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Title: Minimum Critical Masses of Heterogeneous Moderated Plutonium and Uranium Metal Systems and Their Practical Application to Operation Limits

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MINIMUM CRITICAL MASSES OF HETEROGENEOUS MODERATED PLUTONIUM AND URANIUM METAL SYSTEMS AND THEIR PRACTICAL APPLICATION TO OPERATION LIMITS

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ABSTRACT

In criticality safety analysis it is important to recognize the significant differences in reactivity achieved when material transitions from the solid to solution regime. However, the intermediate area of mixed heterogeneous systems (i.e. collections of small pieces) has not been well characterized. To that end, a study has been completed to determine the effect of fissile material piece size/shape on minimum critical mass of a system. The study presented represents a calculation-based investigation of moderated arrays of fissionable material to expand on established plutonium and uranium solution curves of LA-10860 to add the heterogeneous regime between pure a solid and solution of fissionable material. The analysis performed consists of parametric studies utilizing the neutron transport code MCNP6 to calculate the critical mass of systems composed of moderated arrays of varying sizes of spheres, cubes, or elongated rods (height >> diameter). The boundary of the array is increased to find the critical mass for the particular piece geometry and fissile volume density. The different shapes were then compared at points with the same fissile volume density to demonstrate that the key relationship between varying piece shape is the surface area to volume ratio. The results show that as pieces get larger (i.e. more heterogeneous) the minimum critical mass starts to increase. This effect results from the moderation of neutrons becoming less and less effective due to increased self-shielding of larger individual pieces. For plutonium pieces at a surface area to volume ratio of < 13 the reactivity increase from additional neutron moderation can no longer overcome the reactivity decrease from the reduced core density (separation of material pieces). At this point the minimum critical mass is achieved when the plutonium is in a solid metal configuration. This effect is not noticed for uranium which responds much more quickly to moderation and thus almost any sized pieces will increase in reactivity when moderation is introduced. Summarizing the results of the calculation a surface area to volume ratio vs minimum critical mass curve is generated. The curve gives analysts a practical starting minimum critical mass in analysis of heterogeneous systems with known minimum material surface area to volume ratios.

KEYWORDS
Heterogeneous Array, Moderation, Criticality Safety

1. INTRODUCTION

In criticality safety analysis it is important to recognize the significant differences in reactivity achieved when material transitions from the solid to solution regime. However, the intermediate area of mixed heterogeneous systems (i.e. collections of small pieces) has not been well characterized. To that end, a study is underway to determine the effect of fissile material piece size/shape on minimum critical mass of a system.

Different piece shapes of fissile material are related using surface area to volume (SA-VOL) ratio. This study explores the relationship of three characteristic shapes of fissile material: spheres, cubes, and rods. Ultimately a SA-VOL ratio versus critical mass curve was developed for reference by criticality safety practitioners.

2. CALCULATIONAL STUDY

2.1. Description of Calculations

The study presented represents a calculation-based investigation of moderated arrays of fissionable material to expand on the plutonium and uranium solution curves (cf. Figure 31 and Figure 10 of LA-10860) to add the heterogeneous regime between pure a solid and solution of fissionable material.

The analysis performed consists of a parametric study utilizing the neutron transport code MCNP6 with the ENDF VII.1 cross section library to calculate the critical mass of systems composed of moderated arrays of varying sizes of spheres, cubes, or elongated rods (height >> diameter). The boundary of the array was increased to find the critical mass for that particular piece geometry and fissionable material volume density. In this study no bias was used and the critical mass was taken to be the mass in the array at k_{calc}=1.00.

The different shapes were then compared at points with the same fissionable material volume density to demonstrate that the key relationship between varying piece shape is SA-VOL ratio. The SA-VOL ratios are captured in Table I.

Table I. SA-VOL Ratios

Shape	**SA-VOL Ratio**
Sphere	6/D
Cube	6/S
Rod (h>>D)	4/D

Utilizing the information from Table I a SA-VOL ratio versus critical mass curve is generated. The curve establishes the minimum critical mass for a collection of pieces with a given SA-VOL ratio. Additionally, it determines the minimum SA-VOL ratio for which reactivity increases from moderation cannot overcome reactivity decreases from reduced core density (i.e. separation of material pieces).

