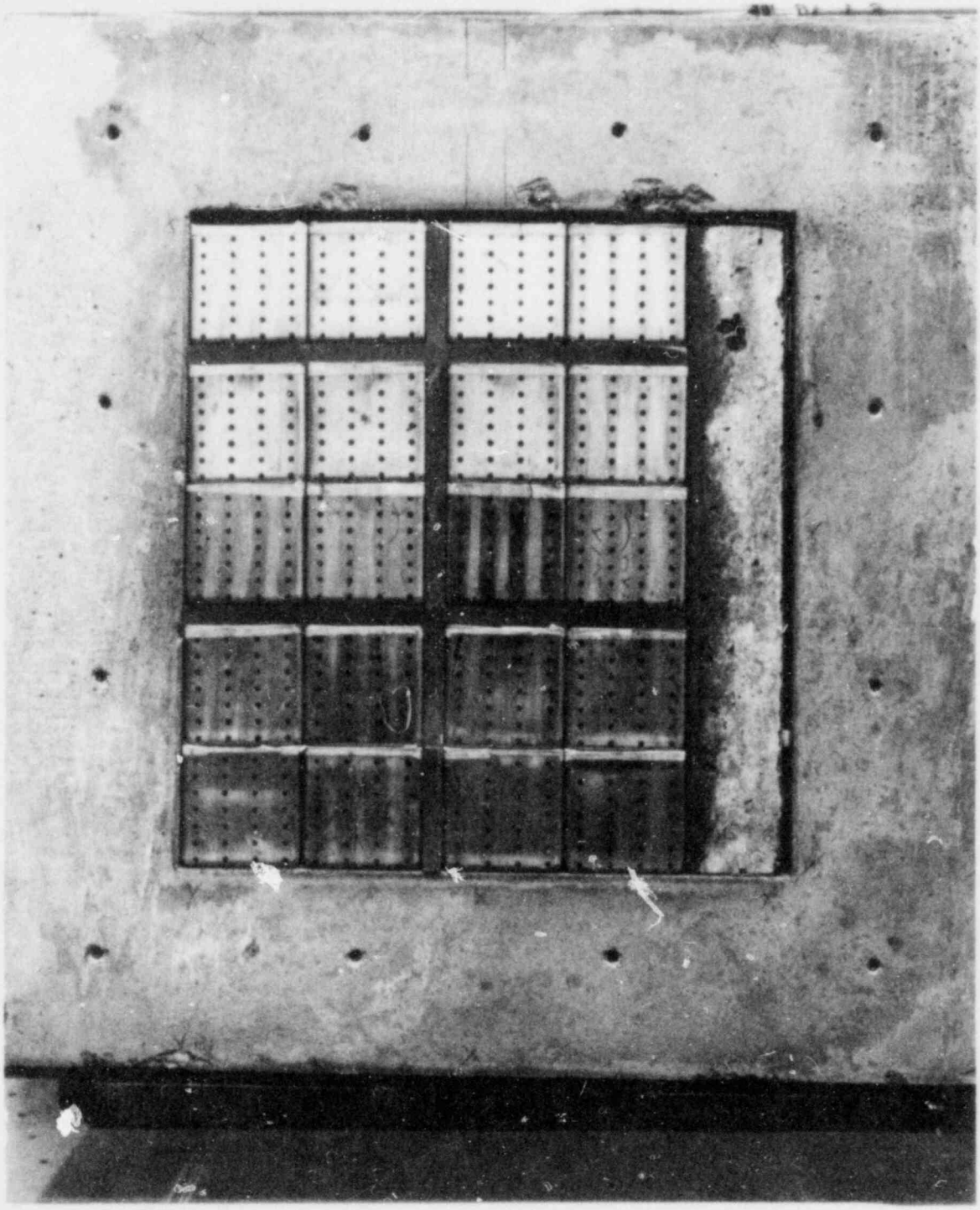

FIGURE 20

Category S experiment, concrete reflector. Partial "super-cans" were necessary on a fifth layer of cans to achieve criticality.

