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Comparative Method for the Evaluation of Array Reflector Materials

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COMPARATIVE METHOD FOR THE EVALUATION OF ARRAY REFLECTOR MATERIALS

J. T. Thomas

ABSTRACT

A general method for the evaluation of materials as reflectors surrounding array of subcritical units of fissile materials is presented. Applied to the materials used in a Safe and Secure Trailer, it is concluded that the carrier effectiveness as a reflector can be expected to be less than that of a 2.5-cm-thick water reflector.

INTRODUCTION

The problem of evaluating the effect of reflector materials and configurations on the neutron multiplication factor of an array of fissile materials is done most easily by comparison to known conditions of criticality. A well-documented body of information on array criticality is the Monte Carlo calculated data base for the American National Standard ANSI N16.5-1975 Guide for Nuclear Criticality Safety in the Storage of Fissile Materials. These data have been shown to have an analytical representation that results in a model which allows interpretation of perturbations to critical configurations and evaluation of major changes in terms of Δk_{eff} or reactivity changes to an array.

A series of experiments performed at the ORNL Critical Experiments Facility from 1962 to 1964 studied, among other parameters, the effect of varying the paraffin reflector thickness surrounding arrays of U(93.2)

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metal cylinders. Expression of these experimental results in terms of the model establishes a method for direct association of the Safe and Secure Trailer (SST) as a reflector with a specific thickness of paraffin or water.

CRITICALITY REPRESENTATION

Any fissile material for which water reflected critical cubic arrays of air-spaced units have been calculated by a validated method are representable in the model. The mass of the units, the number in the array, and their center-to-center spacing define a projected surface density, σ ,

$$\sigma = \frac{nm}{d^2} = \frac{\sigma(m)}{(1 - c/\sqrt{N})^2} \quad (1)$$

where $\sigma(m)$, (g/cm^2) , is a constant for each m , the mass of the unit, $N = n^3 > 27$, the number of units in the array; d the cubic cell dimension; and $c = 0.55 \pm 0.18$ a constant. When the values of $\sigma(m)$ for $k_{eff} = 1$ are plotted as a function of m , the data may also be represented linearly with a slope c_2 as

$$\sigma(m) = c_2(m_0 - m) \quad (2)$$

where m_0 is the unreflected critical mass for the unit geometry. Figure 1 is a representation of water reflected cubic arrays of U(93.2) and of ^{239}Pu as metal spheres. This behavior is typical of spherical units. Illustrated in the figure by the dashed line is the equivalence between the masses of plutonium and uranium necessary to result in criticality in the same array. The value of $\sigma(m)/m$ is determined either by the mass of the units in the array and the characteristic constant c_2

Fig. 1. Criticality representation of water-reflected cubic arrays of U(93.2) and plutonium metal as spherical units. Mass equivalence between fissile materials is displayed by line with slope of $\sigma(m)/m$.

for the material or by the cell dimension and number of units in the array, that is, either by the fissile material properties or by the array geometry. This is evident from the second relation given in the legend of the figure.

If the mass of each unit in the array is increased by the same amount, the array becomes supercritical and the reactivity addition is equal to the reactivity increase of the unit. Conversely, a decrease in the unit reactivity results in an array reactivity loss of the same magnitude. For critical systems with a median energy of fission greater than 0.1 eV, a good approximation of the resultant k_{eff} due to a uniform change in mass of the units is

$$k \simeq (m'/m)^{1/3} = r'/r . \quad (3)$$

Equations (1) and (2) can be combined and generalized to apply to arrays of arbitrary arrangements of units. An applicable expression of this result is

$$\frac{\sigma(m)}{m} = \frac{n}{4d^2} (1 - c/\sqrt{N})(5R^{-0.672} - 1) , \quad (4)$$

where R is a shape factor for an $n_x \times n_y \times n_z = N$ arrangement and is given by

$$R = \frac{N^{1/3}}{3} \left(\frac{1}{n_x} + \frac{1}{n_y} + \frac{1}{n_z} \right) . \quad (5)$$

