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THE EFFECT OF UNIT SHAPE ON THE CRITICALITY OF ARRAYS

J. T. Thomas
Oak Ridge National Laboratory

CRITICALITY DATA CENTER

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THE EFFECT OF UNIT SHAPE ON THE CRITICALITY OF ARRAYS

J. T. Thomas

ABSTRACT

The known criticality of U(93) metal as subcritical cylindrical components in unreflected arrays is used to explore component geometry effects in such arrays. Three basic geometries are chosen; the cube, the sphere, and the cylinder with equal height and diameter. It is shown that the multiplication factor of a unit defines sizes of the three shapes useful in establishing critical arrays equivalent to a given reference array. The number of components and the average uranium density of the equivalent arrays are the same as the reference array. The effects of changes in average uranium density and component mass on the array multiplication factor are investigated.

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INTRODUCTION

There exists a limited body of experimental data¹ which is utilized to establish the nuclear criticality safety of fissile material. A small portion of the data, in particular, arrays of subcritical components of uranium enriched to 93 wt % in ^{235}U as metal or aqueous solution, has recently been analytically extended^{2,3} to the lower average uranium densities directly useful to safety evaluations. The experimental work was accomplished with subcritical components of cylindrical geometry in arrays and the data extension was based upon a simple model and Monte Carlo calculations. It was deemed satisfactory to define the multiplication factor of such assemblages to within ± 0.03 at a 95% confidence interval.

The present work makes use of the same techniques to establish criticality in unreflected arrays of uranium metal of subcritical components having either spherical or cubic shape but equivalent in behavior to the experimental cylindrical shape. The arrays are cuboidal in shape with equal numbers of components along the three directions of the array.

In establishing the criticality of a given number of identical subcritical components one is primarily controlling the leakage of neutrons from the array by adjusting the spacing of the components. The fraction of neutrons leaking from one of the subcritical components is directly related to its multiplication factor, k_{eff} . A portion of the leakage neutrons from one unit is intercepted by other units in the array and the remainder escape the system through the free space. The total fraction of neutrons escaping from the array is distinct from, but related to, the fraction leaking from an individual unit. Array leakage appears to be dependent upon the geometry of the unit and the average uranium density in the array. The destiny of neutrons produced in the array is expressed as simply as possible by those remaining in the material or lost from it by leakage. The rates of the fractions of neutrons being captured, fissioning, and leaking from the array satisfy a constant inter-relationship for systems having a multiplication factor of unity.

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1. H. C. Paxton et al., "Critical Dimensions of Systems Containing U^{235} , Pu^{239} , and U^{233} ," TID-7028 (1964).
  2. J. T. Thomas, "Criticality of Large Systems of Subcritical U(93) Components," ORNL-CDC-1 (1967).
  3. J. T. Thomas, "A Method for Estimating Critical Conditions of Large Arrays of Uranium," SC-DC-67-1305, 189 (1967).

UNITS OF SIMPLE GEOMETRY

The multiplication factor, k_{eff} , and the neutron leakage fraction, $f(\alpha)$, for a given unit, α , of specific geometry can be related to the surface-to-volume ratio of the unit. The ratio of surface area to volume of cubes, of spheres, and of cylinders of equal height and diameter is

$$S/V = 6/d \quad (1)$$

where d is the edge of the cube or the diameter of the sphere or cylinder. The values of k_{eff} and $f(\alpha)$ for each of the units were determined by Monte Carlo calculations utilizing a Hansen-Roach⁴ cross section set in the KENO Code.⁵ The results have a standard deviation of less than 1% and are presented in Table 1 and also in Fig. 1. The following relations between these quantities were established and the constants determined by a least squares fit,

$$k_{eff} = \left(\frac{1}{C} \frac{S}{V} \right)^{-0.924} \quad (2)$$

and

$$f(\alpha) = 1 - 0.4315 k_{eff} \quad (3)$$

where C is a constant for each of the three geometries and is 0.406, 0.345, and 0.386 for the cube, sphere, and cylinder, respectively. The values of k_{eff} and $f(\alpha)$ as determined by these equations have a standard deviation of ± 0.02 and ± 0.01 , respectively. Equations (2) and (3) are represented by the lines in Fig. 1. It is evident that $f(\alpha)$ is independent of the unit geometry for a given k_{eff} . It is also a simple matter to determine the relative values of d for the three geometries having the same k_{eff} and, hence, the same $f(\alpha)$.

