# REFERENCE 191

**J. T. THOMAS, "CRITICAL THREE-DIMENSIONAL ARRAYS OF U(93.2)-METAL CYLINDERS," NUCL. SCI. ENG. 52: 350-359 (1973).**

# NUCLEAR SCIENCE and ENGINEERING®

A JOURNAL OF THE AMERICAN NUCLEAR SOCIETY



NSENAO 52 (3) 283-420 (1973)

VOLUME 52, NUMBER 3, NOVEMBER 1973

NUCLEAR SCIENCE AND ENGINEERING: **52**, 350-359 (1973)

# Critical Three-Dimensional Arrays of U(93.2)-Metal Cylinders

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*Received April 6, 1973*
*Revised July 10, 1973*

Criticality studies were made of three-dimensional arrays of uranium-metal cylinders enriched to 93.2 wt% in $^{235}U$. Four weight groups of units, ranging from 10.4 to 26.2 kg of uranium in five geometries, were employed to determine the critical surface separation between units as a function of the number in an array. The influence on criticality of hydrogenous neutron reflecting and moderating materials, unit shape, array shape, and of other controlled perturbations to some assemblies was examined. Monte Carlo calculations were performed of the experimental assemblies to confirm the neutron multiplication factors and to interpret the behavior of several subcritical assemblies. The Hansen-Roach neutron cross-section sets reproduce the results of the experiments, in a majority of cases, to an accuracy of ~1% in $k_{eff}$.

## INTRODUCTION

A series of experiments performed during 1962-63 in support of nuclear criticality safety in the handling of accumulations of individually subcritical units of fissile materials was part of a continuing program in criticality safety at the Oak Ridge Critical Experiments Facility (CEF). Portions of these results have been previously reported.[1-3] In the experiments, the critical surface separation of cylindrical units of $^{235}U$-enriched uranium metal, usually equal in three directions, was measured as a function of the number of units in an array and of the thickness of paraffin surrounding the array. Units of five sizes were employed, permitting an examination of the effect of varying the mass of the units and their dimensions. A few definitive experiments indicate the effect of adding hydrogenous neutron moderating material between the units of arrays, of changing the geometric shape of the array, and of partially reflecting the array.

The experimental data have contributed to the development and evaluation of calculational techniques,[4] most effectively to the Monte Carlo codes where the understanding and handling of neutronics in hydrogenous reflectors have been advanced.[5-6]

## MATERIALS AND ASSEMBLY DEVICE

Uranium-metal cylinders, enriched to 93.2 wt% in $^{235}U$, were available, which could be combined to provide cylindrical units of several masses. The uranium contained 1.0 wt% $^{234}U$, 0.2 wt% $^{236}U$, and 5.6 wt% $^{238}U$ in addition to the $^{235}U$ isotope.

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[1]L. W. GILLEY and J. T. THOMAS, *Trans. Am. Nucl. Soc.*, **4**, 54 (1961).

[2]J. T. THOMAS, *Trans. Am. Nucl. Soc.*, **6**, 169 (1963).

[3]J. T. THOMAS, "A Method for Estimating Critical Conditions of Large Arrays of Uranium," *Proc. Nuclear Criticality Safety*, SC-DC-67-1305, p. 189, Sandia Corporation (1966); also, J. T. THOMAS, "Critical Three-Dimensional Arrays of Neutron-Interacting Units. Part II—U(93.2) Metal," ORNL-TM-868, Oak Ridge National Laboratory (1964).

[4]G. E. WHITESIDES and N. F. CROSS, *Trans. Am. Nucl. Soc.*, **10**, 239 (1967).

[5]G. E. WHITESIDES and J. T. THOMAS, *Trans. Am. Nucl. Soc.*, **12**, 889 (1969).

[6]G. E. WHITESIDES and N. F. CROSS, "KENO—A Multigroup Monte Carlo Criticality Program," CTC-5, Oak Ridge Computing Technology Center (1969).

The uranium density was 18.76 g/cm$^3$. The cylindrical pieces available are described in Table I. The cylinders were arranged into units varying in mass from 10.4 to 26.2 kg and in height-to-diameter ratio from 0.47 to 1.90. The units in a particular array were made as similar as possible by careful selection of the individual cylinders.

The units were supported in an assembly, with their axes vertical, on stainless-steel rods passing through two 0.508-cm-diam holes in each cylinder parallel to the axis and located 8.547 cm apart on a diameter. Vertical separation of the cylinders was established by spacers of appropriate length cut from Inconel tubing closely fitting the support rods. The rods were mounted in sections of aluminum Unistrut attached to the two parts of the "split table" critical experiment equipment described by Rohrer et al.[7] The horizontal position of the rods was adjustable. A photograph of an unreflected assembly of forty-five 10.4-kg U(93.2) cylinders, shown in Fig. 1, illustrates the means of effecting the spacing and method of adjustment.

[7] E. R. ROHRER et al., "New Critical Experiment Machines," *Neutron Phys. Div. Ann. Prog. Report for Period Ending Sept. 1, 1961*, ORNL-3193, p. 168, Oak Ridge National Laboratory (1961).

