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Neutron Physics Division

CRITICALITY SAFETY TESTS FOR ROVER REACTOR FUEL ELEMENTS

(Title Unclassified)

E. C. Crume* and E. B. Johnson

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CRITICALITY SAFETY TESTS FOR ROVER REACTOR FUEL ELEMENTS

E. C. Crume and E. B. Johnson

ABSTRACT

Critical experiments were performed with Westinghouse type NRXA-3 and NRXA-4 fuel elements to provide data for use in criticality safety analyses of Project Rover fuel element production, storage, and transportation. These experiments supplement similar experiments performed in 1962 with KIWI-B-2A fuel elements, which are similar in composition to the NRXA-type elements but differ in several design features. Each NRXA-type element used in the present experiments is a nominally 52-in.-long hexagonal graphite cylinder 0.870 in. across points (with 0.435 in. sides), containing 19 uniformly spaced longitudinal holes. Pyrolytic-graphite-coated uranium dicarbide beads are distributed uniformly in the graphite to give average uranium concentrations of 0.418 g/cm^3 in the NRXA-3 elements and 0.449 g/cm^3 in the NRXA-4 elements. The uranium is 93.15 percent by weight ^{235}U, giving average C:^{235}U atomic ratios of 90 in the NRXA-3 elements and 87 in the NRXA-4 elements.

Experiments were performed both with the elements directly submerged and with them encased in sealed aluminum tubes, 0.94 in. in inside diameter, which prevented water from coming in contact with the element. In order to establish both the minimum critical number of water-moderated and -reflected elements and the relationship between moderation and critical number, several critical arrays covering a wide range of moderation were assembled. It was found that the minimum critical number of directly submerged elements was 39.5 $\pm$ 0.3, containing 4.84 $\pm$ 0.12 kg of ^{235}U, and occurred at an H:^{235}U atomic ratio of about 275. The minimum critical number of elements in sealed tubes was 51.5 $\pm$ 0.3, containing 6.24 $\pm$ 0.06 kg of ^{235}U, and occurred at an H:^{235}U atomic ratio of about 330. Additionally, it was found that the minimum critical number of submerged, nominally 16-in.-long sections of elements was 52, containing 2.0 $\pm$ 0.2 kg of ^{235}U, and occurred at an H:^{235}U atomic ratio of about 260.

An experiment was also performed to study the effectiveness of boron-carbide-filled steel tubes as fixed neutron absorbers in a 44-element shipping container configuration.

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INTRODUCTION

Since 1962, when the first experiments, described by E. B. Johnson and J. K. Fox,[1] were completed, there have been a number of changes in the procedures and equipment used in the production, storage, and transportation of Project Rover fuel elements. Superficially, at least, the most significant change appears to have been in the design of the fuel elements, further details of which are given below. Since extrapolations of the original data are necessary to aid in answering current plant criticality safety problems at Y-12, it was considered desirable to repeat certain of the original experiments, using elements of newer design. The experiments repeated were those used for the determination of the optimum lattice spacing and the minimum critical number of elements under two conditions. One condition was with the elements in sealed aluminum tubes, which condition is representative of storage. The other condition was with the elements out of tubes, which condition is representative of production operations. Since the uranium carbide is now coated with pyrolytic graphite preventing its exposure to water if the elements were submerged, it was possible to use the same elements for critical measurements both in and out of the sealed aluminum tubes, rather than different ones as was necessary for the original measurements. A new area of investigation was the efficacy of fixed neutron absorbers in shipping containers.

It is desirable to reiterate the statement of the original report that these experiments were done with essentially finished elements and so the critical parameters obtained are not representative of well homogenized slurries of the materials comprising the elements. Additionally, care should be used in extrapolating the critical parameters to conditions found earlier in the manufacturing process where the ^{235}U content of each element is appreciably greater.

1. E. B. Johnson and J. K. Fox, "Critical Mass Studies Part XII: Rover Reactor Fuel Elements," ORNL-TM-264 (Sept. 18, 1962) (Classified).

DESCRIPTION OF FUEL ELEMENTS

The Project Rover fuel elements used in this series of experiments were of two types, one designated as NRXA-3 and the other as NRXA-4. However, except for a difference in uranium content, both types had the same composition--a dispersion of pyrolytic-graphite-coated uranium dicarbide spherical beads in a graphite matrix. The uranium is enriched to 93.15 percent by weight in the ^{235}U isotope. The average diameter of the beads is 0.003 in. and the average thickness of the pyrolytic graphite coating is 0.001 in. The elements are hexagonal cylinders with 0.435-in. sides (0.870 in. across points) containing 19 uniformly spaced longitudinal holes 0.096 in. in diameter in the NRXA-3 elements and 0.099 in. in diameter in the NRXA-4 elements as shown in Fig. 1. The full elements averaged 52.1 in. in length. The elements were not in the finished state in that they did not have the final dimensions nor the required niobium carbide coating in the longitudinal holes and on one end. A number of elements were cut so that nominally 15.-in. long sections were available for some experiments.

The NRXA-3 elements had an average uranium concentration of 0.418 g/cm^3 and the NRXA-4 elements, 0.449 g/cm^3, giving C:^{235}U atomic ratios of 90 in the former and 87 in the latter. The ^{235}U content of individual elements varied from 114 to 129 grams, reflecting not only differences in uranium concentration between the two types of element but also small differences in the length of the elements.

For some of the experiments the elements were encased in 1-in.-OD aluminum tubes with 0.035-in. wall thickness similar to those used for storage of the elements during manufacturing. The tubes were sealed with tight-fitting rubber stoppers to prevent internal moderation of the elements by water during the experiments. Since the tubes were 53.5 in. long, the elements approximately 52 in. long, and the stoppers extended about 0.5 in. into the tubes on each end, about 285 cm^3 of air were trapped with each element, occupying the holes in the element, the space between the element and the tube, and the space between the ends of the element and the stoppers.