2.2. Results

Figure 1 below displays the water reflected plutonium data from Figure 31 of LA-10860 with calculation results of water reflected and moderated arrays of plutonium spheres, cubes, and rods. Figure 2 below displays the water reflected uranium data from Figure 10 of LA-10860 with calculation results of water reflected and moderated arrays of uranium spheres, cubes, and rods. The total array volume in each configuration was varied to find the critical mass.

Although the shapes of the pieces differ, those pieces with equal SA-VOL ratios behave the same neutronically in heterogeneous arrays. This is illustrated by the four colored groupings with equal SA-VOL ratios. Note that the dimensions reported are the diameter of spheres and rods and side length of cubes.

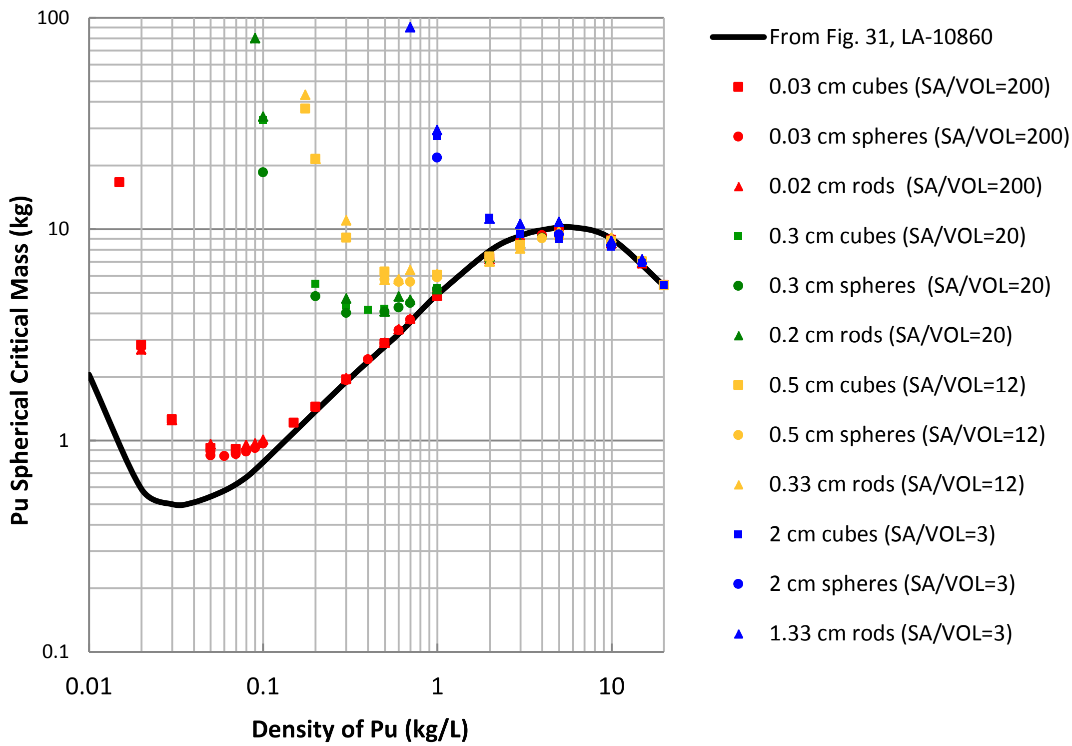

Figure 1 Plutonium Results Compared with Data from Figure 31 of LA-10860.