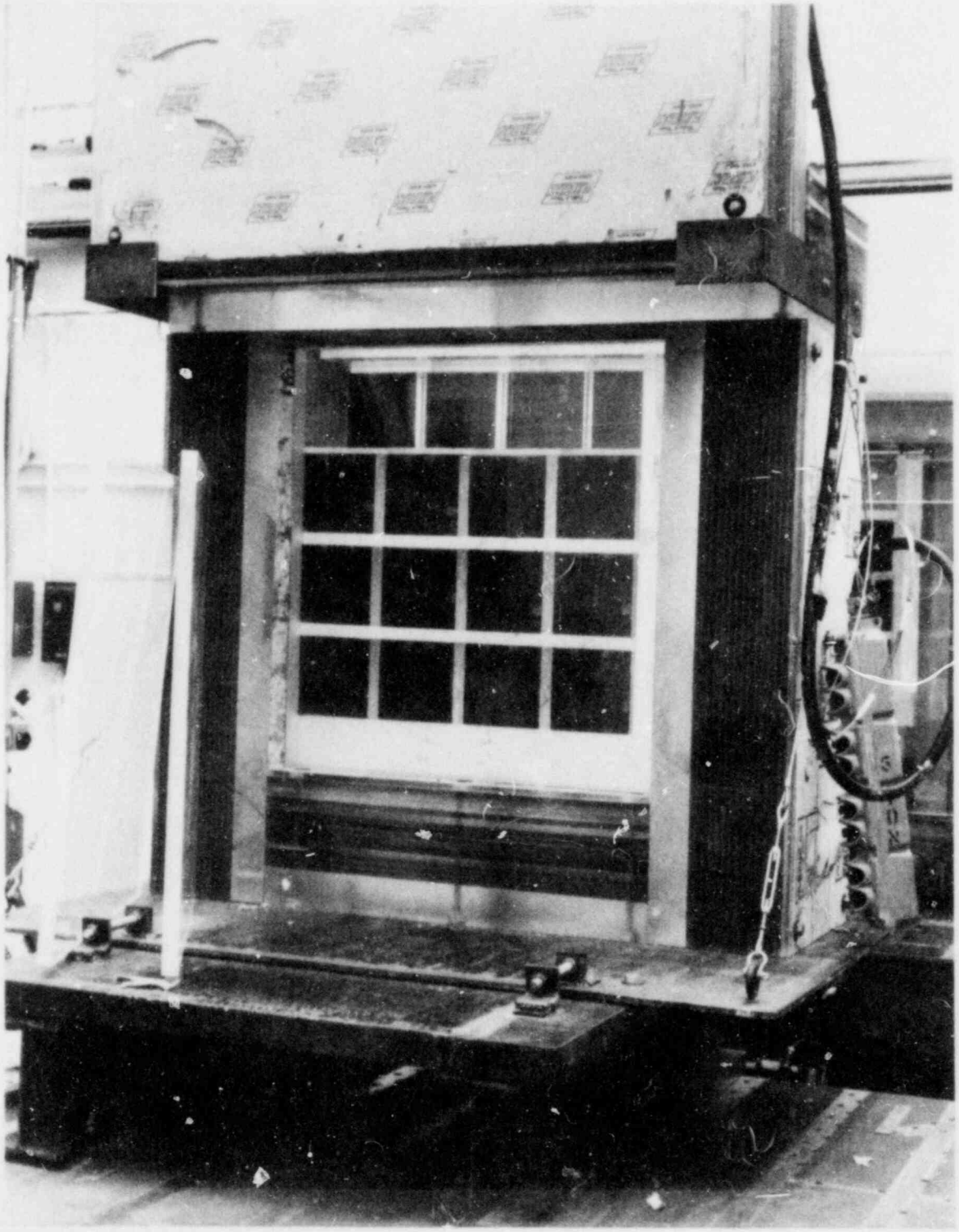

FIGURE 21

Category P experiment, plastic reflector. The south end reflector panel has been raised but not removed completely, and two large filler pieces have been removed from behind the cans and propped against the south frame.

FIGURE 22

Category P experiment, concrete reflector. Criticality was sometimes achieved with an incomplete layer of cans where moderator material might or might not be adjacent to vacancies in the core. Here, moderator exists above the third layer but not to the right of the second can on the fourth. Such material is termed "noninterstitial moderator within the core" and is tabulated in Table VI.

