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Application of the Limiting Surface Density Method to Arrays of 9975 Shipping Packages with Plutonium Oxide

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INTRODUCTION

Criticality Safety Engineering at the Savannah River Site is working to reduce the computational burden for analysis to support the K Area Complex (KAC). Plutonium bearing materials are stored at KAC in Type B shipping packages, primarily the 9975. Applying the Limiting Surface Density (LSD) method can reduce the need for complex Monte Carlo calculations. This work addresses developing the LSD method for 9975 shipping packages with plutonium oxide contents.

References 1 and 2 document previous work on the development and verification of the LSD method for arrays of 9975 shipping packages with plutonium metal contents. Both the previous and current work use a simplified and internally pedigreed model of the 9975 shipping package developed in the SCALE 6.1 code system. KENO-VI was employed with the ENDF/B-VI.1 238-group cross section set. The method development addresses the heterogenous, axially-asymmetric design of the 9975 shipping package. The results shown in References 1 and 2 verified that the LSD method reproduces the Monte Carlo method results within about 2% for plutonium metal.

LSD METHOD IMPLEMENTATION

The original LSD method assumes linear correlation between the fissile mass and the surface density given the center-to-center spacing of the packages ($2a_n$) and the total number of packages, N, for the cubic array ($N = n_x \cdot n_y \cdot n_z$). The practical equation of the LSD method from which the limiting fissile mass per container is set comes from equating two correlations of the surface density:

$$\frac{m_c n}{(2a_n)^2}\left(1-\frac{c}{\sqrt{N}}\right)^2 = c_2(m_c - m_o) \quad (1)$$

Here, n is the number of packages in the one direction, m_c is the limiting fissile mass per package that the user seeks and m_o is the fissile mass that would make a single unreflected package critical. The user must determine the values of c, which is called the geometric constant, and c_2, which is called the material constant. The user then sets the spacing and number of packages for the array. The constant c depends on knowledge of the array's buckling behavior. LSD is sometimes also called the NB_N method because:

$$c = \sqrt{\frac{4\lambda_{array}{}^2 N B_N^2}{3\pi^2}} \quad (2)$$

where NB_N is the number of units times the array buckling. To develop the constants appropriate for Pu oxide, KENO-VI calculations were done for cubic arrays with width by depth by height unit dimensions from 4x4x4 to 10x10x10. Seven values of center-to-center spacing (or $2a_n$) were chosen from 46.6 cm (no edge-to-edge spacing) up to 150 cm. This provides 49 distinct array combinations of size and spacing. Arrays with spacing less than 90 cm retained the vertical height of the 9975 as the axial spacing. Figure 1 shows the KENO-VI results for critical unit mass of the cubic arrays of 9975 shipping packages with dry plutonium oxide. The oxide was assumed to be near theoretical density to achieve criticality.

