ANL/RE/SUMM--88739
CONF-9606116--24

CRITICALITY SAFETY OF LOW-DENSITY STORAGE ARRAYS

by

T. H. Bauer

Reactor Engineering Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Submitted to the American Nuclear Society Annual Meeting, June 16-20, Reno, Nevada.

* Work performed under the auspices of the U. S. Department of Energy.

Work Supported by the U. S. Department of Energy Technology Support Programs under Contract W-31-109-Eng-38.

CRITICALITY SAFETY OF LOW-DENSITY STORAGE ARRAYS

by

T. H. Bauer

Reactor Engineering Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

This note proposes a straightforward and simple method for the criticality safety analysis of fissionable materials configured into large arrays of standard containers. While criticality-safe storage limits have been well-established for standard containers- even under flooded conditions, it is also necessary to rule out the potential for criticality arising from neutronic interactions among multiple containers that might build up over long distances in a large array. Traditionally, the array problem has been approached by individual Monte Carlo analyses of explicit arrangements of single units and their surroundings. Here, we show how multiple Monte Carlo analyses can be usefully combined for wide-ranging general application. The technique takes advantage of low average density of fissionable material in typical storage arrays to separate neutron interactions that take place in the neutron's "birth unit" from subsequent interactions in a highly dilute array. Effects of array size, in particular, are conservatively calculated by straightforward analyses which simply smear array contents uniformly across the extent of the array. For given unit loadings in standard containers, practical expressions for neutron multiplication depend only on overall array shape, size and reflective boundary.

A large, low-density array is conservatively envisioned as a single fissionable medium segmented into single units and configured into a large array. Single units are formed by concentrating the maximum amount fissionable material allowed within a single storage container into a compact shape (typically spherical). Average density of units within the array is determined by container volume and spacing. To highlight array interactions, all space between fissionable units is assumed empty, and any intervening neutron-absorbing material is neglected.

With no absorber present, neutrons either escape or are captured in fissionable material. In low-density arrays, a neutron which escapes its birth-unit has a low probability of being directly reflected back by the other units in the array. Given identical units, the probability, E_u of a neutron escaping its birth unit is not only independent of the unit's particular location in the array but also may be calculated as the averaged escape probability from an isolated unreflected unit. Furthermore, the net probability of a neutron escaping storage array may be written as the product, $E_u \times E_a$, where E_a represents the averaged probability of a "loose" neutron's escape from the remainder of the array. The net neutron multiplication factor of the storage array, k_{eff}, is then:

$$k_{eff} = k_{\infty}(1 - E_u \times E_a) \qquad \textit{(Array with identical single units)} \qquad (1)$$

where k_{∞} is the multiplication factor in an infinite medium.

Figure 1 plots E_a versus array size, as calculated for numerous large low-density arrays. Examples conservatively assume compact cubical arrays with a practical range of single unit loadings. A realistic range of physical boundaries is included by assuming reflection on all sides by water, concrete, or vacuum. For definiteness, we assume all fissionable material is a well-moderated ^{239}Pu-water mixture of density, 0.028 grams $^{239}Pu/cm^3$

(H/Pu ratio=947 and k_∞=1.598). For each array, E_a was calculated from Eq. 1. KENO-V [1] Monte Carlo analyses were used to calculate k_{eff} for the array and E_u for unreflected single units.

Dimensional analysis and self-shielding considerations suggest array size effects be measured by a "shielded scaling variable", $\rho L E_u$. Here, ρ is the average density (g/cm^3) of fissionable material in the array, L (cm) is the linear dimension of the array, and E_u serves as an upper limit to the self-shielding factor that reduces the effective value of ρ in compact single units. (In a compact single unit, an upper limit to the probability that an incident neutron will find its way from the surface to an average interior location is just the probability that a neutron born at an average interior location will escape to the outside; i.e. E_u.)