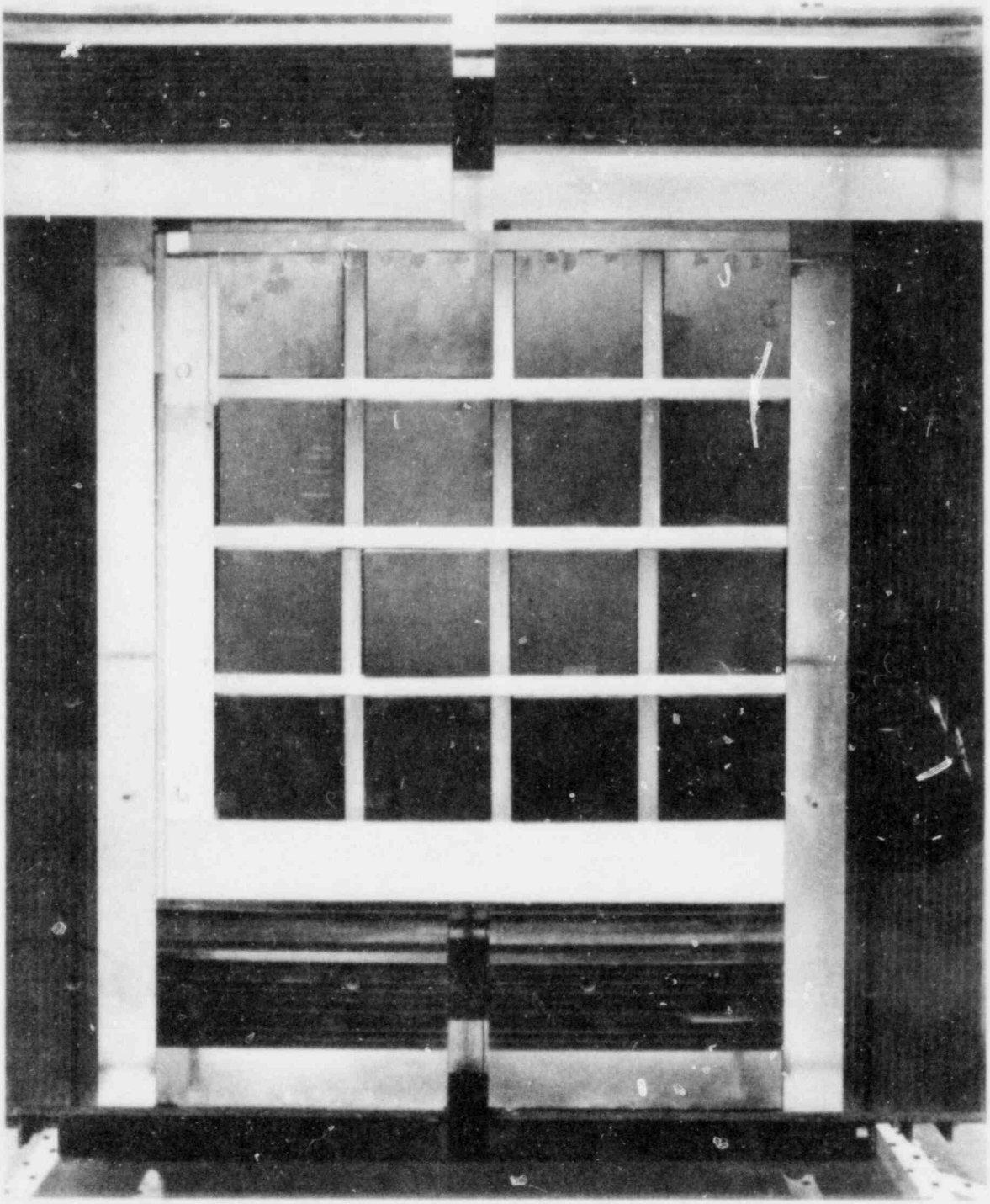

FIGURE 23

Category M experiment, plastic reflector. The slots in the top of the south table reflector frame were used for neutron source removal near criticality. The bottom slot was not used in this program.