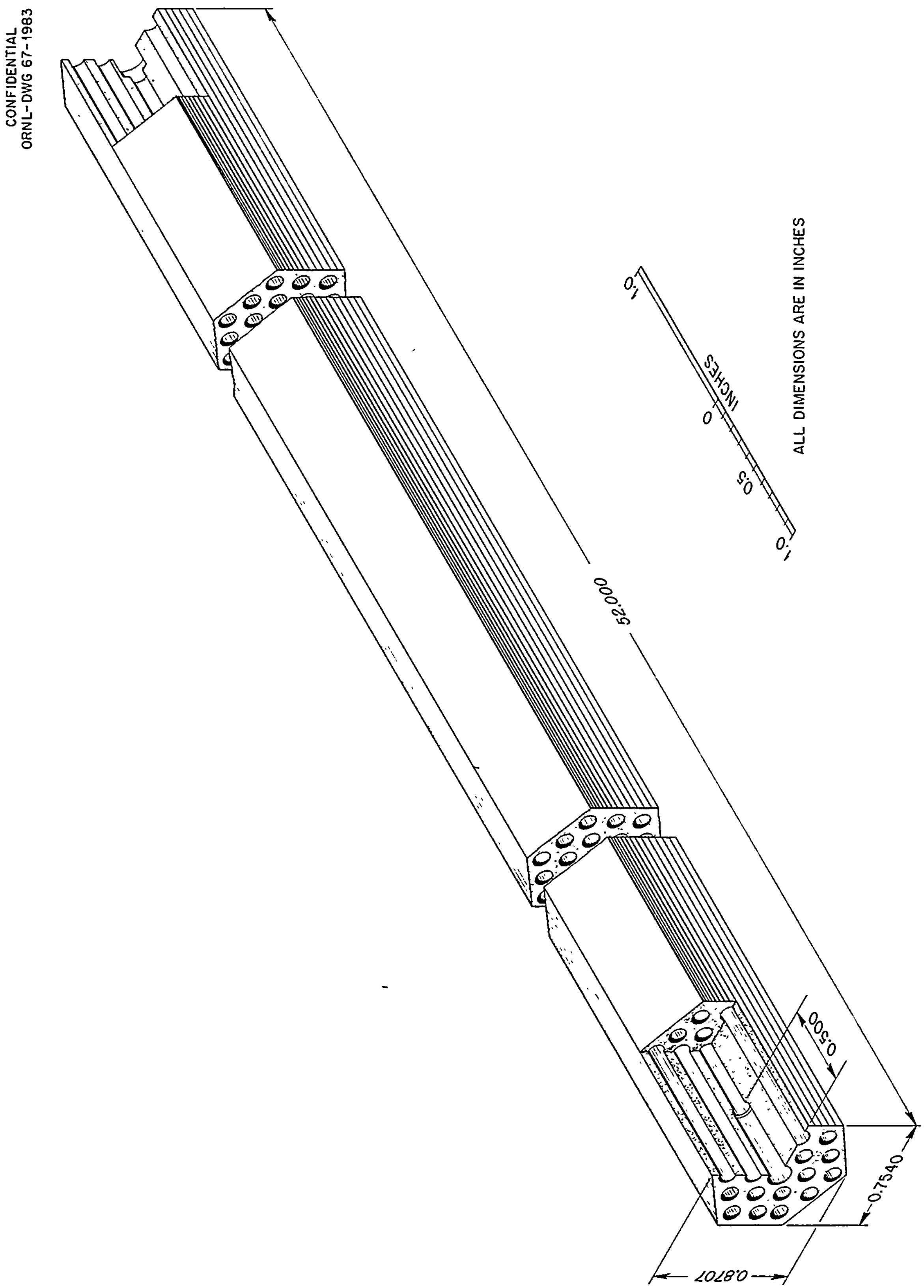

Fig. 1. Sketch of NRXA-Type Fuel Element.

EXPERIMENTAL EQUIPMENT

The experiments were performed utilizing for the most part the same equipment or equipment similar to that used in Ref. 1. As before, milled Plexiglas strips spaced the tubed elements in both square and triangular lattices and the untubed elements in the square lattices. However, in the present experiments, Plexiglas "tube sheets," i.e., flat sheets with circular holes on appropriate centers, were used to space the untubed elements in the triangular lattices.

EXPERIMENTAL RESULTS

Elements in Tubes

The experiments using elements in sealed aluminum tubes were conducted in a manner similar to that described in Ref. 1; i.e. several "rounded" lattices of the tubed elements were assembled on both square and triangular pitches to adequately establish the minimum critical number and to examine the general relationship between moderation and critical number. By "rounded" lattice is meant one in which the peripheral elements are placed so as to minimize the radius of the smallest circle which can be drawn circumscribing the lattice in plan view. Figures 2 and 3 are photographs of typical rounded square and triangular lattices, respectively. A more complete discussion of the types of lattices and illustrations of "rounded" lattices is given in Ref. 1.

Table 1 is a summary of the critical data obtained with the water-moderated and -reflected lattices of tubed elements and of other critical parameters calculated from the data. The surface spacing was determined by the thickness of the Plexiglas spacers. The critical number of elements was determined for all but three of the lattices by bracketing with two loadings, one slightly supercritical and the other slightly subcritical. For those three lattices the quoted number was observed to have been critical. Although fractional elements were not available for these measurements, a fractional element uncertainty in critical number is given in the table. This uncertainty is based on measurements of the reactivity equivalent of an element in terms of top reflector thickness and is not a precise number. However, it is the largest uncertainty that can be

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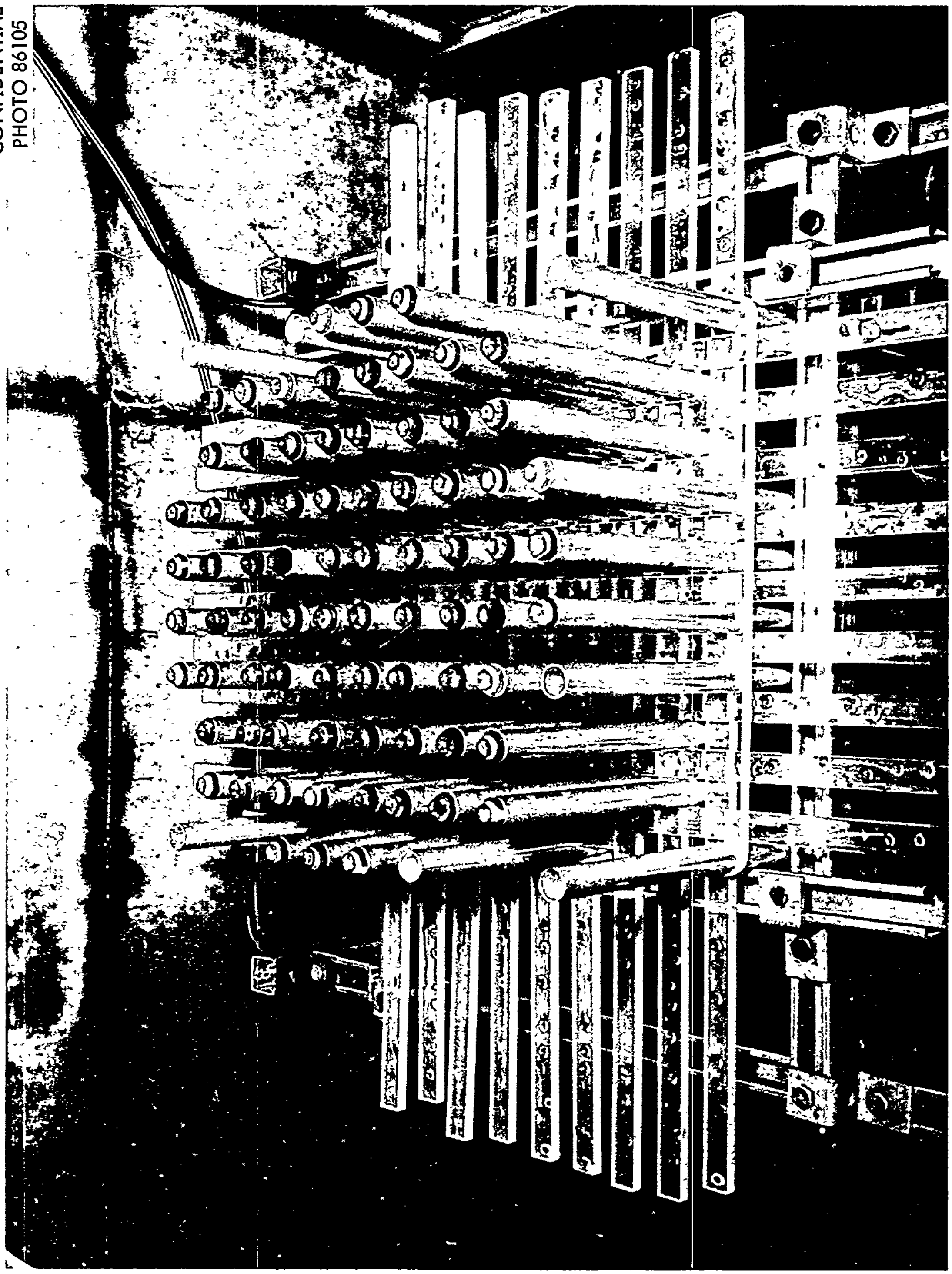