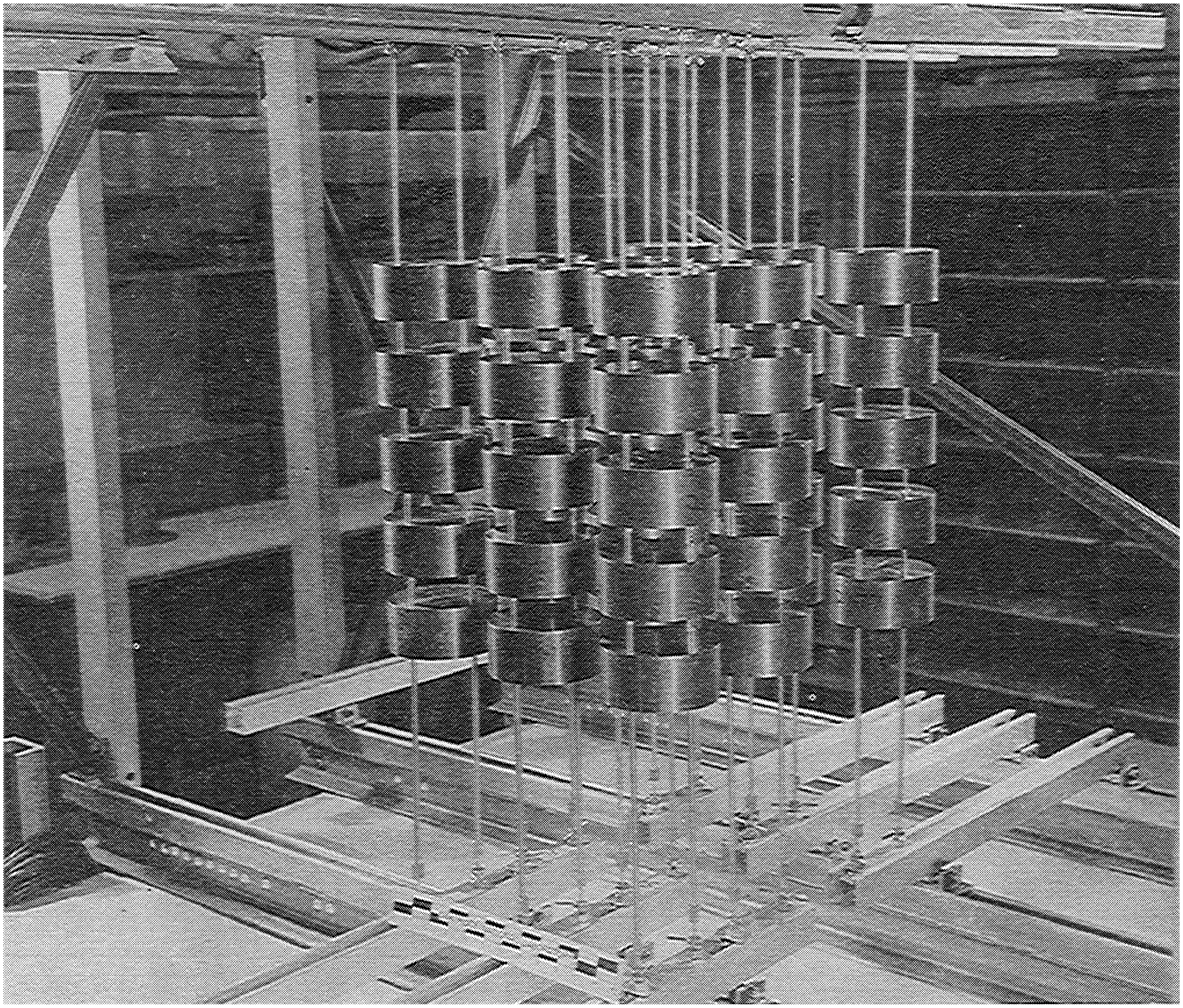

Fig. 1. An unreflected assembly of 10.4-kg U(93.2)-metal cylinders containing 45 units at equal surface separation in the three principal axes of the array. Reactivity control is effected by the horizontal movement of one third of the assembly, the plane of units in the background.

TABLE I

Description of U(93.2)-Metal Cylinders Available for the Experiments

| Number of Cylinders | Average Mass kg U | Average Dimensions of Cylinders (cm) | |
|---|---|---|---|
| | | Radius | Height |
| 54 | 10.439 ± 0.059 | 5.737 ± 0.016 | 5.382 ± 0.003 |
| 27 | 5.236 ± 0.017 | 5.746 ± 0.009 | 2.691 ± 0.003 |
| 54 | 5.247 ± 0.035 | 4.539 ± 0.015 | 4.321 ± 0.003 |

All arrays were constructed with the centers of the units at the corners of rectangular parallelepipeds, thus associating with each unit a cuboidal volume. In a few cases this pattern was cubic.

The reflector material was paraffin ($C_{25}H_{52}$) and could be varied in thickness from 1.3 to 15.2 cm. The density of the paraffin in the 1.3-cm-thick reflector was 0.88 g/cm$^3$; in all other reflectors, it was 0.93 g/cm$^3$. Various thicknesses of Plexiglas, a methacrylate plastic having a density of 1.18 g/cm$^3$ and containing 60.5 wt% C, 8.3 wt% H, and 31.2 wt% O, was the moderator material in one series of experiments.

## EXPERIMENTAL RESULTS

Critical assemblies of the various U(93.2)-metal units are reported in Table II, where each experiment is indexed by a pair of numbers $(i,j)$, $i$ denoting the average unit and $j$ the reflector condition. Reference to an experiment in the table will be made by the notation Expr. $(i,j)$. Although the measured parameters in each experiment were the number of units and their surface separation at criticality, the center separation of the units is reported to facilitate the computation of the cuboidal cell volume. The tabulated description of a unit in an assembly includes a correction of ~0.2% reduction in the radius to compensate for the support rod holes. The location of the reflector in all reflected assemblies was at the outer boundary of the peripheral cuboidal cells. The data contain much of relevance concerning the influence of the unit mass and shape and of the array shape and reflector thickness on the critical spacing and number of units. For example, arrays of units with different masses but of the same shape are displayed by units $i$ = 6, 7, 10, 11, and 12; the effect of unit shape change is recorded by units $i$ = 1, 2, 6, and 7.

