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# Criticality Safety Evaluations on the Use of 200-gram Pu Mass Limit for RHWM Waste Storage Operations

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# CRITICALITY SAFETY EVALAUATION

## On the

## Use of 200-gram Pu Drum Mass Limit for RHWM Waste Storage Operations


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# CRITICALITY SAFETY EVALAUATION On the Use of 200-gram Pu Drum Mass Limit for RHWM Waste Storage Operations

## 1.0 INTRODUCTION

### 1.1 Objective

The purpose of this work is to analyze the use of 200-gram Pu drum mass limit for waste storage operations in Radioactive and Hazardous Waste Management (RHWM) Facilities. In this evaluation, the criticality safety controls associated with the 200-gram Pu drums are established for the RHWM waste storage operations. With the implementation of these criticality safety controls, the 200-gram Pu waste drum storage operations are demonstrated to be criticality safe and meet the double-contingency-principle requirement per DOE O 420.1 [1].

### 1.2 Background

This work establishes the criticality safety technical basis to increase the fissile mass limit from 120 grams to 200 grams for Type A 55-gallon drums and their equivalents (CSAM99-061 Rev.1, 2000 [2]). Current RHWM fissile mass limit is 120 grams Pu for Type A 55-gallon containers and their equivalent. In order to increase the Type A 55-gallon drum limit to 200 grams, a few additional criticality safety control requirements are needed on moderators, reflectors, and array controls to ensure that the 200-gram Pu drums remain criticality safe with inadvertent criticality remains incredible.

## 2.0 FACILITY AND OPERATION DESCRIPTION

### 2.1 Facility Description

The applicable RHWM facilities include Area 514 (A514), Area 612 (A612), Building 169 (B169) Consolidation Waste Accumulation Area (CWAA), the TRU Waste Segments, and the Decontamination Waste Treatment Facility (DWTF), which includes Building 693, the Building 695 Segment (B695S) and the Building 696 Radioactive Waste Storage Area (B696R).

### 2.2 Operations Description

RHWM waste storage operations involve the storage of wastes in containers and arrays as well as the handling operations to maintain the drums and array configurations. The wastes are first placed inside waste container for containment and segregation. The containers are then placed in arrays for further segregation and storage management.

The fissionable material containing wastes in RHWM can be classified into two categories: transuranic (TRU) waste and low-level waste (LLW). TRU waste contains all radionuclides with a half-life exceeding 20 years and an atomic (Z) number larger than that of uranium (Z=92). Its waste constituents are also more radioactive exceeding $10^{-7}$ Ci/gram (or 100 nCi/gram). Typical TRU waste constituents in the LLNL waste streams are uranium, plutonium, americium, and curium. (Uranium with high-level TRU isotope contamination is considered as TRU.) LLW contains mostly radioactive isotopes with a Z number no greater than 92 and has an activity level no greater than $10^{-7}$ Ci/gram. Typical LLNL LLW waste constituents are uranium, in the form of natural and depleted uranium (Nat-/Dep-U). TRU isotopes can only have trace amounts in LLW. For LLNL, TRU waste is of more criticality concern compared to LLW because there is more fissile material inventory in TRU waste.

Containers of various types and sizes are used to store waste containing fissionable materials. The containers used are 5-gallon containers, 30-gallon drums, 55-gallon drums, larger drums, steel waste boxes of different sizes, and containers of miscellaneous shapes and sizes. The applicable criticality safety controls for the RHWM waste storage operations factor in the container sizes. Larger drums (larger than 55-gallon) and steel waste boxes are considered 55-gallon drum equivalents because the 55-gallon drums bound their neutronic interactions. The current criticality safety controls on containers can be divided into four categories: 55-gallon drum and its equivalent, 30-gallon drums, 5-gallon containers, and miscellaneous containers. The current criticality safety controls also factor in the types of fissionable materials. The criticality safety controls on waste containers include controls on the following:

Containers of various types and sizes are placed in arrays for further segregation and waste management. The criticality safety of the arrays is managed by array types (uniform, mixed), stacking height, and array spacing. The fissionable material mass limits are in Pu and Nat-U equivalents, which are discussed in details in CSAM99-061 Rev. 1[2].

Current RHWM storage operations on drums and arrays are based on the criticality safety controls, which are discussed in details in the following subsections:

## 2.2.1 Container Criticality Controls

Container criticality controls, which are based on the content (fissile or Nat-U), are discussed here for 5-gallon containers, 30-gallon drums, and 55-gallon drums and equivalents. Discussions on miscellaneous container controls are included in mixed-container array section in Section 2.2.2.

### 2.2.1.1 Individual Fissile Container Controls

The criticality controls under this item apply to fissile containers of all sizes. Hydrogenous materials with a hydrogen density greater than that of paraffin or polyethylene (0.133 g H/cc) are not permitted. Hydrogenous materials with a hydrogen density no greater than that of paraffin or polyethylene (0.133 g H/cc) are permitted in unlimited quantities. Accordingly, paraffin, polyethylene, Superla White Oil No. 9, TrimSol, and water are allowed.

**Mass Limits for 55-gallon Drums and Equivalents:**

| Fissile/Pu Equivalent Mass Limit | Reflector Mass Limits |
|---|---|
| 120 grams | Only one of the three reflector materials is allowed in any single container with the allowable amount up to:<br><br>a) 100 kilograms of Nat-U equivalent, or<br>a) 300 grams of beryllium, or<br>a) 8 kilograms of carbon or graphite. |
| 65 grams | All of the following three materials are allowed up to the amounts specified:<br><br>a) 100 kilograms of Nat-U equivalent, and<br>b) 300 grams of beryllium, and<br>c) 110 kilograms of carbon or graphite. |

**Mass Limits for 30-gallon Drums:**

| Fissile/Pu Equivalent Mass Limit | Reflector Mass Limits |
|---|---|
| 80 grams | Only one of the three reflector materials is allowed in any single container with the allowable amount up to:<br><br>a) 100 kilograms of Nat-U equivalent, or<br>a) 300 grams of beryllium, or<br>a) 8 kilograms of carbon or graphite. |