Fig. 2. Typical Rounded Array of Elements in Sealed Aluminum Tubes Arranged in Square Pattern.

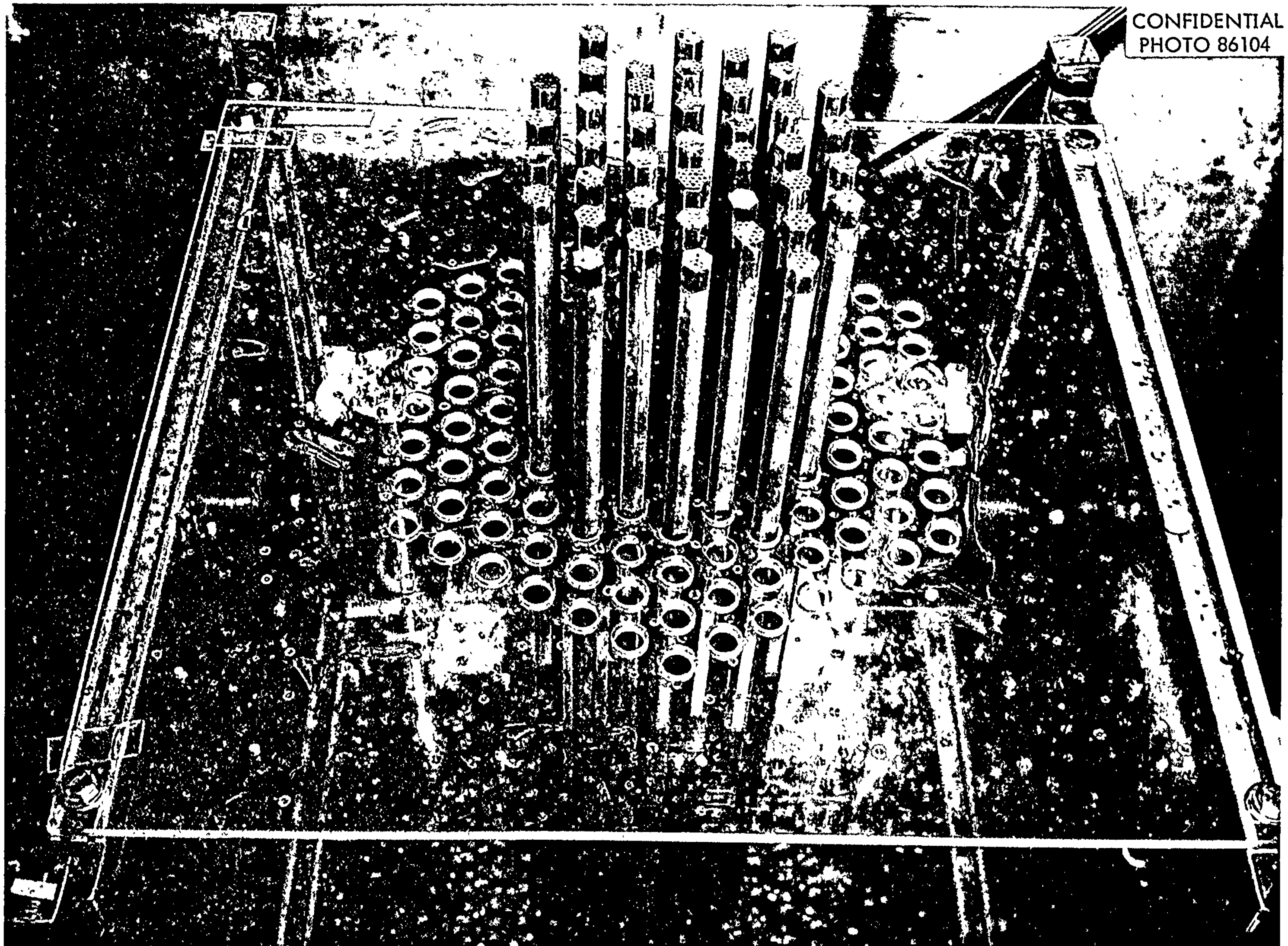

Fig. 3. Typical Array of Elements Arranged in Triangular Pattern.

Table 1. Summary of Water-Moderated and -Reflected Critical Lattices of Uranium-Carbide-Bead-Loaded Graphite Elements in Sealed Aluminum Tubes

Aluminum Tube Surface Spacing (in.)	Critical Number of Elements	$H:^{235}U$ Atomic Ratio	Critical[a] Mass (kg of ^{235}U)	Critical ^{235}U Concentration (g/liter)	Critical Volume (liters)	Critical Core Diameter[b] (in.)	Average Element ^{235}U Content (g)	Average Element Length (in.)	Volume Fraction of Water in Core Region
Square Lattice, Rounded Arrays									
0.10	116.5 ± 0.3	79	13.93 ± 0.13	116	120	13.4	120	52.1	0.351
0.20	79.3 ± 0.3	121	9.55 ± 0.10	98.0	97.4	12.0	120	52.0	0.454
0.30	65.3 ± 0.3	164	7.90 ± 0.08	84.6	93.4	11.8	121	52.0	0.532
0.40	56.3 ± 0.3	215	6.84 ± 0.07	72.8	93.9	11.8	121	52.0	0.599
0.50	52.5 ± 0.3	267	6.39 ± 0.06	63.3	101	12.3	122	52.0	0.651
0.60	51.5 ± 0.3	324	6.27 ± 0.06	56.0	112	13.0	122	51.9	0.693
0.70	53.0 ± 0.3	384	6.45 ± 0.06	49.6	130	14.0	122	52.0	0.728
0.80	57.3 ± 0.3	450	6.96 ± 0.07	44.0	158	15.4	121	52.0	0.757
0.90	66.5 ± 0.3	520	8.04 ± 0.08	39.2	205	17.5	121	52.0	0.762
1.00	76.7 ± 0.3	594	9.24 ± 0.09	35.3	262	19.8	120	52.0	0.804
Triangular Lattice, Rounded Arrays									
0.000	> 145		-	-	-	-	-	-	0.320
0.270	82.5 ± 0.3	112	9.93 ± 0.10	101	98.4	12.1	120	52.1	0.438
0.501	55.0 ± 0.3	215	6.66 ± 0.13	72.8	91.5	11.7	121	52.0	0.598
0.616	52.0 ± 0.3	271	6.30 ± 0.13	63.0	100	12.2	121	52.0	0.653
0.732	51.5 ± 0.3	332	6.24 ± 0.13	54.8	114	13.0	121	52.0	0.698
0.848	53.3 ± 0.3	399	6.45 ± 0.13	48.1	134	14.2	121	52.0	0.734
1.078	67.5 ± 0.3	544	8.16 ± 0.08	37.9	215	17.9	121	52.0	0.790
1.194	85.3 ± 0.3	627	10.26 ± 0.10	33.8	303	21.3	120	52.1	0.812