Essentially all of the arrays were constructed with the surface spacing of the units equal in three directions. Some operational convenience derived from the selection of this pattern, and more importantly, it was possible to construct more critical arrays in a greater variety of shapes than would have been possible had only cubic arrays, i.e., equal center spacing of units, been built. Four arrays were constructed, however, with units at equal center spacing. These results are presented in Table III. The data may be compared to those of corresponding arrays in Table II for equal surface separation. If the average uranium density of an array at criticality is taken as the mass of the unit divided by the volume of the cell occupied by the unit, it is evident that the maximum achievable density is greater in the cubic pattern than in the cuboidal pattern whenever the height-to-diameter ratio $(h/d)$ of a unit is $\geq 1$. The opposite is true when the $h/d < 1$.

Six unreflected assemblies having an unequal number of units along the three axes of an array were also constructed. The average mass of the units in these experiments was 20.89 kg U(93.2). The data are reported in Table IV. These arrays are compared in Fig. 2 to arrays of units of similar mass having an equal number of units along the three axes, from Table II, Exprs. (11,1) and (12,1). The number of units in an array is shown as a function of the average uranium density in the array. The rearrangement of units from equal to unequal numbers in the three directions of an array maintaining the uranium density reduces the array reactivity.

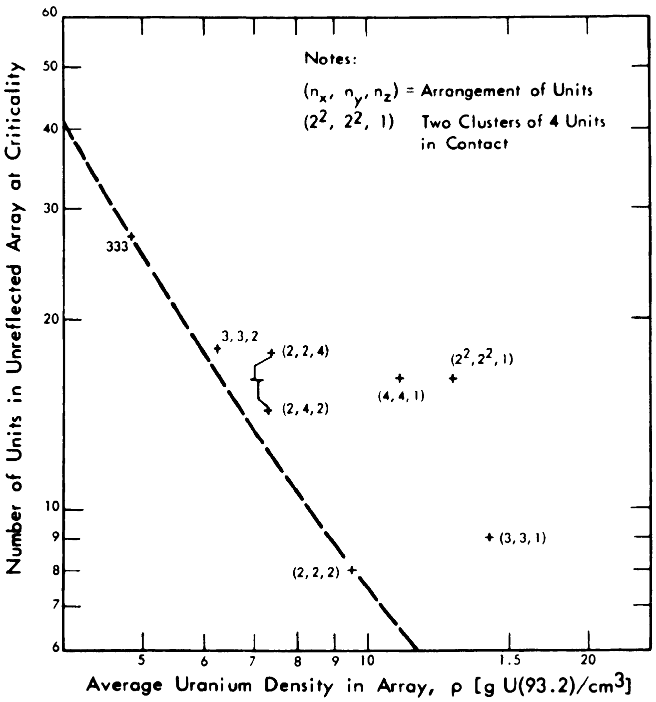


Fig. 2. Influence of array shape on the number of 20.9 kg U(93.2) and on the averaged uranium density in unreflected assemblies.

TABLE II

Experimentally Determined Spacing for U(93.2)-Metal Cylinders Assembled to Criticality in Cuboidal Arrangements for Various Reflector Conditions

| | | | | Reflector Index, $j$ | 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Paraffin Reflector Thickness[a] (cm) | 0.0 | | 1.3[a] | | 3.8 | | 7.6 | | 15.2 | |
| Expr. $(i,j)$ | | Unit Description | | | Center Spacing | | Center Spacing | | Center Spacing | | Center Spacing | | Center Spacing | |
| Cylinder Index, $i$ | Array $n_x,n_y,n_z$ | Radius (cm) | Height (cm) | Mass kg U(93.2) | Horizontal (cm) | Vertical (cm) | Horizontal (cm) | Vertical (cm) | Horizontal (cm) | Vertical (cm) | Horizontal (cm) | Vertical (cm) | Horizontal (cm) | Vertical (cm) |
| 1 | 2 2 2 | 5.748 | 5.382 | 10.482 ± 0.005 | 11.50[b] | 5.38[b] | 11.73 | 5.61 | 13.48 | 7.36 | 14.91 | 8.80 | 15.19 | 9.08 |
| 2 | 2 2 4 | 5.748 | 5.382 | 10.481 ± 0.018 | 12.85 | 6.73 | -- | -- | -- | -- | -- | -- | -- | -- |
| 3 | 3 3 5 | 5.742 | 5.382 | 10.457 ± 0.044 | 14.93 | 8.82 | -- | -- | -- | -- | -- | -- | -- | -- |
| 4 | 4 4 4 | 5.740 | 5.382 | 10.451 ± 0.048 | 15.43 | 9.33 | -- | -- | -- | -- | -- | -- | 23.84 | 17.74 |
| 5 | 3 3 3 | 5.748 | 5.382 | 10.481 ± 0.026 | 13.50 | 7.39 | 14.49 | 8.37 | 17.37 | 11.25 | 19.75 | 13.64 | 20.19 | 14.07 |
| 6 | 2 2 2 | 4.542 | 8.641 | 10.507 ± 0.001 | 9.08[b] | 8.64[b] | 9.69 | 9.24 | 11.45 | 11.00 | 13.05 | 12.61 | 13.39 | 12.95 |
| 7 | 3 3 3 | 4.540 | 8.641 | 10.495 ± 0.025 | 11.52 | 11.08 | 12.51 | 12.07 | 15.66 | 15.22 | 18.10 | 17.66 | 18.51 | 18.08 |
| 8 | 2 2 2 | 5.742 | 8.077 | 15.694 ± 0.003 | 12.39 | 8.98 | 13.39 | 9.98 | 16.45 | 13.04 | 18.88 | 15.47 | 19.31 | 15.90 |
| 9 | 3 3 3 | 5.741 | 8.077 | 15.690 ± 0.020 | 15.69 | 12.28 | 17.16 | 13.75 | 21.67 | 18.27 | 25.18 | 21.77 | 25.68 | 22.27 |
| 10 | 2 2 2 | 5.726 | 10.765 | 20.803 ± 0.004 | 13.67 | 12.98 | -- | -- | -- | -- | -- | -- | -- | -- |
| 11 | 2 2 2 | 5.748 | 10.765 | 20.962 ± 0.004 | 13.74 | 13.01 | 15.17 | 14.44 | 19.70 | 18.97 | 23.01 | 22.27 | 23.48 | 22.75 |
| 12 | 3 3 3 | 5.736 | 10.765 | 20.877 ± 0.026 | 17.84 | 17.13 | 20.05 | 19.34 | 26.24 | 25.53 | 30.19 | 29.49 | 30.62 | 29.91 |
| 13 | 2 2 2 | 5.749 | 13.459 | 26.218 ± 0.005 | 15.04 | 17.00 | 16.92 | 18.88 | 23.03 | 24.99 | 27.20 | 29.16 | 27.88 | 29.84 |
| 14 | 3 3 3 | 5.738 | 13.459 | 26.113 ± 0.022 | 19.97 | 21.95 | 22.80 | 24.78 | 31.08 | 33.07 | 35.97 | 37.96 | 36.47 | 38.45 |
| 15 | 2 2 2 | 4.542 | 17.282 | 21.008 ± 0.001 | 10.55 | 18.75 | -- | -- | -- | -- | -- | -- | 19.41 | 27.61 |