CRITICAL EXPERIMENTS DATA

Uranium metal cylinders containing 93.2 wt % ^{235}U , varying in mass from 10 to 26 kg and having height-to-diameter ratio in the range from

0.4 to 1.2, were utilized in a series of experiments to establish critical conditions for uniform cuboidal arrays having a paraffin reflector of several thicknesses. These data are summarized in Table 1. While these data are predominately for 27 and fewer unit arrays, they do provide information of the relative effect of varying the reflector thickness. Applying Eq. (4) to the data for $N = 27$ results in the relationship displayed in Fig. 2. Also given in the figure are unreflected and water reflected arrays of U(93.2) spheres which appear to bracket the range of experimental data rather nicely.

Adopting characteristic slopes for the various thicknesses of paraffin as a reflector about arrays of spherical units permits the evaluation of the SST as a reflector material in terms of an equivalent water reflector thickness. In particular, applying Eq. (4) to data of constant mass and number of units but with varying reflector thickness yields the following expression relating the characteristic slope and the center spacing of the units.

$$\frac{C_2(t_1)}{C_2(t_2)} = \left(\frac{d_2}{d_1}\right)^2, \quad (6)$$

where t_i is the reflector thickness on the arrays. The results of applying this relation to the data of Table 1 are presented in Fig. 3 where the average value for each reflector thickness is given. The line through the points is representative of Monte Carlo calculated water reflected cubic arrays with spherical units ($0 \leq m \leq 35$ kg U) utilizing the averaged ratios. The dispersion of data at reflector thicknesses of zero and 1.3 cm is attributed to the influence of unit shape and changing unit self-multiplication in the arrays.

Table 1. Criticality of U(93.2) Metal in Arrays

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* (cm)					0.0		1.3 ^b		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	7.38	14.91	8.80	15.19	9.08
2	2 2 4	5.748	5.382	10.481 ± 0.018	12.85	8.73	--	--	--	--	--	--	--	--
3	3 3 3	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 ± 0.038	13.50	7.39	14.49	8.37	17.37	11.25	19.75	13.84	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	15.68	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	5.738	10.765	20.877 ± 0.028	17.84	17.13	20.05	19.34	26.24	23.53	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	27.22	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	36.97	37.96	36.47	38.45
15	2 2 2	4.542	17.282	21.008 ± 0.001	10.55	16.75	--	--	--	--	--	--	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% ²³⁵U, 93.2 wt% ²³⁸U, 0.2 wt% ²³⁶U, and 5.6 wt% ²³⁹U, and the density is 18.76 g/cm³.

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.

*Paraffin density = 0.88 g/cm³; all other paraffin reflectors have a density of 0.93 g/cm³.

^bAssembly is subcritical.

Fig. 2. Limiting surface density representation of critical experiments with U(93.2) metal cylinders of various height-to-diameter ratios. The unreflected data for spherical units extrapolates to the critical mass of an unreflected cube.

Fig. 3. The effect of reflector thickness on the ratio of characteristic slopes, c_2 , of Eq. 2.

Figure 4 displays the water reflected cubic arrays of spherical units. Given for each of the three arrays is the total Δk worth of the reflector defined as the change in the unit k_{eff} (hence, change in the array k_{eff}) in going from a thick reflected to an unreflected array. The region beyond about 35 kg U(93.2) where the unreflected array line is no longer linear, the ratios of characteristic slopes, c_2 , were taken as proportional to the total Δk . This is a generic result to array criticality and is represented in Fig. 5 as the fraction of total Δk worth of the reflector associated with the corresponding water reflector thickness. Expressed analytically, under constraint of array $k_{eff}=1$,

$$\Delta k = 1 - \left[\frac{m(t)}{m(15.2)} \right]^{1/3} \quad (7)$$

or

$$\Delta k = 1 - \left[\frac{\sigma(m;t)}{\sigma(m;15.2)} \right]^{1/3},$$

and the figure represents the fraction $\frac{\Delta k(t)}{\Delta k(15.2)}$ as a function of the reflector thickness, t . The information as presented in Fig. 5 may be applied to arrays of arbitrary shape.