a. The error limits are a combination of ± 0.3 of an element and the 95 per cent confidence level limits on the total mass of the elements.

b. Taken to be the diameter of a right circular cylinder of length equal to the fuel element length and of volume equal to the total fuel element cell volume.

ascribed to the experimentally determined critical number of elements. The uncertainties listed for the critical masses are the 95 percent confidence level limits. They are combinations of both the fractional element uncertainty and the 95 percent confidence level limits on the uranium content of the elements used. The H:^{235}U atomic ratios and other quantities in the table associated with core volume were calculated on the basis of a division of the lattice into cells. For the square-pitched lattices a cell of square cross section was defined, with an edge equal to the lattice pitch and a length equal to the fuel element length. For the triangular-pitched lattices, a cell of hexagonal cross section was defined, with the across-the-flats dimension ($= \sqrt{3}$ times the length of a side) equal to the lattice pitch and a length equal to the fuel element length. The core volume listed for a given spacing is the product of the critical number of tubed elements for that spacing and the corresponding cell volume. Thus, the entire volume of each of the cells associated with the peripheral elements of the lattices is also included in the core volume.

Figures 4 through 7 are plots of critical data and calculated critical parameters. A comparison with Figs. 6, 7, and 8 of Ref. 1 shows that the general features of the critical conditions are similar. Because the element loadings, the aluminum tube sizes, and the "void" volumes in the tubes were markedly different in the two sets of experiments, it was not expected that any other than the general features would be in agreement. Indications that the triangular lattices may have slightly lower, a few percent at most, critical masses than the square lattices of the same H:^{235}U ratio are found upon examination of Fig. 5, in which the 95 percent confidence limit bounds on the points plotted fall well within the identifying symbols.

An investigation was made of the effect of variation in fuel element uranium content on critical mass in both square and triangular lattices. In a square lattice of 1.60 in. pitch (surface spacing = 0.60 in.), the critical number of elements was 51.5, containing a total of 6.27 kg of ^{235}U at an average ^{235}U content of 122 g per element and 55.5 containing a total of 6.54 kg of ^{235}U at an average ^{235}U content of 118 g per element.

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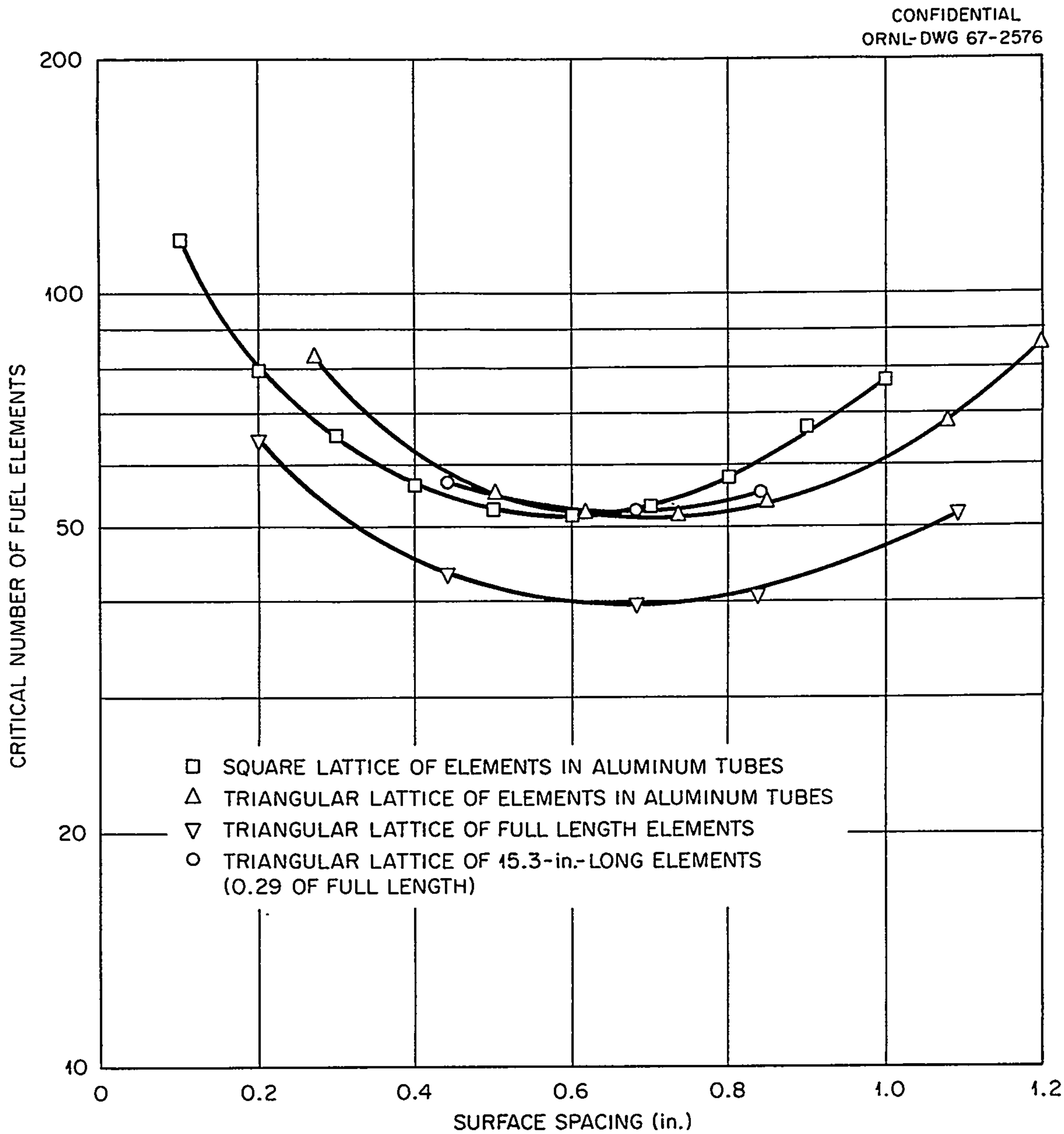

Fig. 4. Critical Number of Fuel Elements vs Surface Spacing.