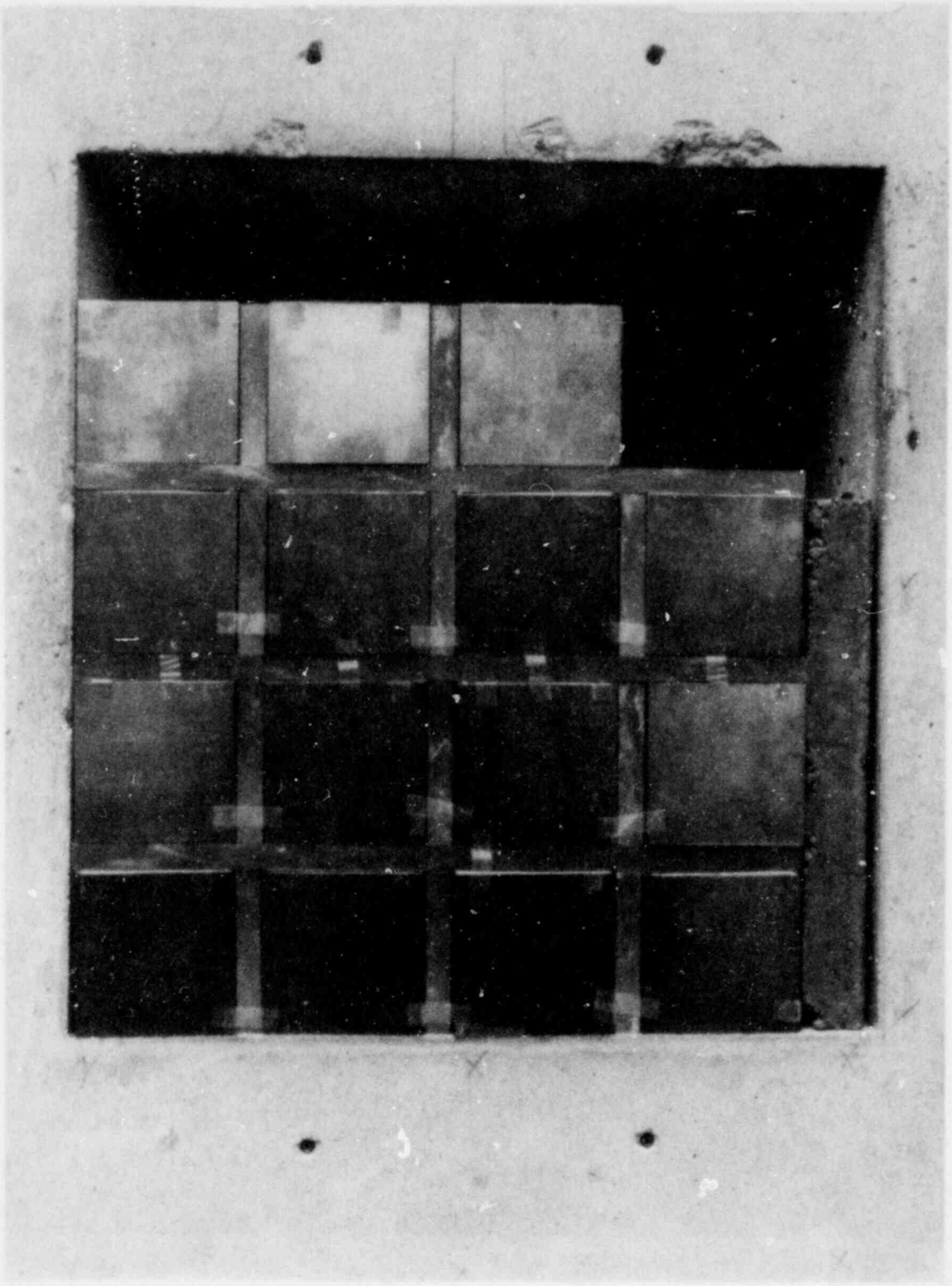

FIGURE 24

Category M experiment, concrete reflector. This was the largest separation between core and reflector not filled with filler pieces.