The coefficient of k_{eff} in Eq. (2) is the reciprocal of η , if one considers a one-group representation, and is in slight disagreement with

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4. G. E. Hansen and W. H. Roach, "Six and Sixteen Group Cross Sections for Fast and Intermediate Critical Assemblies," LAMS-2543, Los Alamos Scientific Laboratory (1961).
  5. G. E. Whitesides and Nancy Cross, Oak Ridge Computing Technology Center, Private Communication (1967).

Table 1. The Surface-to-Volume Ratio, Multiplication Factor,
and Neutron Leakage Fraction for Various Unreflected
U(93) Metal Units of Simple Geometry.

d, cm	S/v, cm ⁻¹	Cube		Sphere		Cylinder	
		k _{eff}	f(α)	k _{eff}	f(α)	k _{eff}	f(α)
6.00	1.000	0.434	0.815	0.366	0.845	0.405	0.827
8.00	0.750	0.576	0.753	0.486	0.793	0.542	0.768
10.00	0.600	0.708	0.695	0.601	0.743	0.673	0.711
12.00	0.500	0.837	0.638	0.717	0.691	0.791	0.659
12.36	0.485	0.850	0.632	0.736	0.683	0.811	0.650
14.00	0.429	0.959	0.585	0.826	0.643	0.906	0.608
14.50	0.414	0.979	0.575	0.852	0.632	0.928	0.597
15.28	0.393	1.029	0.554	0.889	0.616	0.974	0.578
16.00	0.375	--	--	0.924	0.600	1.010	0.561

Fig. 1. The Surface-to-Volume Ratio and the Neutron Leakage Fraction, $f(a)$, of Single U(93) Metal Units as a Function of the Monte-Carlo-Computed Neutron Multiplication Factor.

the value reported by Keepin⁶ for fission induced by typical fast-reactor spectrum neutrons ($\eta = 2.10$), but comparable to the value given for fission induced by ^{235}U fission-spectrum neutrons ($\eta = 2.36$).

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

CRITICALITY OF ARRAYS

Correlation of experimental data of cuboidal arrays of metal cylinders^{1,7} with the neutron leakage fraction parameter of the array has been satisfactory. The model is based on the two postulates

1. The fraction of neutrons that leak from different critical arrays of the same unit is a constant, and
2. The nonleakage fraction is suitably represented by the expression $(1 + NB_N^2)^{-1}$.

The geometric buckling appearing in $(1 + NB_N^2)^{-1}$ is given by

$$B_N^2 = \sum_{i=1}^3 \frac{\pi^2}{[n_i(d_i + \delta) + 2\lambda]^2} \quad (4)$$

where

$$\begin{aligned} N &= \prod n_i \\ n_i &= \text{number of units along the } i\text{th direction of the array} \\ d_i &= \text{unit dimensions} \\ \delta &= \text{surface separation of units, equal in the three directions} \\ \lambda &= \text{a suitable extrapolation distance.} \end{aligned}$$

The two postulates imply directly that for a specified subcritical component

$$NB_N^2 = \text{constant} \quad (5)$$

for any number, N .

Typical units utilized in the experiments are described in Table 2 along with the values of NB_N^2 and λ as determined for the critical arrays by Eq. (5). The k_{eff} of each unit is given in this table and also appears in Fig. 1 where it may be seen that the values do not differ significantly from those for cylinders having a height-to-diameter ratio of unity.

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7. J. T. Thomas, "Critical Three-Dimensional Arrays of Neutron-Interacting Units, Part II. U(93.2) Metal," ORNL-TM-868 (1964).

Table 2. Unreflected Experimental Critical Arrays of U(93) Metal

Unit Designation, α	Unit Description Average Mass (kg U)	Diam (cm)	Height (cm)	h/d	λ cm [From Eq.(5)]	NE_N^2 [From Eq.(5)]	k_{eff}
A ²	10.484	11.509	5.382	0.47	1.86	0.670	0.566
A ⁴	10.489	9.116	8.641	0.95	1.58	0.573	0.602
B ³	15.683	11.490	8.077	0.70	1.63	0.376	0.685
C ³	20.877	11.484	10.765	0.94	1.92	0.249	0.759
D ²	26.113	11.486	13.459	1.17	2.56	0.179	0.800

The array nonleakage fraction can be related to the k_{eff} of these units by the expression

$$P_{NL} = \frac{1}{1 + NB_N^2} = 1.06 k_{eff} \quad (6)$$

The application of Eq. (5) to determine the critical spacings for arrays of the units in Table 2 has been verified by Monte Carlo calculations for values of N greater than 8×10^3 . Equation (6) then allows the application of Eq. (5) to other than the experimental cylinders by means of Eq. (2) or Fig. 1.