As expected, Fig. 1 shows calculated E_a's closely clustered as functions of $E_u \rho L$. Moreover, calculations for *homogeneous* distributions, denoted E_a^H, represent reasonably-close lower bounds. (For unreflected boundaries, the larger difference between E_a^H and E_a is a result of greater neutron streaming and a smaller self-shielding factor than E_u.) Our fundamental result is that k_{eff} may be conservatively estimated from Eq. 1, calculating E_u as an isolated unreflected unit and substituting the lower bound, $E_a^H(E_u \rho L)$ for E_a. Such estimates of k_{eff} are quite practical and require only the function E_a^H and parameters: E_u, ρ, and L. For the example of ^{239}Pu stored in cubic arrays of 55 gallon drums, we conservatively assume 200g per unit and $\rho = 8 \times 10^{-4}$ g/cm^3, while taking E_u=0.632 and the function E_a^H from Fig. 1. Using Eq. 1, we easily deduce minimum critical masses of 91 kg and 280 kg for arrays with concrete and water reflection.

(H/Pu ratio=947 and k_∞=1.598). For each array, E_a was calculated from Eq. 1. KENO-V [1] Monte Carlo analyses were used to calculate k_{eff} for the array and E_u for unreflected single units.

Dimensional analysis and self-shielding considerations suggest array size effects be measured by a "shielded scaling variable", $\rho L E_u$. Here, ρ is the average density (g/cm^3) of fissionable material in the array, L (cm) is the linear dimension of the array, and E_u serves as an upper limit to the self-shielding factor that reduces the effective value of ρ in compact single units. (In a compact single unit, an upper limit to the probability that an incident neutron will find its way from the surface to an average interior location is just the probability that a neutron born at an average interior location will escape to the outside; i.e. E_u.)