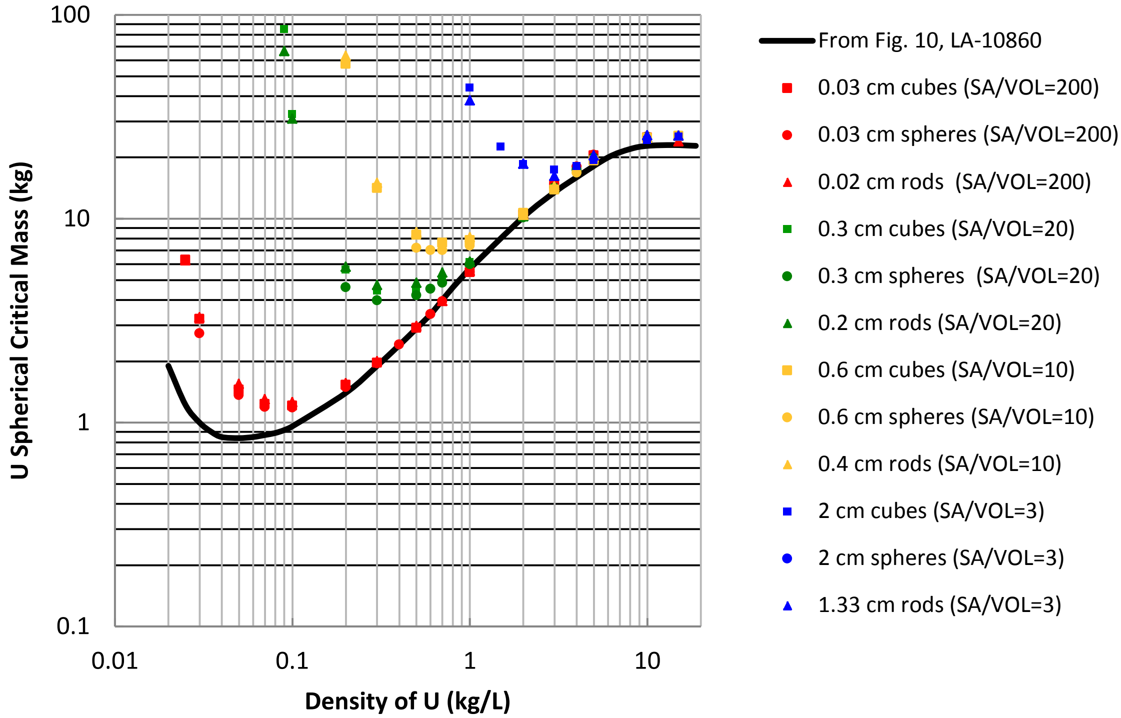

Figure 2 Uranium Results Compared with Data from Figure 10 of LA-10860.

As illustrated in Figures 1 and 2, as pieces get larger (i.e. more heterogeneous with smaller SA-VOL ratio) the minimum critical mass starts to increase. This effect results from the moderation of neutrons becoming less and less effective due to increased self-shielding of larger individual pieces.

For plutonium, once piece sizes reach a SA-VOL ratio of a certain magnitude the reactivity increase from additional neutron moderation can no longer overcome the reactivity decrease from the reduced core density. At this point the minimum critical mass is achieved when the material is in a solid metal configuration. The same effect is much less noticeable for uranium as added moderation almost immediately adds reactivity and decreases the minimum critical mass.

A complete set of data illustrating these trends is shown in Figures 3 and 4 for arrays with varying SA-VOL ratios. Moving from left to right in the figures, the individual piece size increases and the SA-VOL ratio decreases.