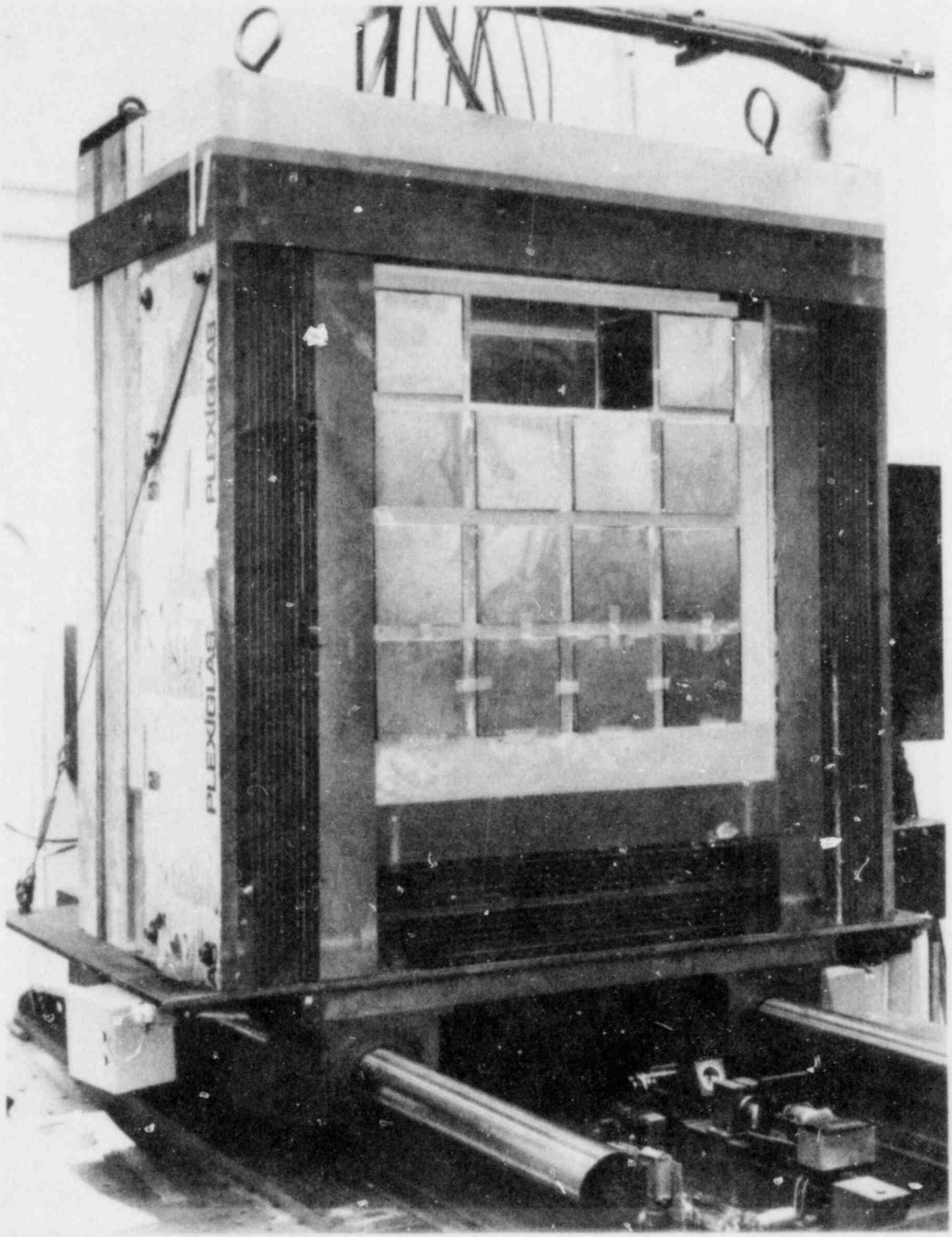

FIGURE 25

Category m experiment, plastic reflector. This photograph does not show the top layer configuration taken to criticality.

