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A Practical Assessment of the Effect of Water Interspersed with Plutonium Metal Hemishells - Summary

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INTRODUCTION

Operations with fissile materials can be performed safely by complying with any of the listed single-parameter subcritical limits in ANS-8.1 [Ref. 1]. For metallic units, the single-parameter subcritical limits apply to a single piece having no concave surfaces. They may be extended to an assembly of pieces, provided that there is no neutron moderating material interspersed with the pieces.

An MCNP6.1 [Ref. 2] study was undertaken at the Los Alamos National Laboratory (LANL) to investigate the effect that interspersed water has on plutonium-metal hemishells [Ref. 3]. At LANL, it is common to have more than one hemishell at any given location, which obviously have concave surfaces. The intent of this paper is to present a high-level summary of the effect of having multiple concave shells, interspersed with water, as well as to discuss the methodology we used to determine the Upper Subcritical Limits (USL's) associated with the results.

DESCRIPTION

The study focused on the plutonium processing areas at LANL, but the results apply globally. Historically, fissile-metal hemishells have been handled and processed at LANL using a 6,000 g plutonium mass limit. More recently, fissile-metal hemishells have been handled and processed using a 4,500 g plutonium mass limit. The single-parameter subcritical limit for plutonium metal is 5,000 g. These three masses were included in this study.

In order to demonstrate where the effects of interspersed water become problematic, a WORM [Ref. 4] deck was generated for use with MCNP6.1, and was run on a LANL High Performance Computer (HPC) cluster. This facilitated the determination of the $k_{eff's}$ associated with a system consisting of one or multiple ^{239}Pu-metal hemishells with various inner diameters, various masses, and with various shell-to-shell spacing.

The plutonium hemishell(s) were modeled as α-phase (19.84 g/cm^3) ^{239}Pu-metal. No other plutonium nuclides were included in the material composition. Three ^{239}Pu-metal masses were modeled, 4,500 g, 5,000 g, and 6,000 g.

The number of ^{239}Pu-metal hemishells were varied, ranging from a single ^{239}Pu-metal hemishell, up to six ^{239}Pu-metal hemishells. For a single ^{239}Pu-metal hemishell, the ^{239}Pu-metal mass would correspond to the mass of the single hemishell. For multiple hemishells, the total ^{239}Pu-metal mass remains constant (one of the three values above), with the mass of each hemishell equally divided. For example, three stacked hemishells would each contain 2,000 g of ^{239}Pu-metal each, adding up to a total mass of 6,000 g.

The inner diameter (I.D.) of the ^{239}Pu-metal hemishell ranged from 0.1 cm (0.0039 in) to 128 cm (50.4 in). For multiple hemishells, variation in the inner diameter applies to all hemishells.

For multiple ^{239}Pu-metal hemishells, the shell-to-shell spacing ranged from 0.1 cm (0.039 in) to 32 cm (12.6 in). Similar to the variation for hemishell inner diameter, the variation in hemishell shell-to-shell spacing applies to all hemishells.

The ^{239}Pu-metal hemishell(s) was surrounded by nominal density water (1.0 g/cm^3) such that the thickness was at least 30 in. For multiple hemishells, water was also modeled within the reentrant portion between the stacked hemishells, and with at least 30 in of nominal density water.

A single hemishell, and a stack of five hemishells were rendered using the 3D Dynamic Plotting feature in the Visual Editor [Ref. 5] as shown in Fig. 1 and Fig. 2. Please note that water reflection was removed in the 3D rendering in order to provide a proper display.

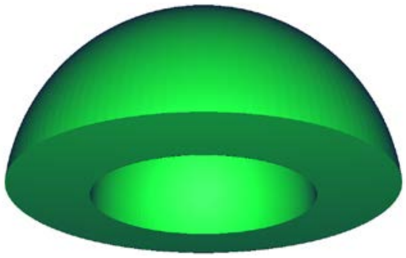

Fig. 1. 3D Rendering of a Single ^{239}Pu-Metal Hemishell.