**Mass Limits for 5-gallon Drums:**

| Fissile/Pu Equivalent Mass Limit | Reflector Mass Limits |
|---|---|
| 40 grams | Only one of the three reflector materials is allowed in any single container with the allowable amount up to:<br><br>a) 100 kilograms of Nat-U equivalent, or<br>a) 300 grams of beryllium, or<br>a) 8 kilograms of carbon or graphite. |

## 2.2.1.2 Individual Nat-U Container Criticality Controls

Hydrogenous materials with a hydrogen density greater than that of paraffin or polyethylene (0.133 gram hydrogen/cc) are not permitted. Hydrogenous materials with a hydrogen density no greater than that of paraffin or polyethylene (0.133 gram hydrogen/cc) are permitted in unlimited quantities. Accordingly, paraffin, polyethylene, Superla White Oil No. 9, TrimSol, and water are allowed with unlimited amounts.

The total natural uranium mass limits expressed in units of Nat-U equivalent are:

a) 650 kilograms per 55-gallon drum equivalent
a) 210 kilograms per 30-gallon drum

The fissile (Pu equivalent) material waivers for Nat-U containers are 0.6 and 1.0 gram Pu-239 equivalent for 30- and 55-gallon drum equivalents, respectively. Nat-U containers with fissile material exceeding the waiver amounts shall be treated as fissile containers.

## 2.2.2 Array Criticality Controls

Criticality controls for uniform and mixed arrays are discussed in the following subsections:

## 2.2.2.1 Uniform- Array Criticality Control Specifications

Uniform array refers to uniform fissile drum array or uniform Nat-U drum array.

- A uniform array shall be made of containers of the same size.
- No mixing of fissile and Nat-U drums within any single uniform array; *i.e.*, fissile drums and Nat-U drums shall not be in the same uniform array at any time.
- Maintain a spacing of no less than 76.2 cm (or 30 in) between arrays. When moving a drum to/from an array, the 76.2-cm (or 30-in) minimum separation for arrays is exempted.
- The stacking limits for waste containers depend on their size.

    a) 5-gallon drums shall be stacked no more than 4-high.
    a) 30-gallon drums and its equivalent shall be stacked no more than 2-high.
    a) 55-gallon drums and its equivalent shall be stacked no more than 2-high and up to 121.92 cm (4 feet) from the ground level to the bottom of any containers on the second tier, whichever is more limiting.
    a) For arrays having only the SWBs, the SWBs may be stacked 3-high when physical restraints are applied ensuring the stacking integrity.

## 2.2.2.2 Mixed Array Criticality Controls

Containers of all sizes and types may be stored in a single mixed array as long as the following controls are adhered to:

- The individual container mass limits given in Sections 4 and 5 do not apply to containers within mixed-size and mixed-type container arrays. The following fissile mass limit applies:

  The aggregate fissile material stored in containers is limited to 120 grams Pu equivalent per defined array area. This material may exist as a single discrete item, or dispersed in a single container (e.g., can, box, bottle, drum, tank, etc.), or distributed within a collection of containers in a defined storage area.

- Up to 300 kilograms of Nat-U equivalent are allowed for each container in a mixed array.
- A maximum of 1,000 kilograms of Nat-U equivalent total is allowed for each mixed array.
- Maintain a spacing of no less than 76.2 cm (or 30 in) between a mixed array and other arrays. When moving a container to/from an array, this 76.2-cm (30-in) minimum separation requirement is exempted.
- There is no stacking limit for containers in the mixed-size and mixed-type container arrays.

## 2.2.3 Special Concerns

Operations that include waste containers exceeding any of the CS control limits listed above (*i.e.* fissile material mass limits, moderator and reflector mass limits, etc.) must be evaluated by CSS on a case-by-case basis to determine what criticality safety controls need to be implemented to allow storage of these waste containers. Other situations where a case-by-case analysis is required by the CSG include:

- Fissionable material dispersed in a matrix or intimately mixed with hydrogenous materials having a hydrogen density greater than that of paraffin or polyethylene (0.133 gram hydrogen/cc).
- Fissionable material intimately mixed with or in close proximity to beryllium and its compounds (in excess of 300 grams of beryllium total), carbon or graphite (in excess of 110 kilograms in 55-gallon drums or their equivalent), carbon or graphite (in excess of 8 kilograms in 5-gallon or 30-gallon drums), and deuterium or its compounds.
- Fissionable material under special conditions, such as in the form of gas or solution or at cryogenic temperatures.

## 2.3 New 200-gram Pu Drum Controls

Currently, for 55-gallon drums and equivalents, the fissile mass limits are 65 and 120 grams, depending on whether the containers have mixed types of reflectors or a single type of reflector as well as their amounts. The 200-gram Pu drum controls established in this evaluation will allow RHWM more operations flexibility. Furthermore, the 200-gram Pu drum controls will align better with the Waste Isolation Pilot Plant (WIPP) waste disposal requirements [3] and the Nuclear Regulatory Commission (NRC) off-site transportation requirements [4]. The WIPP, which is located in Carlsbad, New Mexico, is the only long-term defense TRU waste disposal facility in the U.S. For disposal at WIPP, the LLNL TRU waste containers need to be transported off-site, which is under the jurisdiction of the NRC. Both WIPP waste disposal and NRC off-site transportation requirements have a 55-gallon drum control limit of 200 fissile gram equivalent (FGE), which is similar to the Pu equivalent used at LLNL. Both FGE and Pu equivalent have a one-gram-to-one-gram conversion factors for the major fissile isotopes, U-233, U-235, and Pu-239.

# 3.0 CRITICALITY SAFETY ASSESSMENT METHODOLOGY

The criticality safety assessment methodology used in the development of the 200-gram drum controls includes the use of the established subcritical limits and the neutronic transport analysis. The established subcritical limits are taken from the American National Standard, ANSI/ANS-8.1-1998 [5], on "*Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors*,' and the neutronic transport analysis is performed on simple and complex drum and array storages using computer codes.