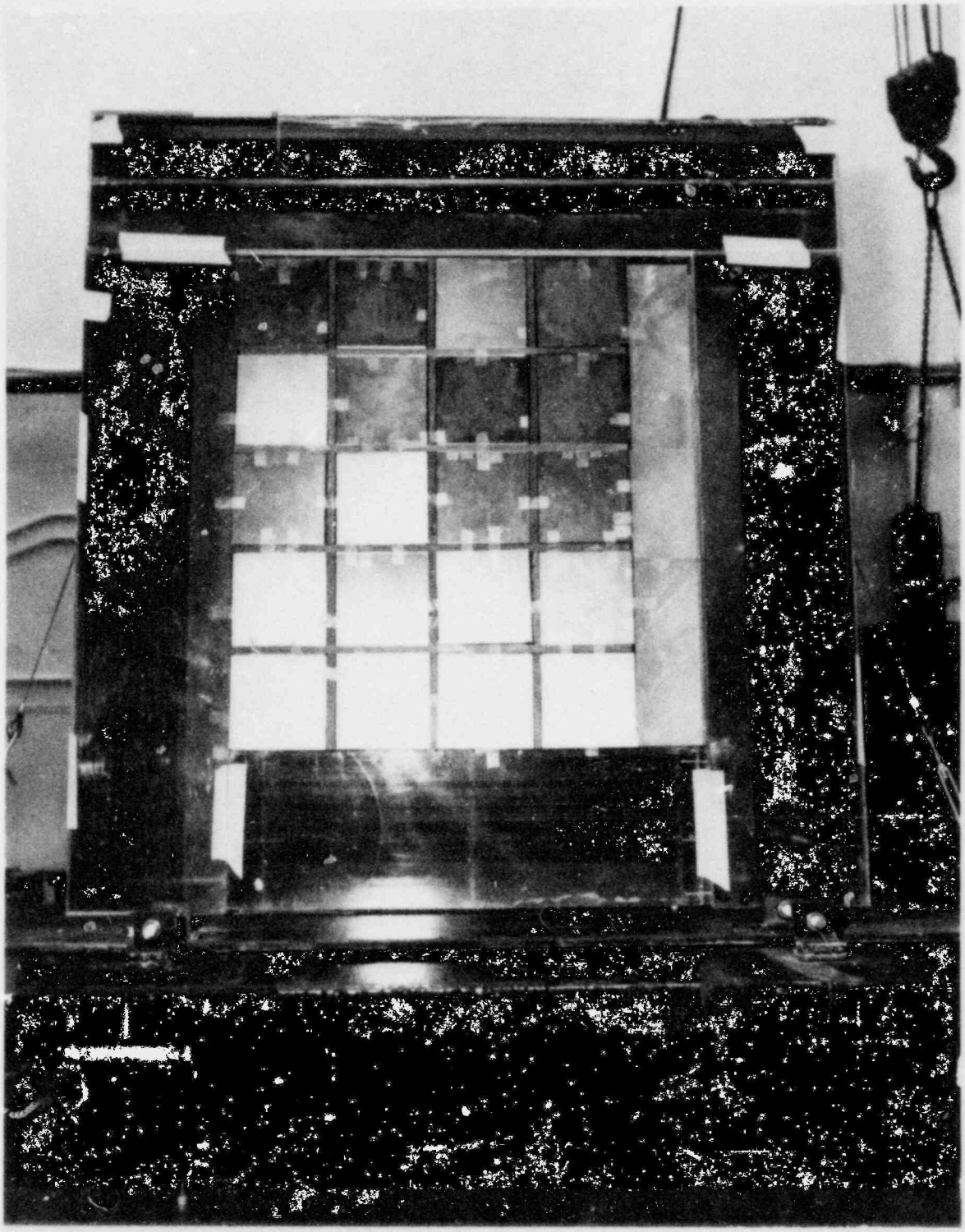

FIGURE 26

Category T experiment, plastic reflector. The south end reflector panel has been removed to expose the most southerly column of cans. The 2.5-cm-thick frame extension is held in place by short strips of vinyl tape.