NOTE: 1. Spacings have an error of ±0.01 cm in experiments with no reflector and ±0.03 for all others.
2. The isotopic content of U(93.2) metal is 1.0 wt% $^{234}U$, 93.2 wt% $^{235}U$, 0.2 wt% $^{236}U$, and 5.6 wt% $^{238}U$, and the density is 18.76 g/cm$^3$.
3. Spacing corresponds to equal surface separation of unit in the direction of the three principal axes.
4. The reflector was located at boundaries of peripheral cells of an array.

[a]Paraffin density = 0.88 g/cm$^3$; all other paraffin reflectors have a density of 0.93 g/cm$^3$.
[b]Assembly is subcritical.

TABLE III

Unreflected Critical Arrays of U(93.2)-Metal Cylinders at Equal Center Spacing and with Equal Number of Units Along the Direction of the Three Array Axes

| Array | | | Expr. | Unit Description | | | Unit Center Spacing |
|---|---|---|---|---|---|---|---|
| $n_x$ | $n_y$ | $n_z$ | $(i,1)$ | Radius (cm) | Height (cm) | Mass kg U(93.2) | (cm) |
| 3 | 3 | 3 | (5,1) | 5.748 | 5.382 | 10.481 ± 0.026 | 11.51[a] |
| 2 | 2 | 2 | (8,1) | 5.742 | 8.077 | 15.694 ± 0.003 | 11.48[a] |
| 2 | 2 | 2 | (11,1) | 5.748 | 10.765 | 20.962 ± 0.004 | 13.50 |
| 3 | 3 | 3 | (12,1) | 5.736 | 10.765 | 20.877 ± 0.026 | 17.60 |
| 2 | 2 | 2 | (13,1) | 5.749 | 13.459 | 26.218 ± 0.005 | 15.78 |

NOTE: 1. Spacings have an error of ±0.01 cm.
2. The isotopic content of U(93.2) metal is 1.0 wt% $^{234}U$, 93.2 wt% $^{235}U$, 0.2 wt% $^{236}U$, and 5.6 wt% $^{238}U$, and the density is 18.76 g/cm$^3$.
3. Expr. $(i,1)$ refers to corresponding units and reflector condition described in Table II.

[a]Array subcritical, $k_{eff} \sim 0.98$.

TABLE IV

Unreflected Critical Arrays of U(93.2)-Metal Cylinders with Unequal Numbers of Units Along the Direction of the Three Array Axes

Unit Description: radius = 5.738 cm; height = 10.765 cm mass = 20.890-kg U(93.2) metal

| Array | | | Unit Center Spacing | |
|---|---|---|---|---|
| $n_x$ | $n_y$ | $n_z$ | Horizontal (cm) | Vertical (cm) |
| (2,2) | (2,2) | 1 | 24.01[a] | -- |
| 4 | 4 | 1 | 12.99 | -- |
| 3 | 3 | 1 | 12.13 | -- |
| 2 | 2 | 4 | 15.38 | 14.67 |
| 2 | 4 | 2 | 15.37 | 14.66 |
| 3 | 3 | 2 | 16.12 | 15.41 |

NOTE: 1. Spacings have an error of ±0.01 cm.
2. The isotopic content of U(93.2) is 1.0 wt% $^{234}U$, 93.2 wt% $^{235}U$, 0.2 wt% $^{236}U$, and 5.6 wt% $^{238}U$, and the density is 18.76 g/cm$^3$.

[a]Two clusters of four cylinders each with lateral surfaces in contact. The center separation between two clusters of four units is given.

Table V records critical reflected and unreflected eight-unit assemblies of units comprised of coaxial cylinders of different diameters. Three of the arrays required a larger average uranium density than did corresponding arrays of similar masses reported in Table II. The remaining array of reflected 20.89-kg U(93.2) units resulted in a slight reduction in the average uranium density.