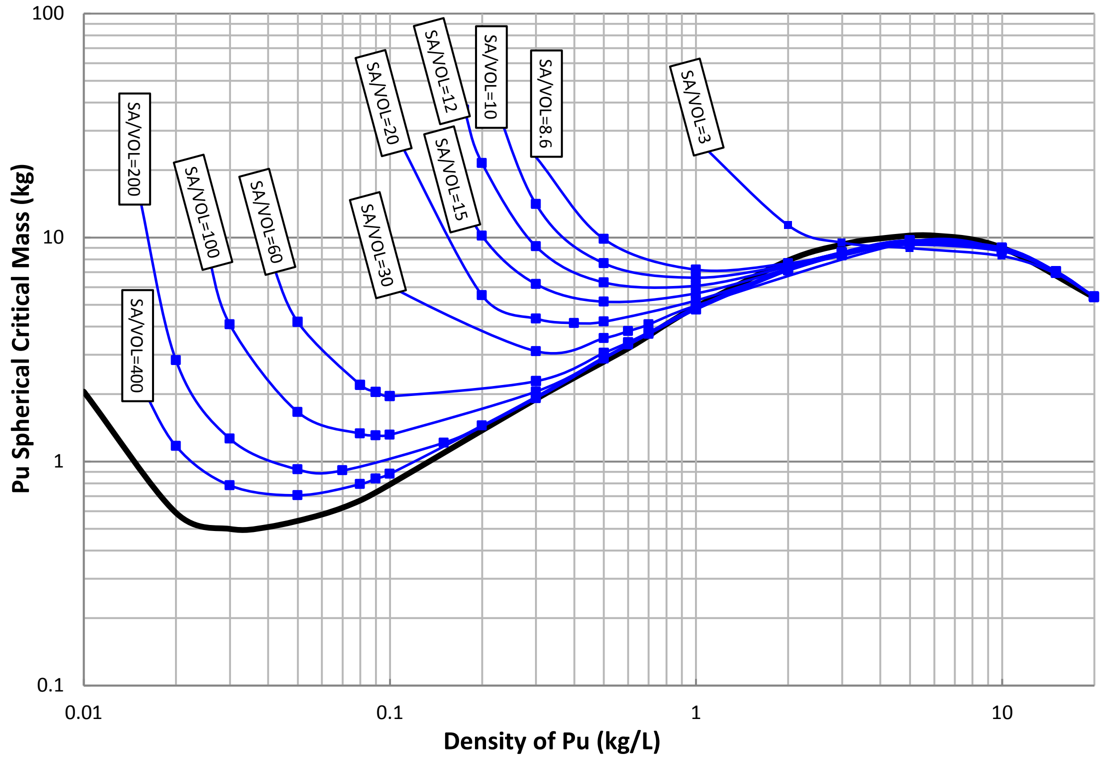

Fig. 3. Plutonium Results of Arrays of Spheres with varying SA-VOL ratios compared with Data from Figure 31 of LA-10860.