## 3.1 Established Subcritical Limits from Consensus National Standards on Criticality Safety

The American National Standards, ANSI/ANS-8.1-1998 [5], on "*Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors*' is used in this analysis. In Section 5.2, the subcritical mass limit is listed as 450 grams for Pu-239 in aqueous mixtures. In Table 1, the ANSI/ANS-8.1-1998 single-parameter subcritical mass limits for uniform aqueous solutions are also listed for U-233, U-235, and Pu-239.

Table 1. Single-Parameter Subcritical Limits for Fissile Solutions (from ANSI/ANS-8.1-1998 [5])

| Parameter | $^{233}UO_2F_2$ | $^{233}UO_2(NO_3)_2$ | $^{235}UO_2F_2$ | $^{235}UO_2(NO_3)_2$ | $^{239}Pu(NO_3)_4$ |
|---|---|---|---|---|---|
| Fissile Mass (g) | 540 | 550 | 760 | 780 | 480 |
| Fissile Concentration (g/L) | 10.8 | 10.8 | 11.6 | 11.6 | 7.3 |

It should be noted that all of the subcritical limits are associated with full water reflection only.

## 3.2 Neutron Transport Analysis

The one-dimensional deterministic code, XSDRNPM [6], and the three-dimensional Monte Carlo code, KENO V.a [6], of the SCALE 4.4 package are used for this evaluation. XSDRNPM is used for parametric studies and KENO V.a is used for the detailed 3-D modeling and simulation.

**Description of Calculational Method**

Both XSDRNPM and KENO V.a of the SCALE4.4 package [6] are used in this evaluation. All calculations were performed on a SUN workstation (Ultra 60) named *Godiva*. *Godiva* is operated under a SUN OS 5.6 UNIX platform and is maintained by the CSG. The SCALE 4.4 ENDF/B-V 44-group cross section library [6] was exclusively used for all XSDRNPM and KENO V.a calculations. This 44-group broad-group library was collapsed from the ENDF/B-V 238-group LAW fine-group cross section library [6].

### 3.2.1 The XSDRNPM Code

Two options can be used in running the XSDRNPM code. The first option is to use the criticality safety analysis sequence (CSAS) driver module, CSAS1X [6]. This CSAS1X driver automatically generates input decks for XSDRNPM. The user only needs to furnish the material and dimension information for the CSAS1X runs. This option is good for all calculations for the $k_{eff}$ values. The other option is to use the XSDRNPM module directly. The two driver modules, CSAS1X and XSDRNPM are individually described and discussed in the following subsections. This evaluation uses the CSAS1X driver module only to perform the 1-D parametric analysis.

#### 3.2.1.1 The CSAS1X Driver Module

The CSAS1X driver module invokes BONAMI [6], NITAWL [6], and XSDRNPM, in the order as specified. BONAMI prepares nuclides with Bodaranko factor information for self-shielding correction on unresolved resonance peaks. NITAWL then prepares nuclides using the Nordhein Integral method for self-shielding correction on resolved resonance peaks. NITAWL also generates the XSDRNPM working library. This follows by XSDRNPM calculations on specified problems.

#### 3.2.1.2 The XSDRNPM Driver Module

XSDRNPM is a 1-D discrete-ordinate transport code and is distributed with the SCALE4.3 package. Since this code employs deterministic methods in the solution for the transport problem, its result, unlike the Monte Carlo KENO V.a or MCNP results, does not come with a statistical uncertainty in the form of standard deviations. It can be used on its own, without going through the CSAS driver sequences. However, under this circumstance the user is required to prepare the XSDRNPM compatible library, which is a tedious process.

### 3.2.2 The KENO V.a Code

In this analysis, CSAS KENO V.a drivers, CSAS25 and CSAS2X [6], are used to perform KENO V.a calculations. The KENO V.a usable cross section library is automatically prepared and processed by the CSAS25 and CSAS2X drivers. This evaluation uses mostly CSAS25 driver module for the majority of the 3-D neutron transport analysis.

#### 3.2.2.1 The CSAS25 Driver

The CSAS25 driver sequence invokes modules BONAMI, NITAWL, and KENOVA (KENO V.a) in the order as specified. Again, BONAMI prepares nuclides with Bodaranko factor information for self-shielding correction on unresolved resonance. NITAWL then prepares nuclides using the Nordhein Integral method to incorporate self-shielding corrections from the resolved resonance peaks into the working cross section library for the KENO V.a usage. KENO V.a will then be driven by the CSAS25 module to calculate for the problem defined.

#### 3.2.2.2 The CSAS2X Driver

The CSAS2X driver sequence invokes modules BONAMI, NITAWL, XSDRNPM, and KENOVA (KENO V.a) in the order as specified. The only difference between the CSAS2X and CSAS25 driver sequences is that an extra module, XSDRNPN, is used to perform lattice cell weighting calculations. Again, BONAMI prepares nuclides with Bodaranko factor information for self-shielding correction on unresolved resonance. NITAWL then prepares nuclides using the Nordhein Integral method to account for self-shielding corrections caused by the resolved resonance peaks in the cross sections. XSDRNPM is then used to generate lattice cell weighted cross sections (Material 500) to account for the lattice cell effect. KENO V.a will then be driven by the CSAS2X module to calculate for the problem defined.

### 3.3 XSDRNPM And KENO V.a Verification

Verification of XSDRNPM and KENO V.a on *Godiva* has been documented by R. Evarts in CSAM99-074 [7]. No further discussion on the verification of XSDRNPM and KENO V.a will be given in this report. For details on verification of the two codes, please refer to CSAM99-074 directly [7].

### 3.4 XSDRNPM and KENO V.a Validation

Validation of XSDRNPM and KENO V.a on *Godiva* has been documented in Sections 4.3.1 and 4.3.2, respectively, of CSM 1087 Rev. 1 (2001) [8]. Only the biases derived in XSDRNPM and KENO V.a validation will be given in this report. For details on validation of the two codes, please refer to CSM 1087 Rev. 1 directly [8].