The effect of a 15.3-cm-thick reflector on three sides of an array, simulating the location of fissile units above a floor adjacent to two intersecting walls, was investigated in two assemblies of units having mass ~20.9 kg U(93.2) and an $h/d$ ratio of 0.94. The results are given in Table VI and are plotted in Fig. 3 for comparison with arrays completely enclosed by paraffin, Exprs. $(11,j)$ and $(12,j)$ of Table II. An additional array of eight units of unit index 11 from Table II is reported in Fig. 3 for a 2.5-cm-thick reflector completely enclosing the array. The measured surface separation of units in this array was 5.710 cm. Reflection on three sides of an array by 15.2 cm of paraffin would not appear to be as effective as complete reflection by a 2.5-cm-thick reflector.

## *Substitutions in Arrays*

The effect on array reactivity of replacing a unit in a critical array by one of different mass or dimensions was examined in two 27-unit assemblies. In one experiment, the central unit in assembly Expr. (12,1) was replaced by a unit from the assembly Expr. (13,1). The substitution of a 26.2-kg U(93.2) unit for one of 20.9 kg U(93.2) maintaining the center spacing resulted in a reactivity increase in excess of 1.5 dollars. Criticality of this perturbed array was achieved by increasing

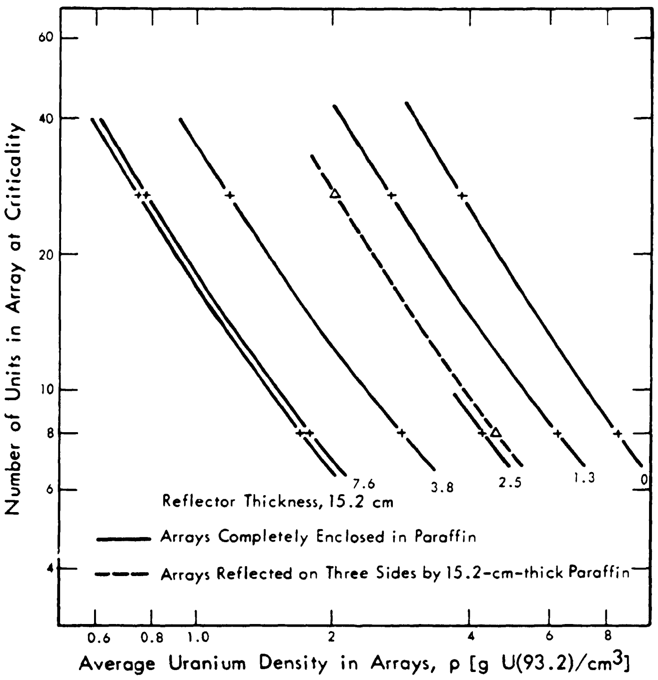


Fig. 3. Influence of uniform reflector thickness and partial, three-corner reflection on the average uranium density required for criticality of 20.9-kg U(93.2)-metal units.

TABLE V

Critical Arrays of Eight Irregular Units of U(93.2) Metal in Unreflected and Paraffin-Reflected Geometries

| Description of Coaxial Cylindrical Components of Unit | | | Average Unit Total Mass kg U(93.2) | Paraffin Reflector Thickness (cm) | Unit Center Spacing | |
|---|---|---|---|---|---|---|
| Radius (cm) | Height (cm) | Mass kg U(93.2) | | | Horizontal (cm) | Vertical (cm) |
| 5.743 | 2.691 | 5.233 ± 0.009 | | 0.0 | 11.71 | 9.93 |
| 4.538 | 4.321 | 5.245 ± 0.004 | 15.696 ± 0.002 | 15.2 | 18.38 | 16.61 |
| 5.734 | 2.691 | 5.217 ± 0.007 | | | | |
| 4.544 | 4.321 | 5.258 ± 0.027 | | 0.0 | 12.45 | 15.04 |
| 5.720 | 5.385 | 10.384 ± 0.011 | 20.893 ± 0.012 | 15.2 | 22.39 | 24.97 |
| 4.545 | 4.321 | 5.259 ± 0.010 | | | | |

NOTE: 1. Spacings have error of ±0.01 cm for unreflected assemblies and ±0.03 for reflected assemblies.
2. Cuboidal cells defined by center spacing of units result in equal surface separation of units along the three principal axes of the array.
3. The reflector is located at the boundaries of peripheral cells of the array.
4. The isotopic content of U(93.2) metal is 1.0 wt% $^{234}U$, 93.2 wt% $^{235}U$, 0.2 wt% $^{236}U$, and 5.6 wt% $^{238}U$, and the density is 18.76 g/cm$^3$.

TABLE VI

Conditions for Criticality of Arrays Reflected on Three Sides by 15.2-cm-Thick Paraffin

| Array | | | Unit Description | | | Paraffin Reflector | Unit Center Spacing | |
|---|---|---|---|---|---|---|---|---|
| $n_x$ | $n_y$ | $n_z$ | Radius $r$ (cm) | Height $h$ (cm) | Mass kg U(93.2) | | Horizontal (cm) | Vertical (cm) |
| 2 | 2 | 2 | 5.748 | 10.765 | 20.962 | a | 16.89 | 16.16 |
| 3 | 3 | 3 | 5.736 | 10.765 | 20.877 | b | 22.01 | 21.31 |

NOTE: 1. Spacings have an error of ±0.03 cm.
2. The isotopic content of U(93.2) metal is 1.0 wt% $^{234}U$, 93.2 wt% $^{235}U$, 0.2 wt% $^{236}U$, and 5.6 wt% $^{238}U$, and the density is 18.76 g/cm$^3$.

[a] The dimensions of the base reflector were 76.2 × 76.2 × 15.2 cm, and the dimensions of the two sides were 76.2 × 45.7 × 15.2 cm.