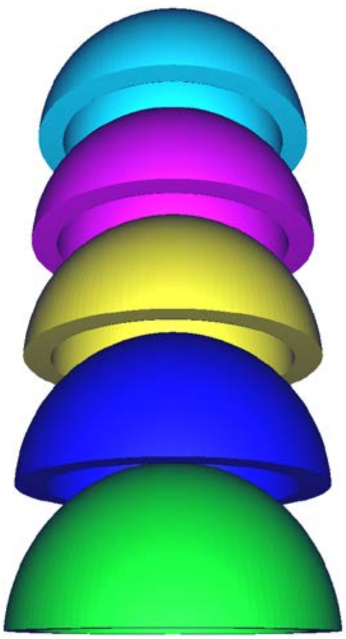

Fig. 2. 3D Rendering of Five Stacked ^{239}Pu-Metal Hemishells with some shell-to-shell spacing.

RESULTS

The results for the single hemishell cases are shown in Fig. 3. The applicable USL's are also shown in Fig. 3. The USL's were determined using Whisper [Ref. 6]. The results are considered to be subcritical when they fall below the associated USL.

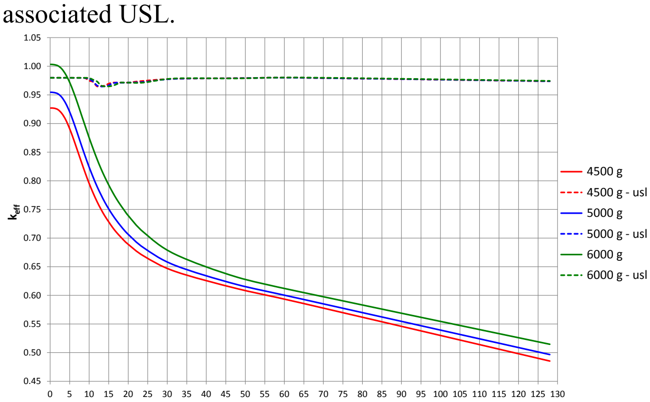

Fig. 3. 4,500-g, 5,000-g, and 6,000-g ^{239}Pu-Metal Hemishell with Various Inner Diameters, Immersed in Water.

Whisper is a sensitivity/uncertainty-based tool, developed by LANL's Monte Carlo Methods, Codes & Applications Group (XCP-3). It may be used for determining baseline USL's. When used for a particular problem, Whisper selects the most relevant benchmarks from a large collection using sensitivity-uncertainty methods, determines bias and bias uncertainty using extreme value theory, estimates the extra Margin-of-Subcriticality (MoS) due to nuclear data uncertainties, and includes an extra MoS to bound unknown code errors. Analyst judgment must provide additional MoS if warranted for area of applicability, material or dimensional uncertainties, etc.

Regarding our study, pure ^{239}Pu was modeled at the maximum theoretical density, and parametric studies were performed varying the dimensions. No further MoS for dimensions or materials is necessary to ensure subcriticality.

For a given mass, as the diameter of the hemishell increases, the thickness decreases. This affects the energy spectrum of the neutron flux. The percentages of fissions caused by neutrons in the thermal, intermediate, and fast ranges vary as the inner diameters of the hemishells are increased from 0.1 cm to 128 cm. As the diameter increases, the system transitions from a fast system to a thermal system through the intermediate range. When the hemishell inner diameter is between 10 and 15 cm, the system transits through the intermediate range. Because of fewer similar benchmarks (or more with less similarity) in that energy regime, Whisper take this into account, and calculates a larger calculational margin (bias + larger uncertainty), resulting in a lower USL.

The study also included cases involving up to six, stacked, hemishells. When multiple hemishells were modeled, the mass of each shell was simply the total mass modeled, 4,500 g, 5,000 g, or 6,000 g, divided by the number of hemishells.

Because the sheer volume of results for each case (three different masses, varying diameter, and varying shell-to-shell spacing) were difficult to interpret, plots of the peak $k_{eff's}$ as a function of inner diameter and shell-to-shell spacing were presented. See Fig. 4 and Fig. 5 for the peak cases involving five-hemishells. For all three masses modeled, dashed lines representing the single-hemishell results were included for comparison, along with dotted lines for the USL's. Please note that USL's are only plotted in regions where the the $k_{eff's}$ for multiples hemishells are higher than that of the single-hemishell. Please also note that the differences in the derived USL's are so minuscule, that they tend to overlap each other.