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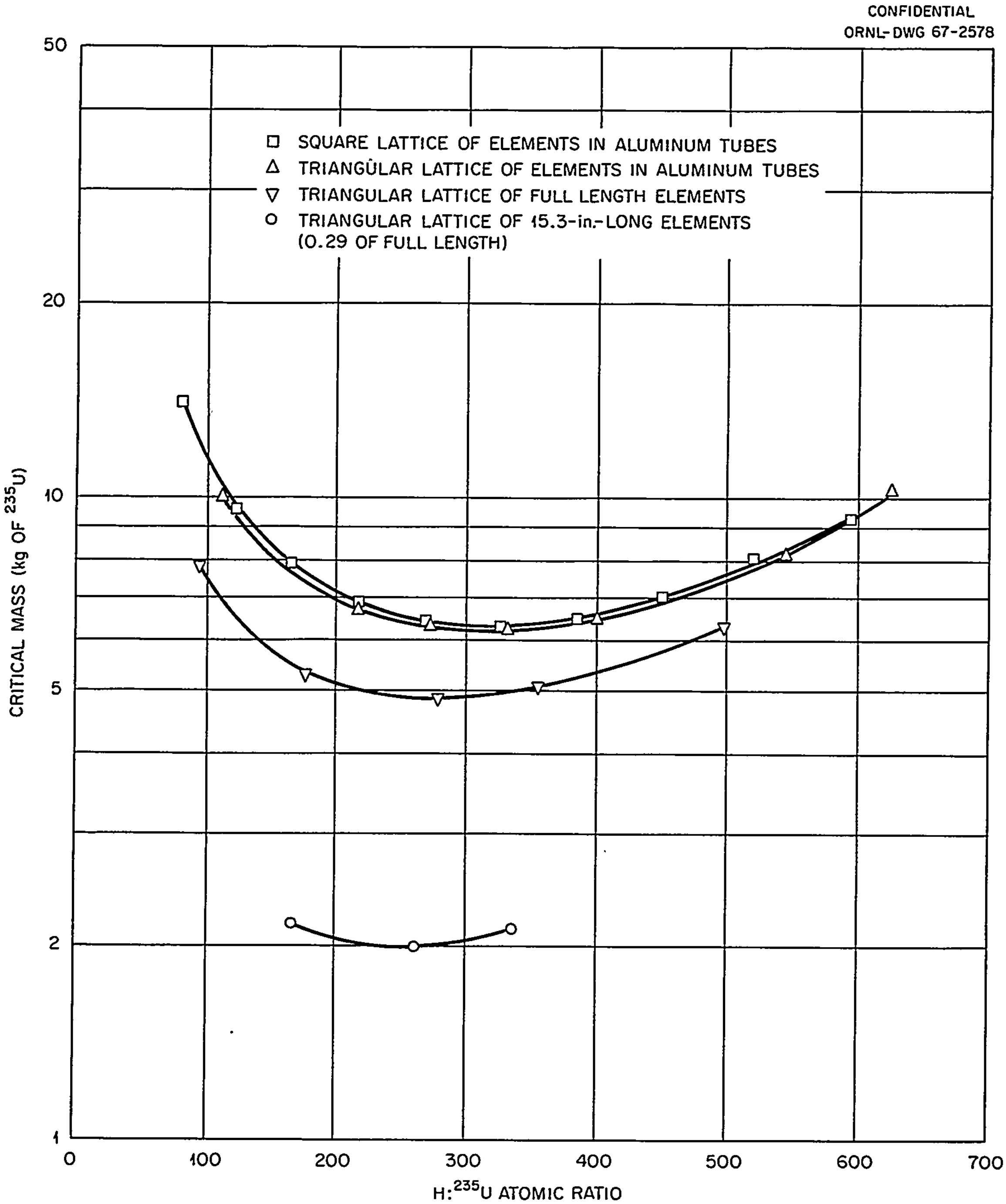

Fig. 5. Critical Mass of Fuel Elements vs H:^{235}U Atomic Ratio.

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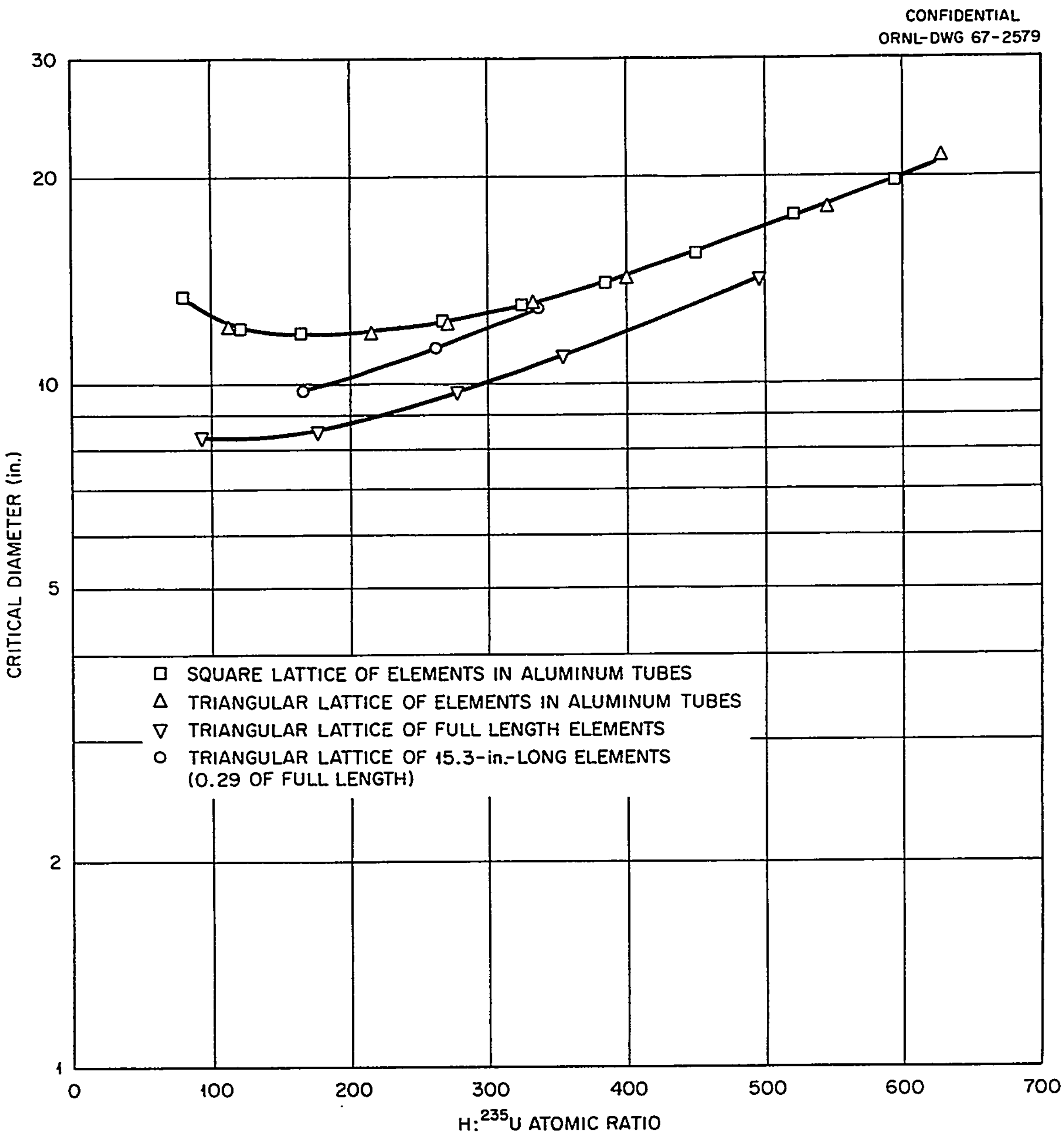