Equivalent Arrays

The number of identical units required for criticality in an array for the units of Table 2 has been established^{2,3} by means of Eq. (5) and verified by Monte Carlo calculations to have a k_{eff} of 1.00 ± 0.03 at a 95% confidence level. Since the fraction of neutrons leaking from a unit having a given k_{eff} is independent of the unit shape, the size of units of other shapes necessary to maintain criticality in an array of the same number of units and same array density can be determined. Beginning with known critical arrays of any experimental unit given in Table 2, Eq. (2) furnishes the size of the cube, sphere, or cylinder having the same k_{eff} and $f(\alpha)$. The average uranium density of the known critical (reference) array establishes the cell size for the unit shape of interest.

As an example, the average uranium density, $\bar{\rho}$, in a 216-unit array of C^3 units, each having a k_{eff} of 0.759, is 1.180 g/cm³ as determined from Eq. (5). From Eq. (3), the sphere having the same k_{eff} and $f(\alpha)$ as the C^3 unit has a diameter of 12.89 cm and a mass of 21.0 kg U. The corresponding cell volume required in the array of spheres to maintain a $\bar{\rho}$ of 1.180 g/cm³ is 17.83 liters and has an edge dimension of 26.13 cm. This 216-unit array of spheres, when computed by the KENO Monte Carlo Code, produced a k_{eff} of 1.006 ± 0.004 which may be compared to a value of 0.994 ± 0.015 determined for the 216-unit reference array of C^3 metal cylinders as computed by the GEM Monte Carlo Code.⁸

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8. P. J. Hemmings, "The GEM Code," Safeguards Division, UKAEA, AHSB(S) RL05 (1967).

The procedure described above was carried out for each of the units of Table 2. Each unit was converted to the three simple geometries and the corresponding arbitrarily chosen N-unit array computed by the Monte Carlo Code. The results are presented in Table 3. Within a 95% confidence interval and the range of height-to-diameter ratios of the experimental units, the results of the simple conversion appear to be satisfactory. There seems to be little difference between the cylinder with $h/d = 1$ and the sphere; however, the cube consistently results in a larger k_{eff} for the array. This is understandable from geometric considerations since an array of cubes results in proportionately less free space in the lattice than do cylinders or spheres. This leads one naturally into a consideration of the relationship between the k_{eff} of the unit and the average uranium density, and their influence on leakage rate from the array. It is plausible to assume the array k_{eff} is directly proportional to the unit k_{eff} , thus

$$\left. \frac{\Delta k}{k} \right|_{\text{array}} = \left. \frac{\Delta k}{k} \right|_{\text{unit}} \quad (7)$$

Define an array leakage probability parameter $K(\alpha)$ as

$$K(\alpha) = 1 - P_{NL}(\alpha), \quad (8)$$

then from Eqs. (3) and (6), we obtain

$$K(\alpha) = 2.458 f(\alpha) - 1.458 \quad (9)$$

The density analogue approximation to Eq. (5) for $27 \leq N \leq 8000$, is

$$N(\alpha) = A \left[\frac{K(\alpha)}{\bar{\rho}} \right]^s \quad (10)$$

hence

$$\frac{\Delta \bar{\rho}}{\bar{\rho}} = \frac{\Delta K(\alpha)}{K(\alpha)} \quad (11)$$

Table 3. Computed Multiplication Factors of Arrays of Uranium Metal Units having Simple Geometry