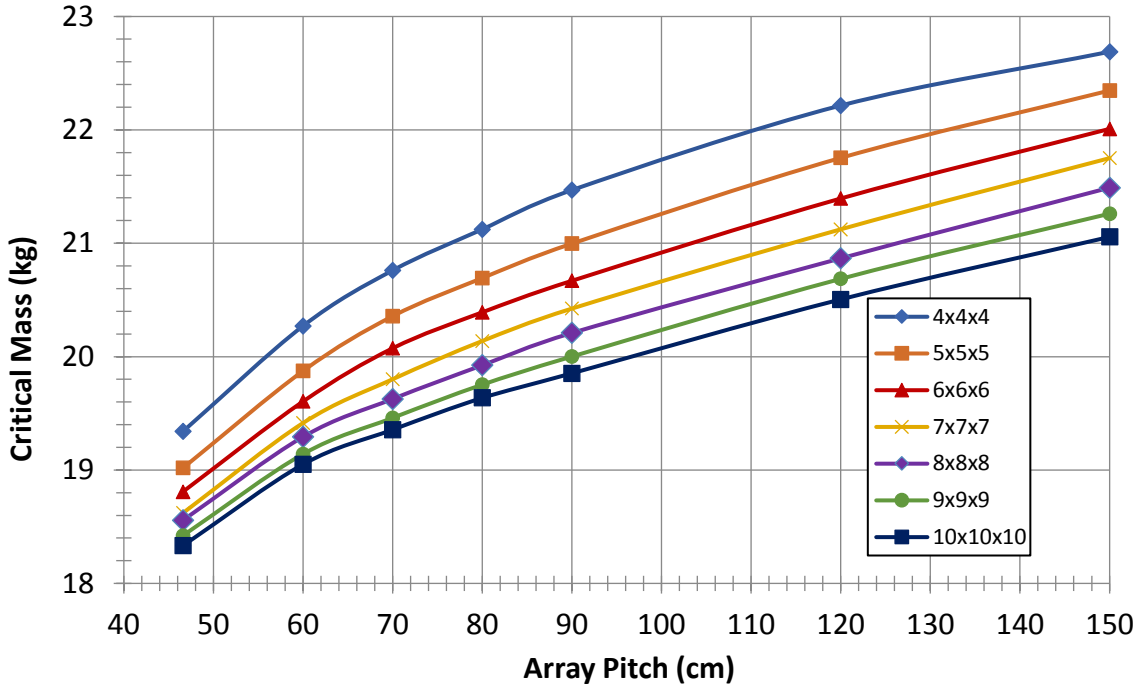

Figure 1. KENO-VI Critical Unit Mass vs. Cubic Array Size and Pitch

The fissile surface density for each of these arrays is the total fissile mass in a column of shipping packages projected on the area of the unit cell. Figure 2 shows this surface density plotted as a function of the cubic array critical unit mass.

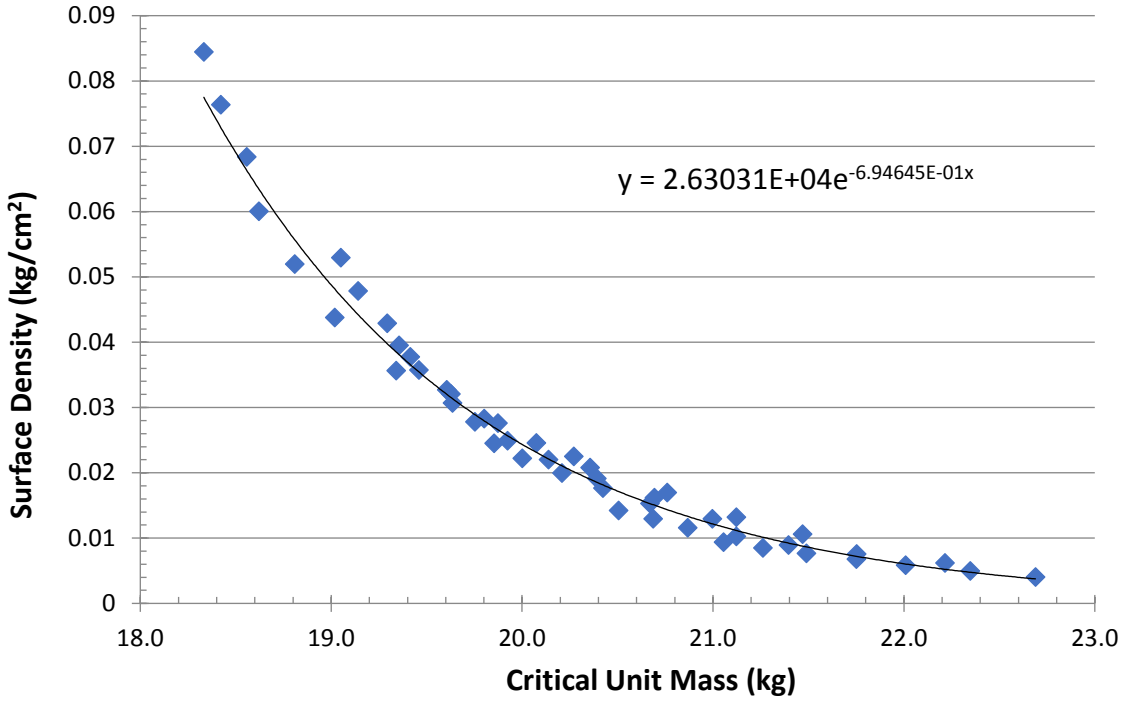

Figure 2. Surface Density vs. Critical Unit Mass for Cubic Arrays

Here, the surface density response is not linear, but is well characterized by the exponential function:

$$\sigma(m_c) = 2.63031x10^4 e^{-0.694645m_c} \quad (3)$$

The precision of 6 significant figures is retained because of the sensitivity of the exponential function to the values. It was chosen to use this form of surface density equated to the geometric (left hand side) of Equation 1 in lieu of the linear correlation. The geometric constant, c, was then estimated using the method described in Reference 2. This gave a value of c = 0.66.

With these new constants for plutonium oxide, LSD was used to estimate critical masses for each of the 49 cubic arrays. The average difference between the KENO-VI and the LSD results is 0.62%, and the maximum difference is 1.7%. It is also important to test the method on arrays with more realistic arrangements. Arrays with width by depth by height unit dimensions of 2x20x1, 2x30x1, 2x20x2, 2x20x3, 4x20x3, and 5x5x3 were chosen to use various shapes and sizes. Figure 3 shows the KENO-VI results for critical unit mass of these arrays.