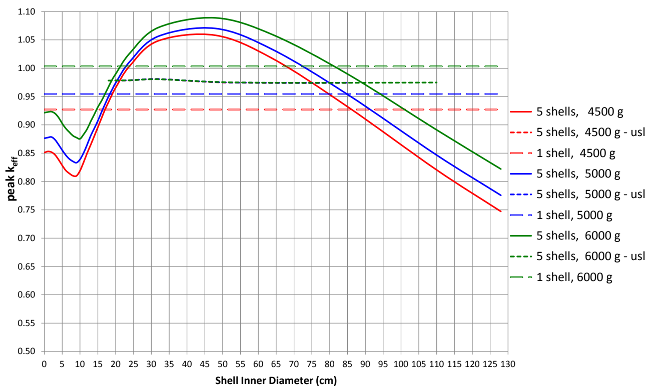

Fig. 4. Peak k_{eff}'s of the Five-Hemishell Results at Various Inner Diameters, Immersed in Water.

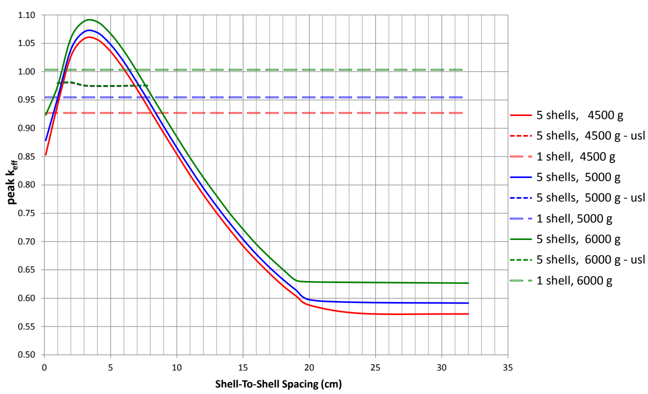

Fig. 5. Peak k_{eff}'s of the Five-Hemishell Results at Various Shell-to-Shell Spacing, Immersed in Water.

All results, from one hemishell, up to six hemishells were compiled into tabular form. See Table I through Table III.

Table I. 4,500 g Results

# of Hemishells	Where Criticality is Possible?
1	N/A
2	N/A
3	N/A
4	24 cm < I.D. < 64 cm ∣ 2 cm < Spacing < 6 cm
5	20 cm < I.D. < 85 cm ∣ 1 cm < Spacing < 7 cm
6	19 cm < I.D. < 85 cm ∣ 0.1 cm < Spacing < 8 cm

Table II. 5,000 g Results

# of Hemishells	Where Criticality is Possible?
1	N/A
2	N/A
3	N/A
4	24 cm < I.D. < 85 cm ∣ 2 cm < Spacing < 7 cm
5	20 cm < I.D. < 85 cm ∣ 1 cm < Spacing < 8 cm
6	18 cm < I.D. < 110 cm ∣ 0.1 cm < Spacing < 8

Table III. 6,000 g Results

# of Hemishells	Where Criticality is Possible?
1	I.D. < 5 cm
2	I.D. < 5 cm
3	I.D. < 3 cm
4	20 cm < I.D. < 85 cm ∣ 1 cm < Spacing < 7 cm
5	18 cm < I.D. < 110 cm ∣ 1 cm < Spacing < 8 cm
6	17 cm < I.D. < 110 cm ∣ 0.1 cm < Spacing < 8 cm

CONCLUSION

The goal of the study was to provide a reference that may be used to demonstrate the effect of water interspersed with one or more plutonium metal hemishells might pose a criticality concern. As summarized in above tables, the potential for criticality varies as a function of discrete number of subdivided hemishells, hemishell inner diameter, and shell-to-shell spacing. It is up to the criticality safety analyst to determine whether such a scenario is credible in his/her facility.

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