### 3.4.1 Validation of XSDRNPM

For the XSDRNPM validation, a sample size of 12 and a degree of freedom of 11 are used. The associated multiplier, $k_p$, is 1.363, 1.796, 2.201, 2.718, and 3.106 for a confidence level of 90%, 95%, 97.5%, 99%, and 99.5%, respectively. The average $k_{eff}$ value, $k_{av}$, is 1.007166 with a standard deviation of 0.005948 from the XSDRNPM validation results.

Table 2. Bias for plutonium systems as a function of confidence levels with n=12 for XSDRNPM using the ENDF/B-V 44-group library for *Godiva*.

| Confidence Level | Multiplier, $k_p$ [9] | Bias, $1.0-k_{av}+k_p\sigma$ |
|---|---|---|
| 90% | 1.363 | 0.00094 |
| 95% | 1.796 | 0.00352 |
| 97.5% | 2.201 | 0.00593 |
| 99% | 2.718 | 0.00899 |
| 99.5% | 3.106 | 0.01131 |

Table 2 shows that the biases range from 0.00094 to 0.01131 for confidence levels of 90% to 99.5%. To be conservative, the 99% confidence level is selected. In this regard, the bias for the XSDRNPM is 0.00899, or about 0.009. It is worth mentioning that XSDRNPM is a deterministic code. No Monte Carlo statistical uncertainty is associated with its results. The system and statistical uncertainties in the cross sections and others are categorically lumped together in the deviations of the biases. A confidence of 99% in the XSDRNPM validation results is inherently associated with this bias of 0.009. For further details, refer to Section 4.4.1 of CSM 1087 Rev. 1[8].

### 3.4.2 Validation of KENO V.a

For the KENO V.a validation, it has a sample size of 19 and a degree of freedom of 18. The multiplier, $k_p$, is 1.330, 1.734, 2.101, 2.552, and 2.878 for a confidence level of 90%, 95%, 97.5%, 99%, and 99.5%, respectively. The average $k_{eff}$ value, $k_{av}$, is 1.006495 with a standard deviation of 0.005413 for *Godiva*.

Table 3. Bias derived for *Godiva* as a function of desired confidence levels for KENO V.a for plutonium systems using the ENDF/B-V 44-group library.

| Confidence Level | Multiplier, $k_p$ [9] | Bias, $1.0-k_{av}+k_ps$, for *Godiva* |
|---|---|---|
| 90% | 1.330 | 0.00070 |
| 95% | 1.734 | 0.00289 |
| 97.5% | 2.101 | 0.00488 |
| 99% | 2.552 | 0.00732 |
| 99.5% | 2.878 | 0.00908 |

Table 3 shows that the biases range from 0.00070 to 0.00908 for *Godiva* with confidence levels ranging from 90% to 99.5%. Again, the 99% confidence level is selected. The 99%-confidence level bias is 0.0077, or 0.008, for *Godiva* KENO V.a calculations using the ENDF/B-V 44-group library. For further details, refer to Section 4.2.2 of CSM 1087 Rev. 1[8].

### 3.5 Safety Margin and Subcritical Limits

A safety margin of 0.02 is used for all calculations using either XSDRNPM or KENO V.a with the ENDF/B-V 44-group library. Therefore, for *Godiva* XSDRNPM calculations, all of the $k_{eff}$ values no greater than 0.971 are subcritical. For *Godiva* KENO V.a calculations, all of the $k_{eff}$ values no greater than 0.972 are subcritical. The KENO V.a bias and its associated subcritical value for this analysis are as shown in Table 4. It should be noted that the calculated $k_{eff}$ values from KENO V.a calculations are defined as the KENO V.a $k_{eff}$ values added with three standard deviations (so that the Monte Carlo statistical uncertainties are properly accounted for to a confidence level of 99.7%). This ensures that the relative statistical uncertainty (99.7% confidence level) from each individual KENO V.a calculation is statistically smaller than the relative statistical uncertainty associated with the subcriticality limit, which has a confidence level of 99% as of the biases. For discussions on the biases and subcritical limits listed in the above, refer directly to Section 4.5 of CSM 1087 Rev. 1 [8].

Table 4. Plutonium system biases derived for *Godiva* with a confidence level of 99% for KENO V.a and XSDRNPM calculations using the ENDF/B-V 44-group cross section library for *Godiva*.

| Computer Code Package | 99% Confidence Level Bias | Subcritical Limit |
|---|---|---|
| XSDRNPM | 0.009 | 0.971 |
| KENO V.a | 0.008 | 0.972 |

### 3.6 Material and Container Information

The materials used in this analysis and their properties are as listed in Table 5. It should be noted that the SCALE4.4 [6] properties are used as the defaults for most of the materials in this table. The material properties for Superla White Mineral Oil No. 9 and TrimSol are taken from CSM 1034 [10] because they are not available in the SCALE4.4 material database.

Table 5. Basic Material Property Information

| **Material** | **Density (g/cc)** | **Remarks** (Unless Otherwise Specified, below listed are SCALE4.4 defaults [6]) |
|---|---|---|
| Beryllium | 1.85 | |
| Carbon Steel | 7.8212 | 99 wt% Fe and 1wt% C |
| Concrete | 2.2994 | ORNL Concrete (composition in wt%): 0.7784 Fe, 0.6187 H, 17.52 C, 41.02 O, 0.02706 Na, 3.265 Mg, 1.083 Al, 3.448 Si, 0.1138 P, and 32.13 Ca. |
| Carbon/Graphite | 2.1 | To be conservative, activated carbon is treated as full-density graphite |
| Plutonium | 19.84 | α-Phase Pu |
| Polyethylene (PE) | 0.923 | $CH_2$ polymer |

| | | |
|---|---|---|
| Superla | 0.86 | $CH_2$ polymer, $C_{15}H_{30}$ at 0.129 g/cc or 15% TD. Superla is used with Nat-U rods to form optimized configurations (CSM 1034 [10]) |
| Uranium, Natural (Nat-U) | 19.05 | 0.005 wt % U-234, 0.711wt % U-235, and U-238 at 99.285 wt %; To be conservative, Dep-U is treated as Nat-U in this study. |

Only 55-gallon waste containers and their equivalents are allowed for the 200-gram Pu drum controls. 55-gallon container equivalents are containers larger than 55 gallons in capacity with their smallest dimensions larger than the diameter (56.55 cm/22.26") of a 55-gallon drum. These 55-gallon container equivalents are bounded by the 55-gallon drums from a neutronic coupling viewpoint. 5-gallon and 30-gallon waste containers and their equivalents are not applicable. Table 6 includes the information on the dimensions of 55-gallon drums and steel waste boxes (SWBs), which are 55-gallon drum equivalents.