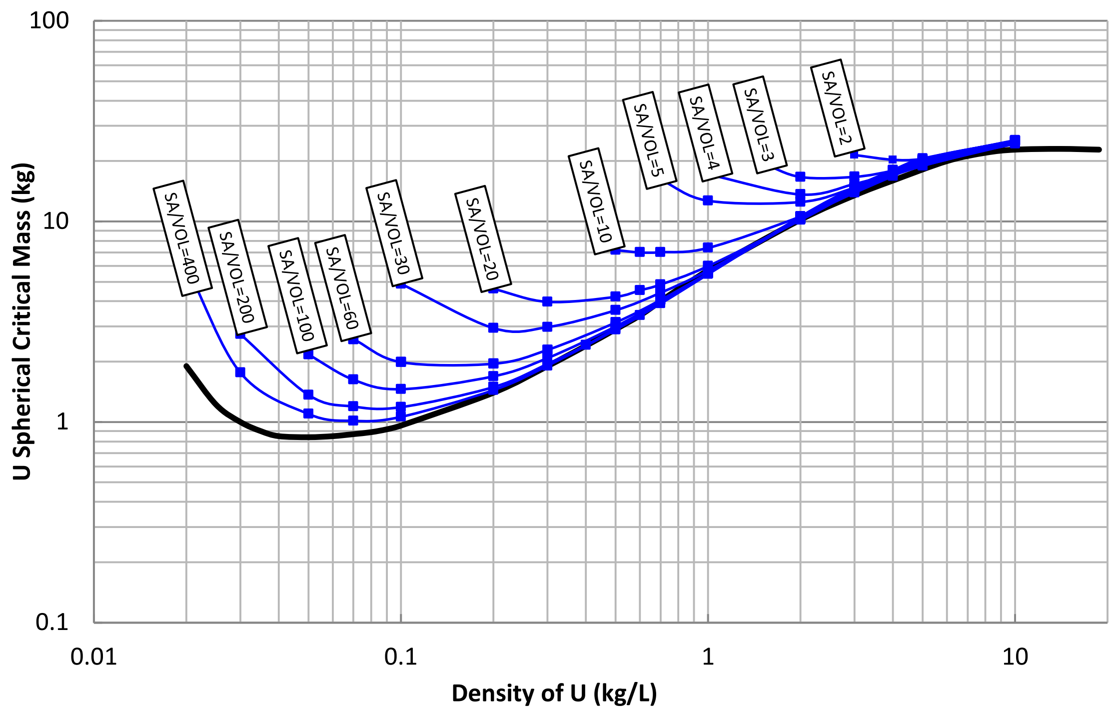

Fig. 4. Uranium Results of Arrays of Cubes with varying SA-VOL ratios compared with Data from Figure 10 of LA-10860.

Plotting the SA-VOL ratio versus the minimum critical masses in Figure 3 and 4, the curves shown in Figure 5 and 6 are generated.

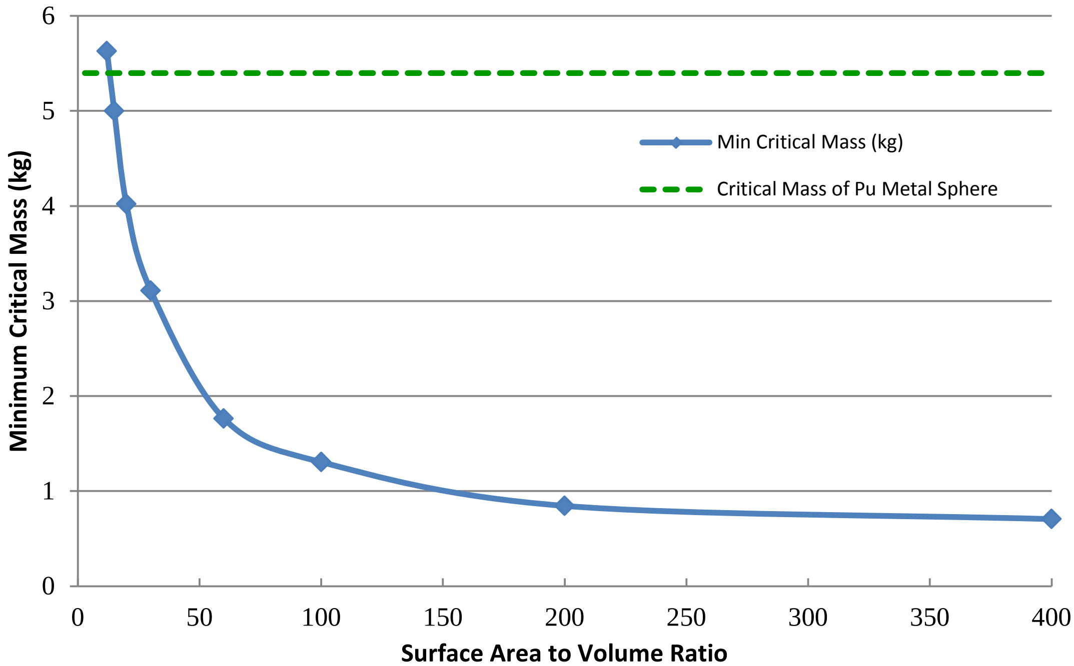

Fig. 5. Plutonium SA-VOL Ratio vs. Minimum Critical Mass for Reflected Moderated Arrays.