[b] The dimensions of the base reflector were 106.7 × 106.7 × 15.2 cm, and the dimensions of the two sides were 106.7 × 76.2 × 15.2 cm.

the separation of one vertical plane of the units by 1.98 cm. In the second experiment, the central unit of assembly Expr. (9,1) was replaced by a unit having a 4.558-cm radius, a 12.962-cm height, and a mass of 15.807 kg U(93.2). This replacement resulted in a measured loss in reactivity of 0.05 dollars.

Additional experiments utilizing parts of unreflected critical eight-unit arrays were performed to illustrate the effect of multiple component replacement. In this series, one-half of each of two different critical arrays were brought together along a common array centerline until their cell boundaries coincided. Each of the three assemblies composed of composite arrays was subcritical. In one experiment, one-half of Expr. (11,1) and one-half of Expr. (13,1) were utilized. The remaining two experiments used units of fissile material as aqueous solution. Each unit had 2.066 kg of U(92.6) as aqueous uranyl nitrate solution at 415 g U/liter at a specific gravity of 1.55, corresponding to an atomic ratio of H:$^{235}U$ of 59. The isotopic content of the uranium was 0.01 wt% $^{234}U$, 0.005 wt% $^{236}U$, and 5.9 wt% $^{238}U$. The nitrogen content resulted in an atomic ratio of N:U of 2.006. The solution was contained in 0.64-cm-thick Plexiglas cylinders having an outside radius and height of 10.16 and 19.05 cm, respectively. Criticality of a (2,2,2) unreflected array occurred at a horizontal center spacing of

21.75 ± 0.01 cm and a vertical center spacing of 20.48 ± 0.01 cm. The volume of solution per unit was 5 liter ±0.3 $cm^3$, determined by weight. One half of this array was assembled with one half of Expr. (15,1). In the third experiment, half of the solution array was assembled with one half of Expr. (11,1). Criticality of the latter assembly was achieved by reducing the center spacing of the metal units by 0.56 cm.

The data of these composite arrays indirectly substantiate results by Thomas and Scriven,[8] which imply, for criticality, that assemblies of different fissile materials in air must be separated by less than the geometric mean of the separations for the individual assemblies.

### *Interspersed Materials*

The effect of hydrogenous material, placed between adjacent units, on the criticality of arrays was examined in assemblies of ~20.9-kg U(93.2) units. Plexiglas boxes of several sizes and wall thicknesses were mounted on the supporting rods and enclosed the uranium units. Some of the arrays were enclosed in a paraffin reflector. In another array, the units were mounted in steel cylinders, actually short sections of pipe, and, in still another, both unit and pipe were located within a Plexiglas box. A unit was always centered in its container. Figure 4 is a photograph of an eight-unit assembly illustrating the mode of assembly with the steel and Plexiglas containers. The critical dimensions of these assemblies and their descriptions are reported in Table VII.

An investigation was made of the effect on the array reactivity of the thickness of hydrogenous material between adjacent units. An array of eight units of cylinder index $i$ = 11 of Table II was subcritical when the center separation of the units was 26.26 cm horizontally and 25.53 cm vertically. Each unit was contained in a box having 1.27-cm-thick Plexiglas walls, described in Table VII. The array was surrounded by a 15.2-cm-thick paraffin reflector. The thickness of only those container walls which separated units was increased. The maximum resulting reactivity addition to the array was observed to occur when the total thickness of Plexiglas was ~4.9 cm. The results of the experiments are summarized in Fig. 5, where the reactivity of the array is given as a function of the total Plexiglas thickness separating the units. The assembly having a total Plexiglas thickness of 7.6 cm between units was subcritical by an amount in excess of one dollar.

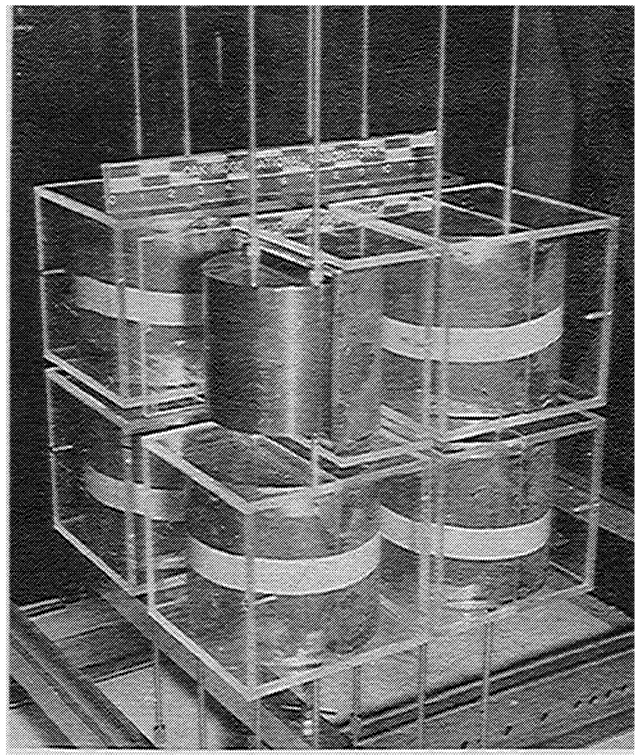

Fig. 4. Combined moderator of iron and Plexiglas in an array of eight 20.9-kg U(93.2)-metal units.

### *Uranium Cylinder*

An experiment established the subcriticality of an unreflected U(93.2) cylinder having an average diameter of 11.48 cm and a length of 140 cm. The total mass was 271.8 kg U(93.2). Negligible change in the apparent neutron source multiplication was observed upon addition of the final ~42 kg U(93.2). This experiment confirms the subcriticality of an unreflected cylinder of this diameter when extended indefinitely in length.