Table 6. Waste Container Dimension Information

| Container Type and Capacity (ID; liters/gallon) | Inner Height (cm/in) | Outer Height (cm/in) | Inner Diameter or Outer Width (cm/in) | Outer Diameter or Outer Length (cm/in) |
|---|---|---|---|---|
| 55-gallon; 207.5/55 | 82.65/32.54 | 83.36/32.819* | 56.534/22.2275 | 57.26/22.543* |
| 2'x4'x7'; >207.5/55 | - | 60.96/24 | 121.92/48 | 213.36/84 |
| 4'x4'x7'; >207.5/55 | - | 121.92/48 | 121.92/48 | 213.36/84 |

*including a 0.135-cm-thick (0.09"-thick) inside polyethylene liner.

Containers with a capacity larger than 55 gallons and with their smallest dimension no less than the diameter of a 55-gallon drum may be treated as a 55-gallon drum. With the same amount of fissionable materials, the larger dimensions of these 55-gall equivalent container result in larger interaction distances for the interaction between such containers. This allows 55-gallon drum arrays to bound the interaction behavior of all arrays with 55-gallon equivalent containers.

Table 7. Non-Exhaustive List of Waste Containers that are 55-Gallon Drum Equivalent

| Container Type | Applications at HWM | Remarks |
|---|---|---|
| Single-Drum Overpack for 55-Gallon Drums | To contain damaged containers, including 55-gallon drums | Larger than 55-gallon drums in all dimension. |
| Waste Box: 2'x2'x7', 2'x4'x7', 4'x4'x7' | To contain general wastes may contain small amount of Nat-U and trace amount of fissile | 60.96 cm (2') |
| Drum Overpack for Multiple Drums or Standard Waste Box (SWB) 4'x4'x7' | To pack TRU drums in a 2x2 formation | An overpack may be treated as a single 55-gallon drum equivalent or as the number of drums inside if the drums inside are all of the 55-gallon drum type |

### 3.7 Regarding the Use of Upper Bound Models

In Paragraph 4.1.2 of the American National Standard, ANS/ANSI8.1-1998 [5], it is written:

> *"Before a new operation with fissionable material is begun, or before an existing operation is changed, it shall be determined that the entire process will be subcritical under both normal and credible abnormal conditions."*

To ensure that this requirement is met for all RHWM operations involving 200-gram Pu drums, the following approaches are taken: first, all normal and credible upset conditions for RHWM operations are identified, and then conservative upper bound models are used to demonstrate the subcriticality of these normal and credible upset conditions for RHWM operations. The use of upper bound models can reduce the analytical needs in assessing many variations in the operations scenarios. In the event that the upper bound models cannot be proven to be subcritical, the more detailed realistic models will then be used.

## 4.0 Normal Operation and Credible Upset Conditions

In this section, the normal operation and credible upset (off-normal) conditions are discussed and summarized. These normal operation and credible upset conditions are then consolidated into the bounding scenarios. These bounding scenarios are derived to cover all normal operation and credible upset conditions. Each of the bounding scenarios is analyzed in Section 5.

### 4.1 Normal Operation Conditions for 200-gram Pu Waste Drum Storage Operations

**The normal operation scenario** for the 200-gram Pu drum storage has the following characteristics:

- The containers are 55-gallon Type A drums or equivalents.
- Each containers have 200 grams Pu. In reality, the average RHWM TRU drum contains around 10 grams Pu.
- Polyethylene (0.923g/CC, of which 0.133 g/CC belonging to hydrogen) is allowed in the waste container. The polyethylene content in the RHWM wastes are primarily composed of disposed bottles, gloves, coveralls, booties, plastic wraps, and others. It is expected that the packing factor for the polyethylene waste is far less than 1.0. Furthermore, TRU drums are not allowed to have free liquid inside.
- No beryllium, Nat-U, and carbon/graphite are allowed to exceed the waiver amount of 50 grams.
- The 200-gram Pu containers are stored in a 3-high infinite X-Y uniform array. In reality, RHWM has 2-wide 3-high (constraint steel waste boxes) linear array configuration with an access aisle width of 30" (76 cm).
- The stacked drums are in direct contact to each other. There is no pallet in between the lower level and upper level drums. In reality, RHWM uses forklifts to move drums to/from arrays and the use of pallets is needed in such operations.

### 4.2 Credible Upset (Off-Normal) Conditions for 200-gram Pu Waste Drum Storage Operations

Some of the abnormal 200-gram drum storage operations could be of criticality concern. It is especially true when the deviations from normal operations involve the non-compliance on the criticality safety controls. As we know, the criticality safety controls ensure the criticality safety in the storage operations for 200-gram Pu drums. A deviation from the criticality safety control requirements may cause reduction or loss of the safety margin. This subsection is to identify the bounding credible off-normal operation scenarios.

#### 4.2.1 Fissile Over Batch

An upper bound fissile over batch scenario is described here: a fissile double batch in a single 200-gram Pu drum resulting in 400 grams Pu, instead of 200 grams. This over batched drum is stored in a 200-g Pu drum storage array. All other drums in the same array meet the 200-gram Pu mass limit. Since RHWM deals with waste operations, the average fissile contents in TRU drums are around 10 grams, the postulation of this fissile over mass scenario is judged to be beyond extremely unlikely (or incredible).