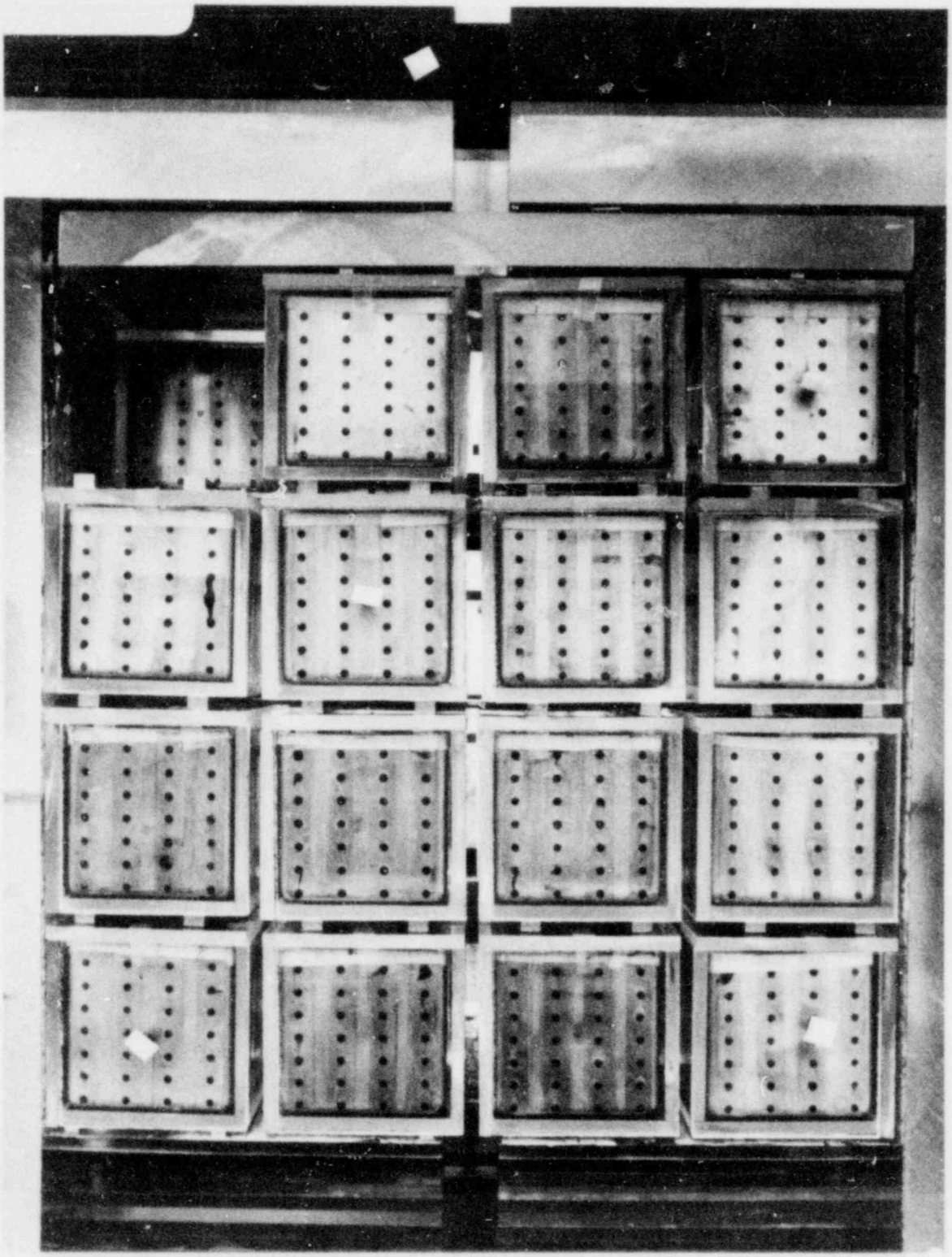

FIGURE 27

Category E experiment, plastic reflector. Five putty mounds, used after the experiment to determine the precise separation which had been achieved between tables, can be seen covered by small rectangles of vinyl tape which prevented their sticking to the opposite face.

UNCERTAINTIES

Many parameters have measured or estimated uncertainties expressed along with the value. Wherever multiple measurements are involved, the uncertainty is the calculated standard deviation. Usually, such multiple measurements are merely a sampling of a much larger set of possible measurements, and here the standard deviation is given by:

$$\left[(N - 1)^{-1}\sum_{1}^{N}(x_i - \bar{x})^2\right]^{\frac{1}{2}}$$

Some parameters, such as the weight of oxide cans used in a given experiment, are the result of measurements of the entire population. In these cases, $\bar{x}$ is known exactly, and the standard deviation is calculated by:

$$\left[N^{-1}\sum_{1}^{N}(x_i - \bar{x})^2\right]^{\frac{1}{2}}$$

This form was used to calculate uncertainties in all parameters of Table III.

The critical table separation was interpolated from two separations, $S_{\pm}$, corresponding to two reciprocal reactor periods, with the uncertainty in the critical separation derived from uncertainties in these other parameters. The two separations, however, were each calculated from the

formula derived in the Procedure section, restated here with subscripts associated with positive and negative periods:

$$\frac{S_{\pm} - S'}{M_{\pm} - M'} = 0.2294 \text{ cm per meter scale division}$$

Here, S and M refer to table separations and meter readings, respectively; and the primes refer to putty mound data. No significant uncertainty is attributed to the constant: < 0.4%. The uncertainty in meter readings was estimated by asking a number of people to read the same setting, and the standard deviation of these was ± 0.035 scale divisions. The uncertainty in the two reactor periods was estimated in a similar manner. Several persons were asked to measure the same 5.88 min. period, and the standard deviation of five determinations was ± 0.15 min. (2.6%). The largest contribution to uncertainty in the critical table separation is in S′, the table separation measured by the putty mound data. Table XIII addresses perturbations to an assumed closure of two parallel planes, and these data may be applied to each experiment individually. An approximate worst case from Table XIII has an uncertainty of ~ ± 2 mm in the table separation. Combining all uncertainties related to the above equation suggests that the maximum uncertainty in any table separation given in this paper is dominated by the ability to interpret putty mound data.