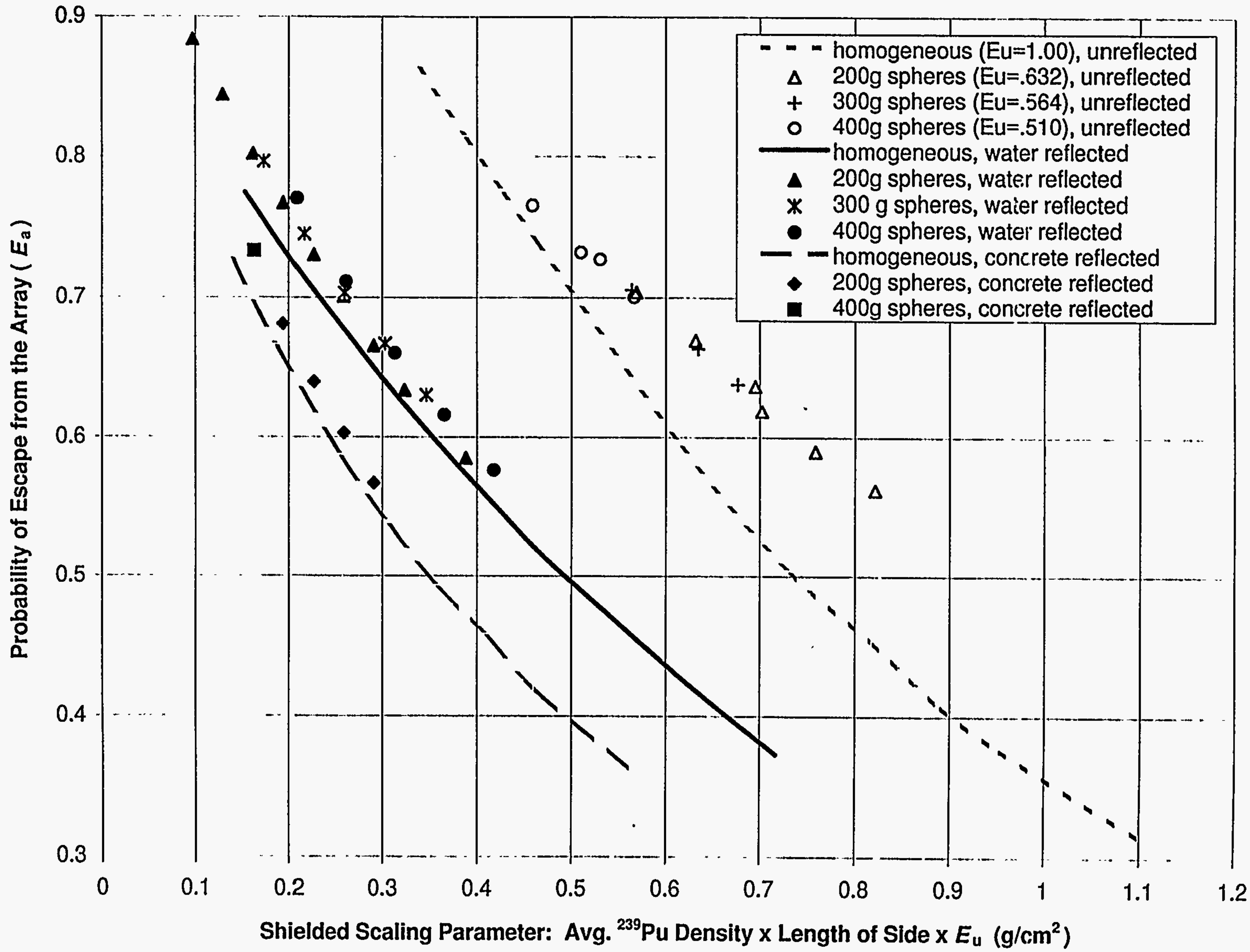
As expected, Fig. 1 shows calculated E_a's closely clustered as functions of $E_u \rho L$. Figure 1 also shows that the E_a's are closely-bounded below by the curves calculated for *homogeneous* distributions, denoted E_a^H. (Note that significant neutron streaming causes increased self-shielding and a somewhat larger gap between E_a^H and E_a in unreflected versus reflected arrays.) The practical conclusion is that k_{eff} may be conservatively estimated from Eq. 1, calculating E_u as an isolated unreflected unit and substituting the lower bound, $E_a^H(E_u \rho L)$ for E_a. Only the function, E_a^H and "generic" parameters: E_u, ρ, and L are needed for an analysis. For the example of ^{239}Pu stored in cubic arrays of 55 gallon drums, we conservatively assume 200g per unit and $\rho = 8 \times 10^{-4}$ g/cm^3, while taking E_u=0.632 and the function E_a^H from Fig. 1. Using Eq. 1, we easily deduce minimum critical masses of 91 kg and 280 kg for arrays with concrete and water reflection.

REFERENCE:

1. L. M. Petrie and N. F. Landers, "KENO V.a An Improved Monte Carlo Criticality Program with Supergrouping," NUREG/CR-0200, Rev. 4 (1992).

FIGURE CAPTION:

1. Calculated Array Escape Probabilities (E_a) for Large Compact Cubic Arrays of Water-Moderated ^{239}Pu and Representative Array Boundaries. Results for Various Single Unit ^{239}Pu Loadings are Shown As Symbols, and Results for Large Homogeneous Distributions (E_a^H) are Shown as Curves.



Probability of Escape from the Array (E_a)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
homogeneous (Eu=1.00), unreflected
200g spheres (Eu=.632), unreflected
300g spheres (Eu=.564), unreflected
400g spheres (Eu=.510), unreflected
homogeneous, water reflected
200g spheres, water reflected
300 g spheres, water reflected
400g spheres, water reflected
homogeneous, concrete reflected
200g spheres, concrete reflected
400g spheres, concrete reflected
Shielded Scaling Parameter: Avg. ^{239}Pu Density x Length of Side x E_u (g/cm^2)