#### 4.2.2 Reflector Over Batch

The drum controls for other 55-gallon drums allow for reflectors. For instance, 120-gram Pu fissile drums are allowed with one of the following:

- 300 grams beryllium, or
- 100 kilograms Nat-U, or
- 8 kilograms carbon/graphite

And 65-gram Pu fissile drums are allowed with all of the following:

- 300 grams beryllium, and
- 100 kilograms Nat-U, and
- 110 kilograms carbon/graphite

Therefore, the possible reflector over batch scenarios for the 200-gram drums may involve the following scenarios based on the available drum control requirements:

1. A drum is over batched with 300 grams beryllium
2. A drum is over batched with 100 kilograms Nat-U
3. A drum is over batched with 8 or 110 kilograms carbon/graphite

However, a reflector over batch of 110 kilograms is not credible for 200-gram drums because this would be a non-compliance for 120-gram drum as well. Based on the fissile content loadings of the RHWM TRU drums, the average fissile loading in a drum is around 10 grams. The majority of the drums only have a few grams of fissile material each. The number of drums falls off rapidly with higher fissile loadings. Therefore, statistically, 110 kilograms carbon/graphite loadings are expected to be more of a compliance problems for 120-drum drums because RHWM are expected to have far more 120-gram drums than 200-gram drums. Any non-compliance on the carbon/graphite content will raise the facility awareness level through corrective actions and lessons learned. Therefore, it is considered incredible for 200-gram drums to have a 110-kilograms carbon/graphite over mass.

Based on the discussions in the above, the credible reflector over batch scenarios for the 200-gram drums will involve are:

a) A drum is over batched with 300 grams beryllium
b) A drum is over batched with 100 kilograms Nat-U
c) A drum is over batched with 8 kilograms carbon/graphite

### 4.2.3 Moderator Over Batch

In this evaluation, optimized moderation has been considered for 200-gram Pu drum storage operations. Therefore, over batch in moderators can only serve to over moderate the fissile material in the drum resulting in deviations from the optimized moderation conditions. In this regard, over batch in moderators will be of no criticality safety concern for 200-gram Pu drum storage operations

### 4.2.4 Loss of Interaction Control

A 30" (or 76 cm) spacing is required between arrays. The credible scenarios for loss of interaction controls are dealing with array spacing not maintained between a 200-gram array and other arrays. The potential loss of interactions controls deal with the following scenarios:

1. Array spacing is not maintained between a 200-gram drum array and another 200-gram drum array.
2. Array spacing is not maintained between a 200-gram drum array and a 120-gram 55-gallon drum or array.
3. Array spacing is not maintained between a 200-gram drum array and a 65-gram 55-gallon drum or array.
4. Array spacing is not maintained between a 200-gram drum array and a 80-gram 30-gallon drum or array.
5. Array spacing is not maintained between a 200-gram drum array and a 40-gram 5-gallon container or array.
6. Array spacing is not maintained between a 200-gram drum array and a 120-gram mixed container or array.
7. Array spacing is not maintained between a 200-gram drum array and a 650-kg Nat-U 55-gallon drum or array.
8. Array spacing is not maintained between a 200-gram drum array and a 210-kg Nat-U 30-gallon drum array.
9. Array spacing is not maintained between a 200-gram drum array and a waiver drum array with excessive amount of beryllium, or graphite.

It should be noted that moving a container through the aisle (or the spacing) between arrays is allowed. It is not considered to be a loss of spacing control.

### 4.2.5 Loss of Stacking Controls

Type A 55-gallon containers maintain their structural integrity with a 4-foot drop. Therefore, 55-gallon drums are limited to 2-high stacking to ensure that the fissionable material content remains confined and segregated in individual drums. However, when steel boxes are constrained, they are allowed to stack 3-high. Therefore, the credible loss of stacking controls scenario deals with a 4-high stacking.

### 4.2.6 Flooding/Moisture/Fire Water

In this upper bound scenario, the 200-gram Pu drum array is fully flooded on the outside. To be conservative, the flood level is assumed to be high enough to provide full reflection from the top of the array. This scenario is regarded as extremely unlikely (or incredible). The flood level needs to be more than 3-drum high to achieve this event. However, this scenario would upper bound all flooding scenarios.

#### 4.2.6.1 Fire Damage and Flooding

The physical consequences of fires may go beyond flooding by firewater. Fire damage to the tank farm may result in tank structural failure and a waste spill.

### 4.2.7 Spills

The credible scenario for a spill deals with the content of a single drum. Therefore, up to 200 grams Pu or the maximum fissile material contents in a single drum are involved in a single spill. It should be noted that multiple spills of drums are considered incredible.

### 4.2.8 Seismic Considerations

RHWM facilities meet the design base earthquake (DBE) with an acceleration of 0.57 g and a frequency of $10^{-3}$/yr. The structural integrity of the RHWM facilities is expected to remain intact for earthquakes with a magnitude up to that of the DBE.

## 4.3 Summary of Normal Operation and Credible Upset Conditions for 200-gram Pu Drum Waste Storage Operations

The normal and credible upset (abnormal) conditions identified in Sections 4.1 and 4.2 are summarized in Table 8.