Fig. 6. Critical Diameter of Lattices vs H:^{235}U Atomic Ratio.

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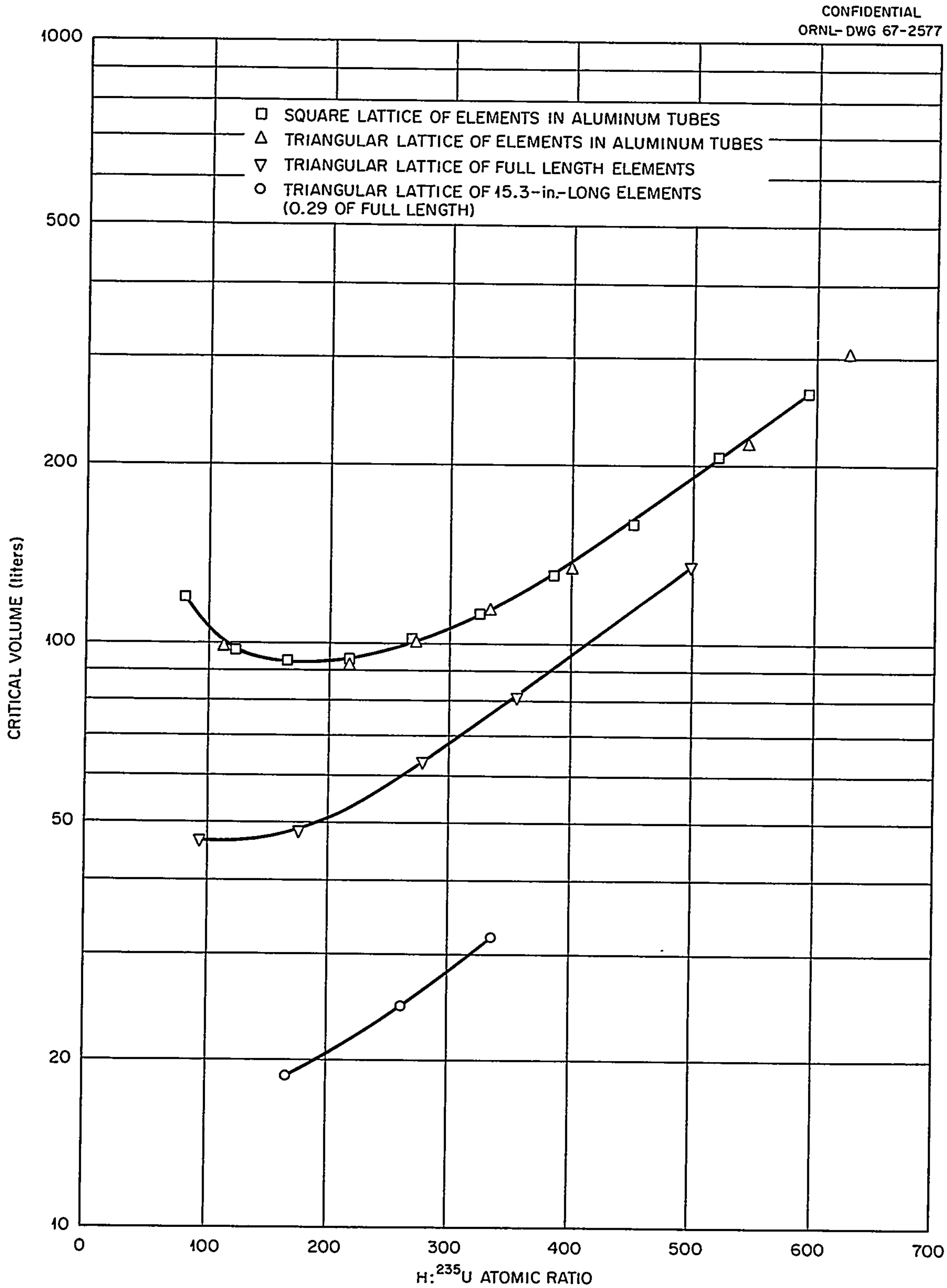

Fig. 7. Critical Volume of Lattices vs H:^{235}U Atomic Ratio.

[redacted]

In a triangular lattice of 3.272 in. pitch (surface spacing = 0.732 in.), the critical number of elements was 51.5 containing a total of 6.24 kg of ^{235}U at an average ^{235}U content of 121 g per element, and 53.5 containing a total of 6.30 kg of ^{235}U at an average ^{235}U content of 118 g per element. As is seen from Fig. 5, where these data are plotted, it cannot be conclusively stated whether or not the minimum critical mass is independent of the ^{235}U loading of the element in the range covered, 118 to 122 g ^{235}U per element.

Elements Out of Tubes

Water-moderated and -reflected triangular lattices were constructed with elements removed from their aluminum storage tubes. In these lattices, the water moderator not only surrounded each element but also filled the 19 longitudinal holes in each element. The critical data and other critical parameters calculated from the data are summarized in Table 2 and are plotted with the data from the experiments with the elements in tubes in Figs. 4 through 7.

It is apparent from the figures that the air and the aluminum present in the element-in-tube experiments significantly affect the critical parameters. Not only are the minimum critical parameters 20 or more percent lower with the elements out of the tubes but also the minima occur at significantly lower H:^{235}U atomic ratios. Although the effect was noted, it was not possible to state its origin conclusively in Ref. 1 because of the differences between the composition and ^{235}U loading of the elements which were used in tubes and the elements which were used out of tubes. A comparison of Figs. 4 through 7 in this report with Figs. 6 through 8 of Ref. 1 shows that, within the indicated limits of error, the out-of-tube critical parameters are essentially the same in the two cases. This is a little surprising since several differences between the types of elements are evident. Among the more prominent are that the present elements are about 1.5 in. longer, are hexagonal rather than round, have 19 holes rather than seven, contain about 5 percent more ^{235}U and essentially no oxygen, whereas about one mole of oxygen was in each of the previous elements. It follows that the effects of these differences, if any, must be either small or mutually compensating.