## CALCULATIONS

The neutron multiplication factors of a number of the experimental arrays were computed by the KENO Monte Carlo code utilizing Hansen-Roach[9] 16-group neutron cross-section sets. The uranium was characterized by its two principal constituents since the influence of the remaining isotopes on $k_{eff}$ are negligible. The cross-section set U(235)-1R and the set U(238)-5R were selected

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[8] A. F. THOMAS and R. A. SCRIVEN, "Neutron Interaction in Fissile Assemblies," *Technology, Engineering and Safety*, Progress in Nuclear Engineering, Series IV, Vol. 3, Pergamon Press, New York (1960).

[9] GORDON E. HANSEN and WILLIAM H. ROACH, "Six and Sixteen Group Cross Sections for Fast and Intermediate Critical Assemblies," LAMS-2543, Los Alamos Scientific Laboratory (1961).

TABLE VII

Conditions for Criticality of Plexiglas-Moderated Arrays of ~20.9-kg U(93.2)-Metal Units

| Moderator Description | | | | Paraffin Reflector Thickness (cm) | Unit Center Spacing | |
|---|---|---|---|---|---|---|
| | Outside Dimensions (cm) | | | | Horizontal (cm) | Vertical (cm) |
| Material | Base | Height | Thickness | | | |
| Array: $n_x, n_y, n_z$ = 2,2,2<br>Unit Description: radius = 5.748 cm; height = 10.765 cm; mass = 20.962 ± 0.004 kg U(93.2) | | | | | | |
| Plexiglas box | 12.9 × 12.9 | 12.1 | 0.64 | 0.0 | 15.58 | 14.85 |
| | | | | 15.2 | 24.16 | 23.43 |
| Plexiglas box | 15.6 × 15.6 | 14.8 | 0.64 | 0.0 | 15.74 | 15.00 |
| | | | | 1.3 | 17.37 | 16.64 |
| | | | | 7.6 | 24.07 | 23.34 |
| | | | | 15.2 | 24.43 | 23.69 |
| Plexiglas box | 17.9 × 17.9 | 17.2 | 1.27 | 0.0 | 18.12 | 17.38 |
| | | | | 1.3 | 20.11 | 19.38 |
| | | | | 15.2 | 26.00 | 25.27 |
| Plexiglas box | 21.4 × 21.4 | 20.7 | 2.38 | 0.0 | 21.74 | 10.24 |
| | | | | 15.2 | 27.94 | 27.21 |
| Steel cylinder | $r$ = 7.05 | 13.2 | 0.66 | 0.0 | 14.74 | 14.00 |
| Steel cylinder in Plexiglas box | $r$ = 7.05<br>15.6 × 15.6 | 13.2<br>14.8 | 0.66<br>0.64 | 0.0 | 16.67 | 15.93 |
| Array: $n_x, n_y, n_z$ = 3,3,3<br>Unit Description: radius = 5.736 cm; height = 10.765 cm; mass = 20.877 ± 0.026 kg U(93.2) | | | | | | |
| Plexiglas | 21.4 × 21.4 | 20.7 | 2.38 | 0.0 | 27.79 | 27.05 |

NOTE:
1. Spacings have an error of ±0.01 cm for unreflected assemblies and ±0.03 for reflected assemblies.
2. Units are centered in cuboidal cells defined by center spacing and result in equal surface separation of units along the three principal axes of the array.
3. The reflector is located at the boundaries of peripheral cells of the array.
4. The isotopic content of U(93.2) metal is 1.0 wt% $^{234}$U, 93.2 wt% $^{235}$U, 0.2 wt% $^{236}$U, and 5.6 wt% $^{238}$U, and the density is 18.76 g/cm$^3$.
5. Units are centered in moderating materials fabricated as cuboidal boxes.
6. Steel is nominal 5-in. Schedule-40 iron pipe with end plates. Units are centered in pipe. In addition to iron, the significant constituents in wt% are 0.8 Mn, 0.2 Si, 0.1 Mo, and 0.2 Ni, as determined by emission spectroscopy.

and the fission-spectrum-weighted neutron cross sections were used for hydrogen in the reflector. The calculated $k_{eff}$'s are displayed in Table VIII and correspond to the arrays given in Table II with the exception of those having a 7.6-cm-thick paraffin reflector. The entries of Table VIII were determined by the usual neutron-batch method. Presented at the bottom of each column is the average $k_{eff}$ with the deviation of the mean for the entries under a specified reflector thickness. Comparison of those averages as the reflector thickness is increased shows a monotonically increasing $k_{eff}$. Since the experimental data of Table II are as measured, i.e., uncorrected for the effects of the assembly device on the array reactivity, the computed $k_{eff}$ increases with the increasing shielding of the units from the assembly device.

Calculations of the two unreflected assemblies of 27 units in which the central unit was replaced were performed with $10^5$ neutron histories to compare the $k_{eff}$'s obtained. In one, the unperturbed array of 20.9-kg U(93.2) units, Expr. (12,1), resulted in a $k_{eff}$ of 0.9903 ± 0.0024. When the central unit was replaced by a 26.2-kg U(93.2) unit, $k_{eff}$ was 1.0034 ± 0.0027. The reactivity