Unit Shape	Height	Unit	Unit	k_{eff}	
	Diameter	Dimension d(cm)	Mass (kg U)	Unit	Array*
Reference Array: 1000 A ² Units, $\bar{\rho} = 1.112 \text{ g/cm}^3$					
Cylinder; A ²	0.47	11.509	10.5	0.566	0.992 ± 0.015
Cylinder	1.00	8.389	8.7	0.566	0.976 ± 0.004
Sphere	--	9.380	8.1	0.566	0.975 ± 0.004
Cube	--	7.980	9.5	0.566	0.993 ± 0.004
Reference Array: 512 A ⁴ Units, $\bar{\rho} = 1.325 \text{ g/cm}^3$					
Cylinder; A ⁴	0.95	9.116	10.5	0.602	1.007 ± 0.015
Cylinder	1.00	9.087	11.1	0.602	0.984 ± 0.004
Sphere	--	10.161	10.3	0.602	0.964 ± 0.004
Cube	--	8.644	12.1	0.602	0.997 ± 0.004
Reference Array: 216 B ² Units, $\bar{\rho} = 1.618 \text{ g/cm}^3$					
Cylinder; B ²	0.70	11.490	15.7	0.685	1.008 ± 0.015
Cylinder	1.00	10.314	16.2	0.685	0.995 ± 0.004
Sphere	--	11.533	15.1	0.685	0.987 ± 0.004
Cube	--	9.811	17.7	0.685	1.016 ± 0.004
Reference Array: 216 C ³ Units, $\bar{\rho} = 1.180 \text{ g/cm}^3$					
Cylinder; C ³	0.94	11.484	20.9	0.759	0.994 ± 0.015
Cylinder	1.00	11.528	22.6	0.759	1.006 ± 0.004
Sphere	--	12.891	21.0	0.759	1.006 ± 0.004
Cube	--	10.967	24.7	0.759	1.031 ± 0.004
Reference Array: 64 D ² Units, $\bar{\rho} = 1.778 \text{ g/cm}^3$					
Cylinder; D ²	1.17	11.486	26.1	0.800	1.002 ± 0.015
Cylinder	1.00	12.203	26.8	0.800	1.008 ± 0.004
Sphere	--	13.646	25.0	0.800	0.996 ± 0.004
Cube	--	11.609	29.4	0.800	1.017 ± 0.004

*Standard deviation is given. Reference arrays were computed by the GEM Code⁸ and the equivalent arrays by the KENO Code.⁵

Equations (3), (7), (9), and (11) provide the necessary information to compensate for slight changes in k_{eff} of the unit or the array, the average uranium density, $\bar{\rho}$, or the array leakage fraction parameter $K(\alpha)$. One can maintain the unit size and change the average density, and hence $K(\alpha)$, or one can maintain the average density but change the unit size to produce changes in $K(\alpha)$ and hence the array k_{eff} .

For example the 216-unit array of cubes equivalent to the $\alpha = B^2$ units had k_{eff} of 1.016 at $\bar{\rho} = 1.618$ g U/cm³. The assumption stated in Eq. (7) requires the k_{eff} of each unit in the array to be reduced by 1.6%, then by Eqs. (9) and (11) the corresponding decrease in the average density, $\bar{\rho}$, is 0.087 g U/cm³. Therefore, the array of cubes, each of mass 17.7 kg U, must be respaced so as to produce an average uranium density of $1.618 - 0.087 = 1.531$ g U/cm³. On the other hand, one can keep the array density at 1.618 g U/cm³ but reduce the mass of the individual cubes by the use of Eq. (2) and, thus, produce a new lattice volume. This procedure was carried out for the arrays of metal cubes equivalent in each case to the experimental cylinders for $\alpha = B^2$, C^3 , and D^2 . The results are presented in Table 4 where the computed k_{eff} is also given and compared to the value determined for the reference array described in Table 3.

It is of interest at this point to explore briefly two items often encountered. Given a critical array of cylindrical units, what is the effect on the array k_{eff} due to changing the shape of the unit? This change results in a constant cell volume and average uranium density for the arrays. Consider the array of 216 cylindrical units, each having a mass of 22.6 kg U with equal height and diameter, having an array k_{eff} of 1.006 ± 0.004 . The unit in this array has a k_{eff} of 0.759 and occupies a cell volume of 19.1 liters in the array producing a $\bar{\rho} = 1.180$ g/cm³. A 22.6 kg U unit as a sphere or as a cube will have a k_{eff} of 0.776 or 0.738, respectively. The k_{eff} for the array of spheres was determined to be 1.017 ± 0.004 and that for the array of cubes as 1.014 ± 0.004 by Monte Carlo calculations. The effect is not large and the result may be considered general over the range of masses reviewed and simple geometries treated. Table 5 compares arrays of cubes with arrays of cylinders for five of the arrays given in Table 2.