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Table 2. Summary of Water-Moderated and -Reflected Critical Triangular Lattices of Uranium-Carbide-Bead-Loaded Graphite Elements

Lattice Pitch (in.)	Element Surface Spacing[a] (in.)	Critical No. of Elements	H:^{235}U Atomic Ratio	Critical Mass[b] (kg of ^{235}U)	Critical ^{235}U Concentration (g/liter)	Critical Volume (liters)	Critical Core Diameter[c] (in.)	Average Element ^{235}U Content (g)	Average Element Length (in.)	Volume Fraction of Water in Core Region
Full Length Elements										
0.991	0.20	64.5 ± 0.3	93	7.80 ± 0.14	167	46.8	~~9.36~~ 8.36	121	52.0	0.596
1.231	0.44	43.3 ± 0.3	176	5.30 ± 0.12	110	48.3	8.51	122	51.9	0.738
1.471	0.68	39.5 ± 0.3	277	4.84 ± 0.12	77.0	62.9	9.71	123	51.9	0.817
1.631	0.84	41.3 ± 0.3	354	5.06 ± 0.12	62.7	80.8	11.0	123	51.9	0.851
1.881	1.09	51.7 ± 0.3	497	6.29 ± 0.13	46.6	135	14.2	122	52.0	0.888
Nominally 15-in. Long Elements										
1.231	0.44	56.5 ± 0.3	166	2.16 ± 0.16	116	18.6	9.72	38.2	15.3	0.738
1.471	0.68	52.3 ± 0.1	262	2.00 ± 0.16	81.3	24.6	11.2	38.2	15.3	0.817
1.631	0.84	55.5 ± 0.3	336	2.12 ± 0.16	66.0	32.1	12.8	38.2	15.3	0.851

a. Taken to be the surface spacing of right circular cylinders of the same cross-sectional area as the elements.

b. The error limits are a combination of ± 0.3 of an element and the 95 percent confidence level limits on the total mass of the elements.

c. Taken to be the diameter of a right circular cylinder of length equal to the full element length and of volume equal to the total fuel element cell volume.

[redacted]

The possibility that some shorter length elements, ranging from 12 to 18 in., would be manufactured prompted the construction of triangular lattices of nominally 15-in.-long sections. Normal length elements were cut into 3 1/16-in.-long sections and stacked to a 15.3 in. height. The results are summarized in Table 2 and plotted in Figs. 4 through 7. It is noted that the critical mass and the critical volume of the more optimumly shaped arrays possible with these shorter sections are only about 40 percent of those of the normal length elements. In Ref. 1 it was noted that the critical diameter or volume of shorter sections could be predicted from critical data for the normal length elements by equating values of the buckling using an extrapolation distance of 7 cm. The critical diameters of the 15.3-in.-long cores of the present measurements can be predicted within 2 percent by the same method using an extrapolation distance of 6 cm, appropriate to water-reflected cylinders of $U(93.2)O_2F_2$ solutions of approximately the same h/d ratio as these cores.

EFFECT OF NEUTRON ABSORBERS IN A SHIPPING CONTAINER

A container of the design depicted in Fig. 8 has been used for shipments of large numbers of elements from the Y-12 Plant. It was found[2] that containers of the exact design shown cannot be assumed watertight after regulation drop and fire tests.[3] A calculational analysis using reactor transport theory indicates that if the containers are not watertight only an undesirably small number of them can be shipped safely at one time as a Class II shipment. One way to increase the number of containers that can be safely shipped at one time would be to modify the containers by placing fixed neutron absorbers in the interstices between the fuel element tubes. To investigate the effect of such neutron absorbers on the criticality of a single water flooded container, assemblies of the type shown in Fig. 9 were constructed.

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2. Private communication from W. T. Mee, (1966).
3. For details of these tests see AEC Manual Chapter 0529 Appendix.

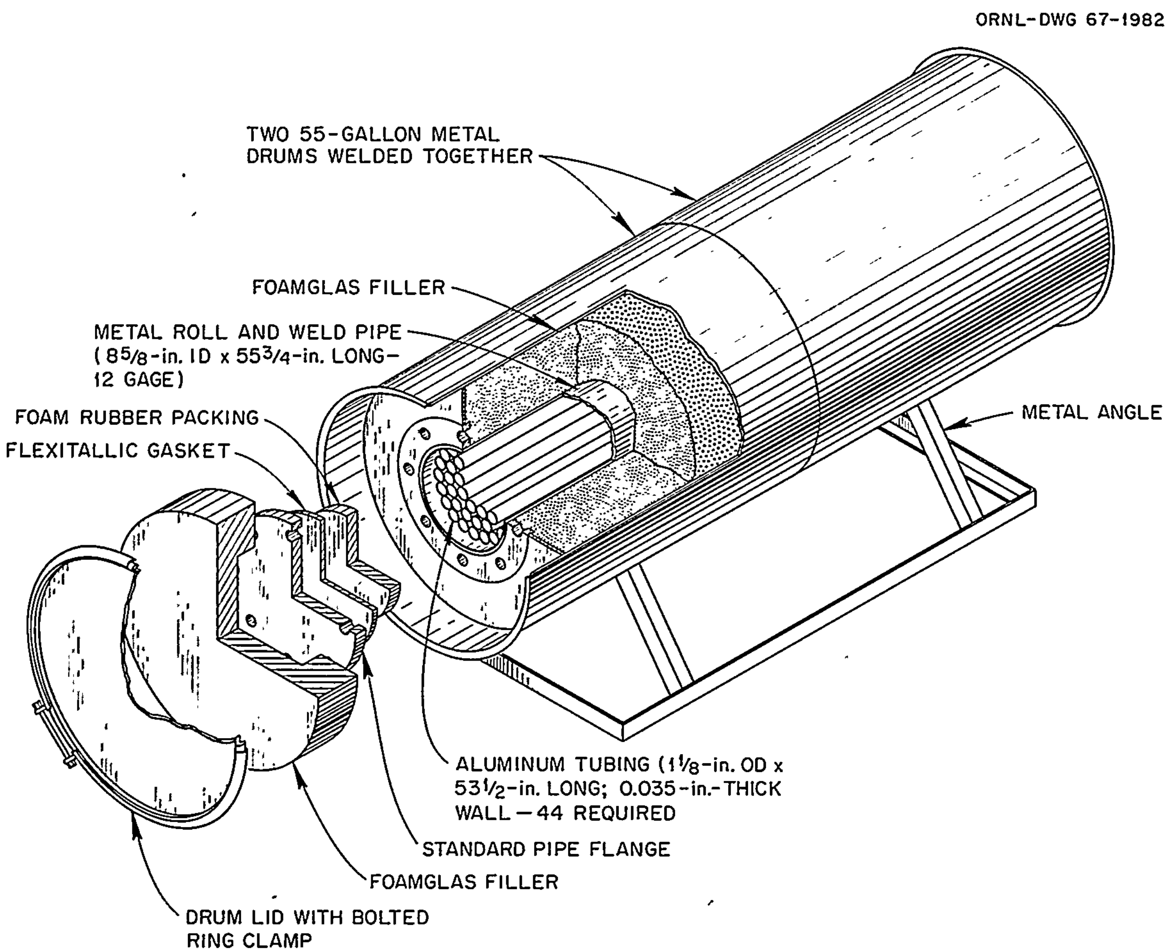

Fig. 8. Fuel Element Shipping Container (Forty-Four Element).