Some parameters in this report do not have an uncertainty specified. In such cases, the number of significant figures has been selected to approximate the certainty attributed to that parameter. A very conservative approach would be to round off any published parameter to one fewer significant figures.

The hydrogen content of the concrete is an important but elusive parameter. Absorbed water and waters of hydration in the sand (and, to a lesser extent, the limestone aggregate) are difficult to measure and have been assigned an accuracy of ± 10%. The water lost during the 16 months cure is equally questionable: ± 10%. The uncertainty in the amount of water added at the cement plant is assumed to be ± 5%. Combining these, the water weight-fraction and its uncertainty becomes about 0.053 ± 0.003, corresponding to a hydrogen weight-percent of about 0.59 ± 0.03 (5%).

REFERENCES

1. Validation of Calculational Methods for Nuclear Criticality Safety, ANSI-N16.9, American National Standards Institute (1975).

2. C. L. Schuske, et.al., Reference Critical Experiments Progress Report for Period July 1, 1975, through December 31, 1975, RFP-NUREG-2481, Rockwell International, Rocky Flats Plant (1976).

3. H. Neltrup, Benchmark Calculations on Homogeneous Spheres, RISO-M-1526, Riso, Roskilde, Denmark (1972).

4. F. G. Welfare, "Evaluation of Very Low Moderation, Low Enrichment UO_2 Systems", Trans.Am.Nuc.Soc., 19, 201 (1974).

5. P. B. Cripps, Calculations and Review of Criticality Data for Homogeneous Water-Moderated, 5 Weight-Percent Enriched Uranium Dioxide Systems, AAEC/F-308, Australian Atomic Energy Commission (April, 1974).

6. G. Tuck and I. Oh, Benchmark Critical Experiments on Low-Enriched Uranium Oxide Systems with H/U = 0.77, NUREG/CR-0674, U. S. Nuclear Regulatory Commission (1979). Available for purchase from U.S. NRC/GPO Sales Program, Washington, D.C. 20555 and the National Technical Information Service.

7. R. E. Rothe and I. Oh, "Benchmark Critical Experiments on High-Enriched Uranyl Nitrate Solution Systems", Nuclear Technology, 41, 207 (1978).

8. I. Oh and R. E. Rothe, "A Calculational Study of Benchmark Critical Experiments on High-Enriched Uranyl Nitrate Solution Systems", Nuclear Technology, 41, 226 (1978).

9. E. H. P. Cordfunk, The Chemistry of Uranium, Elsevier Publishing Company (1969).

10. F. A. Rough and A. A. Bauer, Constitutional Diagrams of Uranium and Thorium Alloys, Addison-Wesley Publishing Company, Inc. (1958).

11. G. R. Keepin, Physics of Nuclear Kinetics, Addison-Wesley Publishing Company, Inc. (1965).

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The critical separation between two tables supporting arrays of cans containing low-enriched uranium oxide has been measured for twenty-one (21) reflected configurations having interstitial layers of moderating material between cans. The critical separation varied between 0.23 and 1.84 cm. The uranium oxide (U_3O_8) is enriched to 4.46% ^{235}U, compacted to a density of 4.7 g/cm^3, and adjusted to an H/U atomic ratio of 0.77 by the addition of water. Each can weighs 16 kg and is a 15.2 cm cube. Interstitial plastic moderator 1.0, 1.3, or 2.5 cm thick separates cans of the three-dimensional array. Some experiments include thin sheets of neutron absorbing materials, such as mild steel or polyvinyl chloride, surrounding each can. Arrays are closely reflected by thick cuboidal shells of plastic or concrete. The parameter varied to achieve criticality is the number of cans in the array. The smallest number of cans (40) occurs with 2.5-cm-thick moderator, no absorber, and concrete reflector. The largest (100) occurs for several combinations of absorber and moderator in both reflectors. For otherwise similar configurations, concrete is the better reflector in all cases.

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