Table 8. Lists of Normal and Credible Abnormal Conditions

| Event ID | Description of Normal/ Off-Normal Conditions | Contingency Ensuring Criticality Safety |
|---|---|---|
| 1 | Normal Operation: 200-gram Pu drums with no beryllium or carbon/graphite in a storage array. The drums are stacked 3-high. | Fissile Mass, Reflector Controls, Moderator Controls/Optimized Moderation, Array Spacing, Stacking Height, Pu Equivalent |
| 2 | Fissile Over Batch: A single 400-gram Pu drum in a 200-gram Pu drum array. No beryllium and carbon/graphite are in drums. The drums are stacked 3-high | Reflector Controls, Moderator Controls/Optimized Moderation, Array Spacing, Stacking Height, Pu Equivalent |
| 3 | Reflector Over Batch: A single 200-gram Pu drum with 350 grams Be, or 100 kilograms Nat-U, or 8 kilograms C/Graphite in a 200-gram Pu drum array. No beryllium and carbon/graphite are in all other drums. The drums are stacked 3-high | Tank Farm Fissile Mass, Reflector Controls/Full Reflection, Moderator Controls/Optimized Moderation, Array Spacing, Stacking Height, Pu Equivalent |
| 4 | Moderator Over Batch: 200 Pu drum array with each drum filled with unlimited amount of PE or hydrogenous materials superior to water | Fissile Mass, Reflector Controls, Array Spacing, Stacking Height, Pu Equivalent |
| 5 | Loss of Interaction Control: Array spacing of 30" (76 cm) is not maintained | Fissile Mass, Reflector Controls, Moderator Controls/ Optimized Moderation, Stacking Height, Pu Equivalent |
| 6 | Loss of Stacking Control: Stacking limit of 3-high is not maintained. | Fissile Mass, Reflector Controls, Moderator Controls/ Optimized Moderation, Array Spacing, Pu Equivalent |
| 7 | Flooding/Moisture/Fire Water: A 200-gram Pu drum array is submerged in water and is fully reflected from the top. | Fissile Mass, Some of Reflector Controls, Moderator Controls/Optimized Moderation, Array Spacing, Stacking Height, Pu Equivalent |
| 8 | Spills: Spill of the content of a single 200-gram Pu drum | Fissile Mass, Some of Reflector Controls, Moderator Controls/Optimized Moderation, Array Spacing, Stacking Height, Pu Equivalent |
| 9 | Seismic Consideration | Mass Limit, Reflector Controls, Moderator Controls/ Optimized Moderation, Array Spacing, Stacking Height, Pu Equivalent |

The normal and credible upset conditions discussed in Sections 4.1 and 4.2 are the bounding scenarios for the 200-gram drum storage operations because they are very conservative. For instance, a fissile over mass upset would realistically involve only a few tens grams of Pu instead of the full amount of 200 grams because the average fissile content of a RHWM content is around 10 grams. The use of the upper bound scenarios in this evaluation is discussed in Section 3.7.

## 5.0 ANALYSIS

In this evaluation, the analysis is based on the normal operation conditions of a 3-high infinite X-Y array. The upset conditions are but perturbations to the normal 3-high infinite X-Y array. The array behavior automatically bounds the single container behavior. The infinite array is reflected by 40-cm-thick concrete underneath. The infinite array configuration is modeled by using periodic conditions for the X- and Y-directions. The infinite arrays are modeled using unit cells. The unit cells are modeled using the 4-plex nearest corner configuration, which maximize the fissile interaction among the four drums. The 4-plex configuration consists of 4 drums in 2x1x2 formation. The fissile content in these four drums are modeled as spheres, which are placed on the nearest corners to each other. The unit cell of a 3-high configuration consists of a 6-drum formation made of a 4-plex formation in the bottom with the top two drums in a 4-plex formation on the top. And the unit cell of 4-high configuration consists of a 8-drum formation made of two 4-plex formations with one on the top of the other. Detailed modeling of the normal and upset arrays is presented in Appendix A.

**Bounding Scenario 1:** 200-gram Pu drums with neither beryllium nor carbon/graphite in a 3-high infinite X-Y array

Bounding Scenario 1 deals with the normal operation condition for a 200-gram Pu drum array. Each drum in the array contains 200 grams Pu-239. The drums are stacked 3-high in an infinite X-Y array. Parametric studies are performed to investigate the system reactivity of such an array as a function of the Pu volume fraction in the core. The 4-plex configuration with six drums are used as the unit cell. The first model assumes that all drums are filled with regular polyethylene (PE). Variations in the Pu volume fraction cause the variation in size of the Pu core. It should be noted that the plastic waste in RHWM drums are mostly filled with disposed glove, coverall, booties, emptied bottles, and others. These materials have very high porosities even compressed. Therefore, the hydrogen density of the PE waste in RHWM drums is expected to be less than that of water, which has a hydrogen density equivalent to 83% of the fully dense regular PE (0.111 vs. 0.133 g H/cc). Based on this, the second model assumes that all drums are filled with water except for one drum, which remains filled with PE, in the 6-drum formation. The results of the analysis are shown in Table 9 below:

Table 9 $k_{eff}$ values as a function of Pu volume fraction for 55-gallon drums each with a 200-gram Pu core in a 3-high infinite X-Y array with all PE and 1out 6 with PE moderation and reflection from KENO V.a-44-Group calculations.

| Pu VF | Core Volume (CC) | Core Radius (cm) | KENO V.a Result | | | k-effective (k+3σ) | | |
|---|---|---|---|---|---|---|---|---|
| | | | All PE | 1 in 6 PE | All Water | All PE | 1 in 6 PE | All Water |
| 0.10% | 10081 | 13.40088 | 0.9037±0.0013 | 0.8816±0.0012 | 0.8674±0.0015 | 0.9076 | 0.8852 | 0.8719 |
| 0.11% | 9164 | 12.98183 | 0.9169±0.0012 | 0.8922±0.0011 | 0.8758±0.0013 | 0.9205 | 0.8955 | 0.8797 |
| 0.12% | 8401 | 12.61071 | 0.9281±0.0012 | 0.9029±0.0013 | 0.8805±0.0012 | 0.9317 | 0.9068 | 0.8841 |
| 0.13% | 7754 | 12.27870 | 0.9348±0.0012 | 0.9088±0.0013 | 0.8862±0.0013 | 0.9384 | 0.9127 | 0.8901 |
| 0.14% | 7200 | 11.97910 | 0.9419±0.0013 | 0.9132±0.0012 | 0.8885±0.0013 | 0.9458 | 0.9168 | 0.8924 |
| 0.15% | 6720 | 11.70675 | 0.9480±0.0013 | 0.9145±0.0014 | 0.8949±0.0014 | 0.9519 | 0.9187 | 0.8991 |
| 0.16% | 6300 | 11.45759 | 0.9542±0.0013 | 0.9192±0.0012 | 0.8943±0.0012 | 0.9581 | 0.9228 | 0.8979 |
| 0.17% | 5930 | 11.22838 | 0.9561±0.0013 | 0.9226±0.0014 | 0.8933±0.0014 | 0.9600 | 0.9268 | 0.8975 |
| 0.18% | 5600 | 11.01647 | 0.9615±0.0013 | 0.9250±0.0014 | 0.8989±0.0016 | 0.9654 | 0.9292 | 0.9037 |
| 0.19% | 5306 | 10.81971 | 0.9585±0.0013 | 0.9232±0.0016 | 0.8984±0.0014 | 0.9624 | 0.9280 | 0.9026 |
| 0.20% | 5040 | 10.63629 | 0.9638±0.0018 | 0.9282±0.0013 | 0.8955±0.0014 | 0.9692 | 0.9321 | 0.8997 |
| 0.21% | 4800 | 10.46470 | 0.9649±0.0013 | 0.9256±0.0013 | 0.8936±0.0015 | 0.9688 | 0.9295 | 0.8981 |
| 0.22% | 4582 | 10.30368 | 0.9648±0.0016 | 0.9231±0.0014 | 0.8940±0.0014 | 0.9696 | 0.9273 | 0.8982 |
| 0.23% | 4383 | 10.15214 | 0.9634±0.0014 | 0.9191±0.0013 | 0.8919±0.0012 | 0.9676 | 0.9233 | 0.8955 |
| 0.24% | 4200 | 10.00913 | 0.9645±0.0015 | 0.9227±0.0014 | 0.8911±0.0014 | 0.9690 | 0.9269 | 0.8953 |