EVALUATION OF THE SST AS A REFLECTOR

The SST encloses a volume approximately 2-m square by 11.3-m long and was described in the Monte Carlo code with the dimensions and number densities given in Table 2. The thickness of the reflector and atom number densities were applied initially to cubic arrays and resulted in criticality as represented by the darkened points shown in Fig. 4.

Fig. 4. Application of experimentally determined effect of varying the reflector thickness on water-reflected cubic arrays.

Fig. 5. Generic representation of reactivity controlled by water reflector of thickness t on water-reflected arrays of arbitrary shape.

Table 2. SST Description in Monte Carlo Code Input

Reflector Material	$\pm x$ (cm)	$\pm y$ (cm)	+z	-z
Core Boundary	91.44	563.88	106.68	106.68
Carbon Steel	92.13	564.57	106.68	106.68
Aluminum	92.13	564.57	106.58	107.32
Poly-Steel (1)	120.07	564.57	134.26	107.32
Poly-Steel (2)	120.07	592.51	134.26	135.26
S.S. (304L)	120.12	592.56	134.31	135.31
Void	200.0	200.0	135.0	277.55

- Notes: 1. Vacuum boundary on all but -z face of array.
 2. 41-cm-thick concrete reflector on -z face.

Atom Number Densities

	<u>Poly-Steel (1)</u>	<u>Poly-Steel (2)</u>
^{12}C	1.01201-3	1.01201-3
^1H	2.27702-3	2.27702-3
^{16}O	1.68669-4	1.68669-4
^{14}N	8.43342-5	8.43342-5
Fe	2.40775-4	3-6117-4

Arrays in the SST are not cubic and necessitate the use of Eq. 4 and Fig. 5 to demonstrate that the SST as a reflector is properly characterized independent of unit reactivity and array shape.

Assuming an array with 30.48-cm cubic cells filling the volume of the SST and using Eqs. 4 and 5 to define the spherical mass of the units required for criticality of the resultant $6 \times 37 \times 7$ array when water reflected results in a mass of about 8.0 kg U(93.2).

Additional calculations varying the reflector condition, center spacing, and mass of the units are summarized in Table 3. These data are displayed graphically in Fig. 6. These data confirm the evaluation of the SST materials performed on cubic arrays and support the contention that the relation in Fig. 5 is generic.

It may be concluded that the SST as a reflector is slightly sensitive to the mass of the units but is not as effective as a 2.5-cm-thick water reflector. The presence of packaging materials can be expected to further reduce the effectiveness of the SST as a reflector on arrays.

Table 3. Monte Carlo Calculated Arrays of U(93.2) Metal Spheres for Various Reflector Condition:

Array Reflector and (n_x, n_y, n_z) thickness (cm)	Dimension of Cubic Cell (cm)	Mass of Unit kg U(93.2)	Calculated k_{eff}	$\pm \sigma$	
6 x 37 x 7	Water, 30	30.48	8.02	1.009	0.004
	Concrete, 41		5.25	0.991	0.004
	SST		8.02	0.747	0.004
	SST		16.30	1.006	0.005
	Unreflected		19.61	1.004	0.005
4 x 25 x 4	Water, 30	45.72	20.94	0.999	0.005
	Unreflected		37.182	1.006	0.005
	SST		34.10	1.004	0.004
	SST ^a		29.00	1.000	0.005
3 x 18 x 3	SST	60.96	44.30	0.996	0.005
			42.07	0.991	0.005
	Water, 1.8		45.85	0.999	0.005
	Unreflected		32.50	0.999	0.005
	Water, 30				

^aSubmerged with no inleakage of water.

Fig. 6. Comparison of the reflector effectiveness of the SST carrier to water reflector effect on arrays of similar shape.

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