Table 4. Comparison of Monte Carlo Calculated Array k_{eff} for Compensations in Array k-excess by Either Unit Mass or Average Uranium Density Changes for Units of Cube Geometry

Represented Unit (α)	Change ^a	Unit Mass (kg U)	Array Δk	Unit Δk Eq. (7)	Array Leakage $\Delta k(\alpha)$ Eq. (9)	Density Change $\Delta \rho$ (Eq.) 11	$\bar{\rho}$ (g/cm ³)	k	k ^b Reference Array
B ³	$\bar{\rho}$	17.7	0.016	0.011	0.012	0.087	1.531	1.005 $\pm$ 0.004	1.008
B ³	M	16.8	0.016	0.011	--	--	1.618	1.009 $\pm$ 0.003	1.008
C ³	$\bar{\rho}$	24.7	0.031	0.024	0.010	0.148	1.033	0.997 $\pm$ 0.004	0.994
C ³	M	22.3	0.031	0.024	--	--	1.180	0.995 $\pm$ 0.003	0.994
D ³	$\bar{\rho}$	29.4	0.018	0.014	0.015	0.175	1.603	0.994 $\pm$ 0.005	1.002
D ³	M	27.7	0.018	0.014	--	--	1.778	1.000 $\pm$ 0.004	1.002

a. Change is either in average array density, $\bar{\rho}$, or the unit mass, M, with $\bar{\rho}$ constant.

b. From Table 3, standard deviation is $\pm$ 0.015.

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Table 5. Comparison of Calculated Array k_{eff} and of Unit Shape for Simple Geometries of Constant Unit Mass and Cell Volume

Unit Mass (kg U)	Cylinder		Cube		Cell Volume (l)	Number of Units (N)	Array k_{eff} *	
	$\bar{d}$ (cm)	k_{eff}	$\bar{d}$ (cm)	k_{eff}			Cubes	Cylinders
8.7	8.389	0.566	7.740	0.550	7.822	1000	0.971	0.976
11.1	9.087	0.602	8.384	0.592	8.344	512	0.976	0.984
16.2	10.313	0.685	9.516	0.666	9.990	216	0.995	0.995
22.6	11.529	0.759	10.637	0.738	19.132	216	1.014	1.006
26.8	12.203	0.800	11.259	0.778	15.060	64	1.001	1.008

*Standard deviation $\pm$ 0.004.

Given two critical arrays having the same number of units and the same average uranium density but having different cell volumes associated with their units, the second item concerns the question of how much must the units in the array having the smaller cell volume be increased in size if they were to replace the units in the array with the larger cell volume. Again, consider two equivalent arrays of Table 2. The 216-unit arrays with $\bar{\rho} = 1.180 \text{ g/cm}^3$, one of cylinders having a mass of 22.6 kg U, a cell volume of 19.1 l, and a k_{eff} of 1.006 ± 0.004 ; the second of spheres having a mass of 21.0 kg U, a cell volume 17.8 l, and a k_{eff} of 1.006 ± 0.004 . If the spheres were to be placed in the larger cell volume, this should cause a decrease in the density of 0.081 g/cm^3 . Using Eqs. (11), (9), and (3), the corresponding change in the unit k_{eff} required to compensate for the density change is 0.0126. Equations (1) and (2) then furnish the new sphere size having a mass of 22.1 kg U. The 216-unit array of spheres with this mass in a cell volume of 19.1 l had a k_{eff} of 1.005 ± 0.004 when computed by the Monte Carlo Code. The required increase in mass is, thus, 1.6 kg U.

Remarks

Although the treatment in this work has been of uranium metal with 93 wt % ^{235}U , there is no apparent reason why the technique could not be applied to other chemical forms and enrichments. It has been demonstrated that for nuclear safety requirements the criticality estimates of arrays in any one of the three simple unit shapes, i.e., cubes, spheres, or right cylinders, is adequate. Further, within the accepted error limits, a given mass per unit in any of the three basic shapes may be considered to define the same array. The application of the proper reflection factors will produce reflected array densities for criticality which may be utilized for unit shapes in the range $0.4 < h/d < 1.2 \text{ cm}^{-1}$.

The method is particularly suited to the problem of a given volume in an array such as when specification containers are to be evaluated and mass limits established.

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