TABLE VIII

Monte Carlo Computed $k_{eff}$ for Some of the Experimental Arrays of U(93.2)-Metal Units Described in Table II

| Expr. $(i,j)$ Unit Index $(i)$ | Reflector Index, $j$ | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 5 |
| 1 | 0.942 | 1.009 | 1.004 | 0.997 |
| 2 | 0.996 | -- | -- | -- |
| 3 | 0.979 | -- | -- | -- |
| 4 | 0.991 | -- | -- | 0.993 |
| 5 | 0.978 | 0.988 | 1.000 | 0.997 |
| 6 | 0.996 | 0.978 | 0.998 | 0.996 |
| 7 | 0.995 | 0.985 | 0.997 | 0.997 |
| 8 | 1.004 | 0.999 | 0.993 | 0.996 |
| 9 | 0.996 | 0.984 | 0.989 | 1.004 |
| 10 | 0.993 | -- | -- | -- |
| 11 | 0.992 | 0.989 | 0.985 | 0.988 |
| 12 | 0.985 | 0.986 | 0.992 | 1.007 |
| 13 | 0.990 | 0.987 | 0.998 | 0.991 |
| 14 | 0.985 | 0.991 | 0.990 | 0.995 |
| 15 | 0.976 | -- | -- | 0.996 |
| Average $k_{eff} \pm \sigma$ | 0.990 ± 0.008 | 0.990 ± 0.004 | 0.995 ± 0.002 | 0.996 ± 0.002 |

NOTE: 1. The assemblies Expr. $(i,j)$ are described in Table II.
2. The standard deviation for each entry does not exceed ±0.006.

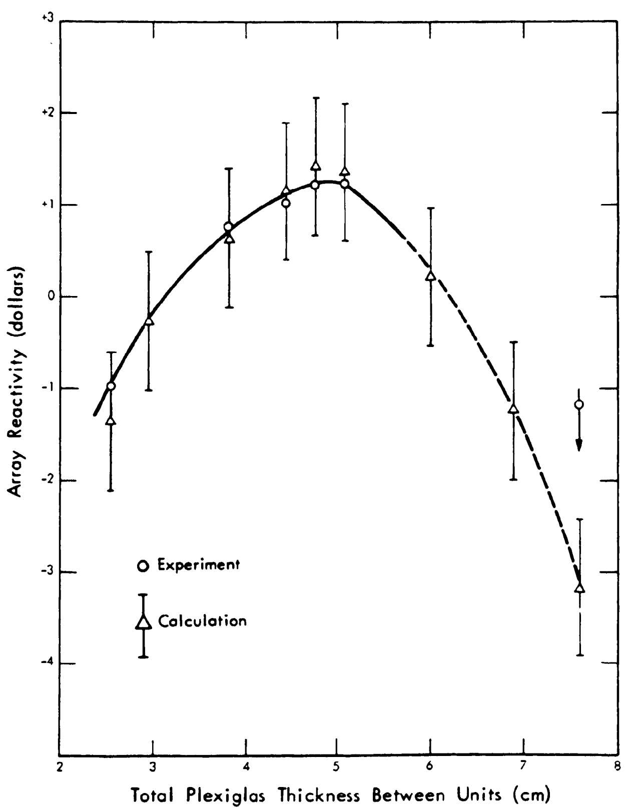


Fig. 5. Reactivity effects of Plexiglas placed between 20.9-kg U(93.2) cylinders in an eight-unit array reflected by 15.2-cm-thick paraffin.

corresponding to this change in $k_{eff}$ is 2.00 ± 0.38 dollars, assuming $\beta_{eff}$ (Ref. 10) is 0.0066. The reactivity for the substitution was observed experimentally to be >1.50 dollars. In the second assembly, Expr. (9,1) of nominal 15.7-kg U(93.2) units, the change in the central unit of the array was one of geometry, from an $h/d$ ratio of 0.7 to 2.8, with only a slight increase in mass, ~0.1 kg U(93.2). As was expected, no essential difference in the calculation of the unperturbed and perturbed arrays was evidenced.

Examples of calculations performed on the reflected and moderated arrays are displayed in Fig. 5 for the reflected eight-unit arrays of nominal 20.9-kg U(93.2) units in which the Plexiglas thickness between the units is varied. The cross-section set for hydrogen averaged over the fission spectrum was used for the Plexiglas region in the calculations reported. Other calculations of these arrays utilized the $dE/E$-averaged cross-section set[9] for the moderator; however, these failed to yield a correspondence between reactivity and Plexiglas thickness.

## CONCLUSIONS

The series of experiments described herein was initiated and conducted to fulfill the need for a

[10] G. R. KEEPIN, *Physics of Nuclear Kinetics*, Addison-Wesley Publishing Co., Inc., Reading, Massachusetts (1965).

better understanding of how criticality may be influenced in arrays of neutron-coupled subcritical components as necessary support to nuclear criticality safety evaluations in the handling of fissile materials. Cylinders of metal with different $h/d$ ratios, ranging in mass from 10.4 to 26.2 kg U(93.2), were examined experimentally under a variety of conditions and perturbations. These were, principally, number of units, degree of reflection and moderation by hydrogenous materials, spacing of units, and the shape of the assemblies. The data have provided a comprehensive test of Monte Carlo calculations and beneficial guidance for evaluation of the magnitude of factors affecting array criticality.

For the purposes of this work, the KENO Monte Carlo code with the Hansen-Roach neutron cross-section sets reproduces the results of the experiments with a precision determined by the number of neutron histories. The accuracy, however, depends on both the cross-section data and statistical vagaries and is ~1% in $k_{eff}$. Reliable extensions of criticality data and evaluations of conditions encountered in practical situations are possible. In the area of nuclear criticality safety, the KENO code and the Hansen-Roach 16-group neutron cross-section sets constitute a valid method for examining critical conditions for U(93.2) metal.

ACKNOWLEDGMENTS

The generous cooperation of the Oak Ridge Critical Experiments Facility staff is gratefully acknowledged.

The cheerful and able assistance of Cleois Cross during the conduct of the experiments, E. R. Rohrer for the operational instrumentation, and W. C. Tunnell for the assembly design and the procurement of special materials were an essential support to the program. The efforts of G. E. Whitesides and Nancy F. Cross in performing the computations were invaluable.