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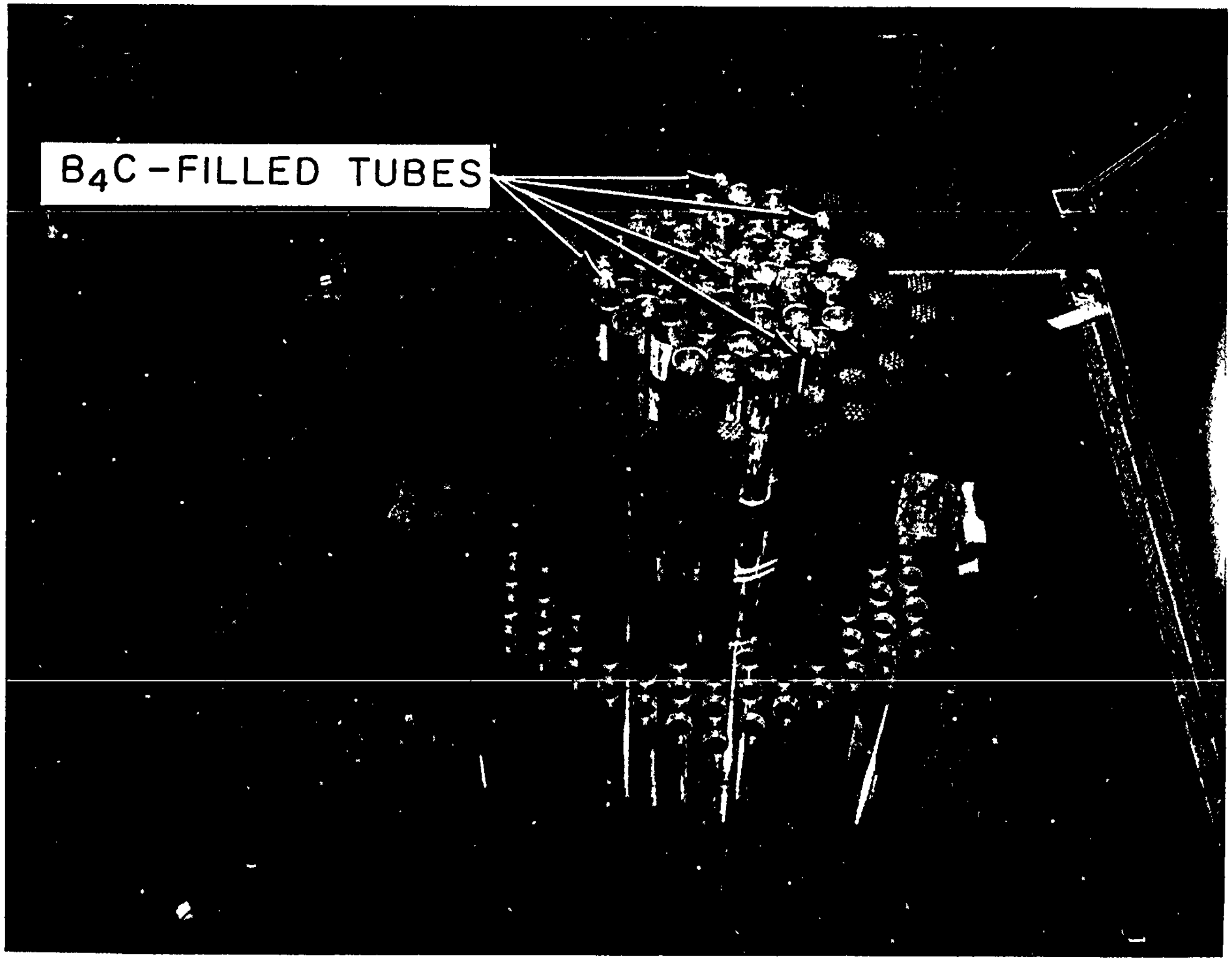

Fig. 9. Experimental Arrangement for Investigating Criticality of Fuel Element Shipping Container.

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In the central portion of the array, the elements were spaced as they are in the shipping container; i.e., they were confined to a cylinder of a diameter equal to the inside diameter of the steel tube indicated in Fig. 8. The aluminum tubes containing the elements were open at both ends to allow the free passage of water. In the outer portion of the array, the elements were spaced on a pitch of 1.379 in. (surface-to-surface spacing 0.59 in.), which is seen from Fig. 4 to be in the range for the minimum critical number of elements.

The assembly was designed so that it would be made critical by adding peripheral elements while maintaining in the central portion a neutron energy spectrum representative of that which would be found in an actual shipping container if flooded. This design was necessary because the number of elements available was insufficient to attain criticality with all elements spaced as in the central portion.

Neutron absorber rods were prepared by filling nominally 53.75-in.-long, 0.375-in.-OD, type 304 stainless steel tubes of 0.032 in. wall thicknesses with natural boron carbide (B_4C) granules and sealing off both ends. The average B_4C loading per tube was 88.2 g. The measurements consisted of evaluating the reactivity worth of the B_4C-filled tubes added at various radial positions in terms of the number of peripheral elements added to re-attain criticality after one or more tubes had been inserted in the central region of the array. The results of the measurements are summarized below.

Number of B_4C-Filled Tubes Added	Critical Number of Elements	Change in Critical Number of Elements Over Base
None (Base)	60.3 ± 0.3	--
1	62.5 ± 0.3	+ 2 ± 0.4
2	64.5 ± 0.3	+ 4 ± 0.5
3	66.5 ± 0.3	+ 6 ± 0.6
4	68.5 ± 0.3	+ 8 ± 0.7
5	70.5 ± 0.3	+ 10 ± 0.7
5 (Repeat)	70.5 ± 0.3	+ 10 ± 0.7
9	78.3 ± 0.3	+ 18 ± 0.8

[redacted]

For the second measurement with five B_4C-filled tubes in the core, elements which had been in the first ring of peripheral elements for the first measurement were moved into the partially filled second ring. No significant change in the reactivity of the system resulted.

Thus, it can be concluded that a B_4C tube added in the central region is equivalent to the removal of at least two peripheral elements from the array. The application of this information to analyses of shipping container safety will be reported at a later date in an Oak Ridge Y-12 Plant report.

ACKNOWLEDGMENTS

The authors express their appreciation to the several people who contributed significantly to the completion of these experiments: to R. K. Reedy for performing the experiments; to F. M. Tench, W. T. Crow, D. R. Vanover, and L. V. Thornton of the Y-12 Plant for their efforts in obtaining the materials; to W. C. Tunnell for the design and procurement of special equipment; and to E. R. Rohrer for assistance in instrumentation.

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