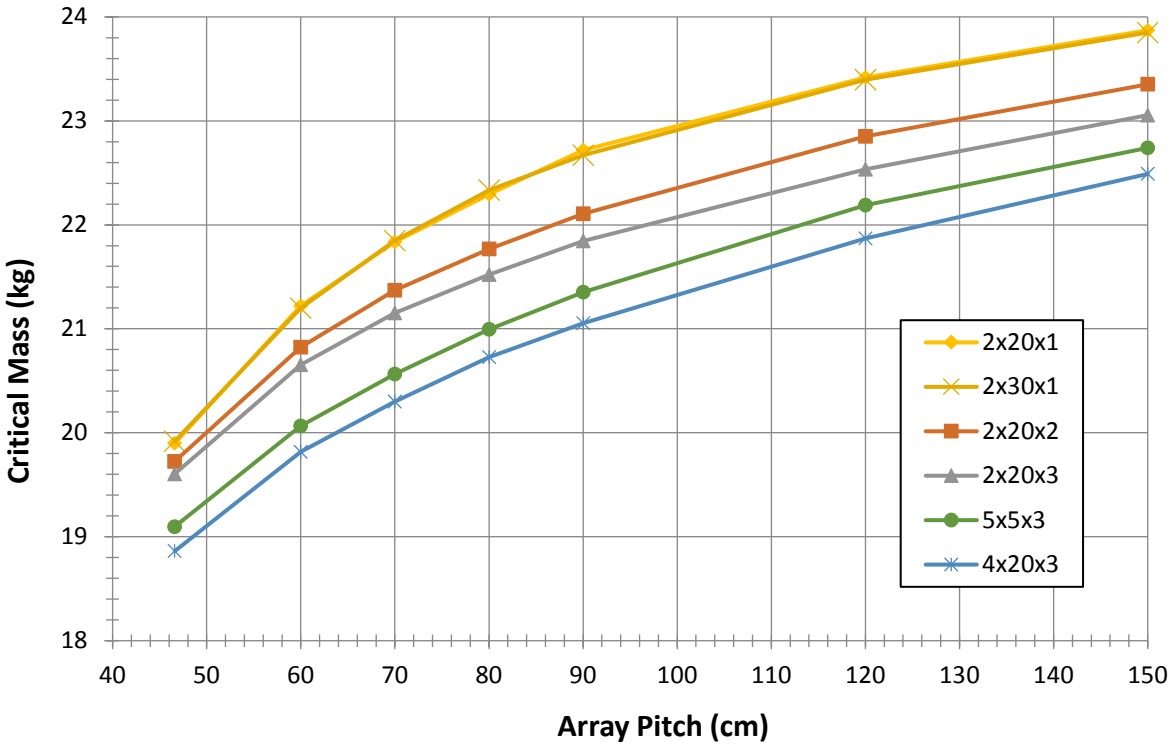

Figure 3. KENO-VI Critical Unit Mass vs. Non-Cubic Array Unit Shape and Pitch

The LSD method was used to estimate the critical unit mass values for these realistic arrays, and those results were compared to the KENO-VI values. The average difference for the realistic arrays is 2.5%, and the maximum difference is 5.2%. These differences are reasonable for an empirical method, yet are somewhat higher than those for arrays with Pu metal, as described in References 1 and 2. A detailed review of the results indicates that the larger size of the oxide units results in more complex interaction effects from changing the array shape and spacing, relative to the same arrays with plutonium metal units. Empirical adjustments to improve these results were derived based on the array pitch, P, and the shape factor, R. The adjusted critical mass, $m_{c,adj}$, is given by:

$$m_{c,adj} = m_c \frac{(1 + R^{2.5})}{100} * \left(1.01 - (14.3P^{-1.58})\right)$$

Where: R = Shape Factor, given by: $R = \frac{\sqrt[3]{N}}{3}\left(\frac{1}{n_x} + \frac{1}{n_y} + \frac{1}{n_z}\right)$

P = Horizontal Pitch (or unit cell dimension) in centimeters

Applying this adjustment, the average difference between the KENO-VI and the LSD critical mass values is reduced to 0.8%, and the maximum difference is 2.2%.

CONCLUSION

Extension of the LSD method to arrays of 9975 shipping packages with plutonium oxide has been verified to reproduce Monte Carlo results with very good agreement for an empirical method. The results are within 5.2% without the shape factor correction, and are within 2.2% using the shape factor correction. This method is recommended for arrays with $R \leq 2$, and pitch values between 46.6 cm and 150 cm.

REFERENCES

1. BAKER J., RATLIFF M., STOVER T., and MITSCHELEN G., "Verification Suite for the Application of the Limiting Surface Density Method to Arrays of 9975 Shipping Packages", *Trans. Am. Nucl. Soc.*, 2017 NCSD Topical Meeting, (2017).
2. STOVER T., BAKER J., RATLIFF M., and MITSCHELEN G., "Limiting Surface Density Method Adapted to Large Arrays of Heterogenous Shipping Packages with Nonlinear Responses", *Nucl. Sci. Eng.*, **190**, *2*, 176 (2018).