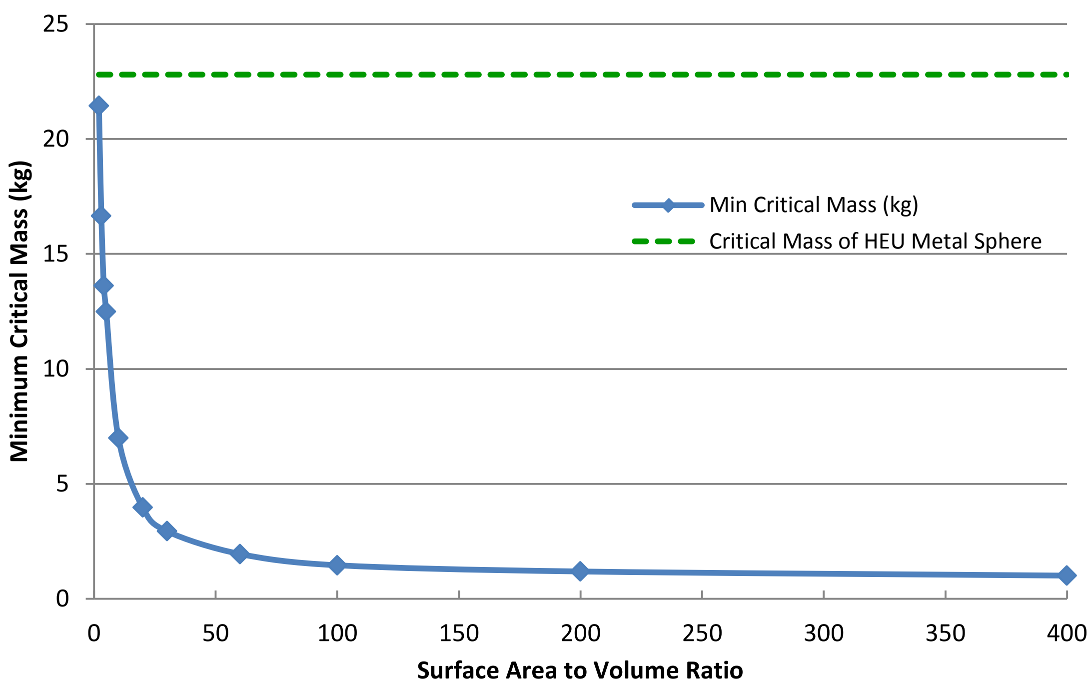

Fig. 6. Uranium SA-VOL Ratio vs. Minimum Critical Mass for Reflected Moderated Arrays.

For plutonium systems there is a point for pieces of a certain SA-VOL ratio where the reactivity increase from increased moderation and reactivity decrease from reduced core density would be completely balanced. Interpolation of the data in Figure 5 suggests an SA-VOL ratio of 13 as the point at which this holds true. Arrays of pieces that have a SA-VOL ratio < 13 cannot be made more reactive with increased moderation and thus for these pieces, the most reactive configuration is in a solid metal chunk. Arrays of pieces that have a SA-VOL ratio > 13 can achieve more reactivity with increased moderation and thus will be more reactive when optimally spaced in a moderated array.

For uranium systems moderation makes a nearly immediate impact as the reduction in core density does not have nearly as large of an impact as the increase in moderation. This trend is seen in the much steeper decline in minimum critical mass versus SA-VOL ratio in Figure 6 as compared to the plutonium data displayed in Figure 5.

The data in Figures 5 and 6 yield useful insight into the minimum critical mass achievable for an array of material pieces with known SA-VOL ratio. If an operation includes batches of material with known dimensions, the SA-VOL ratio of the material pieces can be calculated and the associated minimum critical mass can be obtained simply by looking at the curves in Figure 5 or 6. The SA-VOL versus minimum critical mass curves provide a valuable baseline for future criticality safety analyses.

3. CONCLUSIONS

The calculation study presented sheds additional light on the behavior of plutonium and uranium systems as they transition from homogenous solution systems to metal systems. Plutonium pieces with a SA-VOL ratio < 13 cannot be made more reactive by increasing moderation and thus these pieces are most reactive as a solid metal chunk. Plutonium pieces with a SA-VOL ratio > 13 can be made more reactive by adding moderation to the system. Uranium responds much more quickly to moderation and thus pieces of nearly any size will become more reactive with the addition of moderation. The figures and trends presented in the minimum critical mass vs SA-VOL ratio provide a valuable baseline for future criticality safety analyses.

ACKNOWLEDGMENTS

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