The bounding normal array storage operation conditions are subcritical because the system k-effective results are below the subcritical limit. Therefore, the normal operation scenario of the 200-gram Pu drum array is criticality safe. It should be noted that when water is used to replace PE in 5 drums and all drums in the six-drum formation, there are drop of 0.04 and 0.07, respectively, in system k-effective values. These configuration are very conservative for RHWM drum storage operations because the hydrogen content in water is 83% of that in PE. In reality, the average hydrogen content in RHWM drums is less than that in water and much less that in PE. Therefore, the realistic bounding system k-effective value for normal 200-gram Pu drum arrays is less than 0.90.

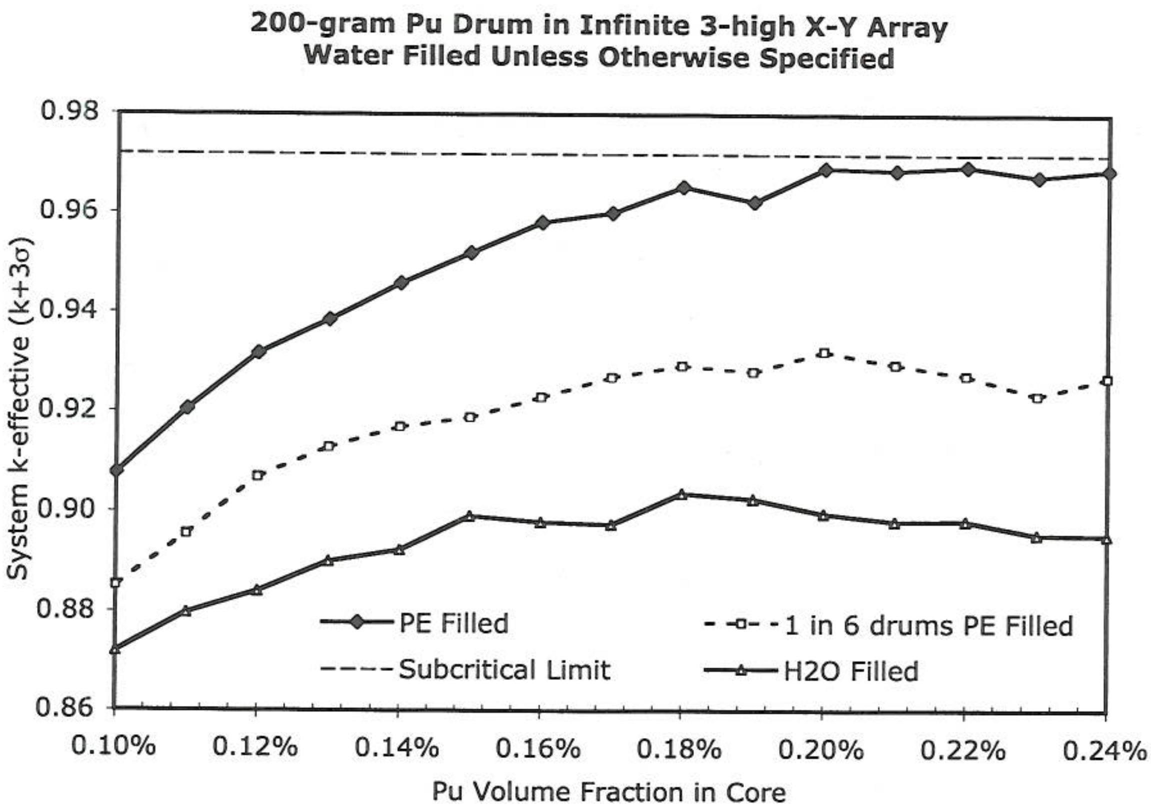



Figure 1. The system k-effective as a function of the Pu VF for PE-only, water-PE and water-only filled arrays using the nearest corner model in the KENO V.a-44 group calculations.

Furthermore, the RHWM wastes are mostly materials contaminated with fissionable materials. This implies that the fissionable materials are mixed with all other waste, instead of being concentrated in a sphere in the nearest corners.

**Bounding Scenario 2:** 400-gram drums mixed with 200-gram Pu drums with neither beryllium nor carbon/graphite in a 3-high infinite X-Y array

Bounding Scenario 2 deals with the fissile over mass operation upset for the 200-gram Pu drum array. One drum in the array contains 400 grams Pu-239. The drums are stacked 3-high in an infinite X-Y array. In infinite array setting, it is not possible to have only one drum over massed with 400-grams Pu. Two six-drum formations are used as the unit cells. One of the six-drum formations consists of 200-gram Pu drums only. The other consists of one 400-gram Pu drum and five 200-gram drums. The two six-drum formations are used to form a super unit cell. The super unit cell consists of a 5x10 formation using one 6-drum formation with a 400-gram Pu drum and forty-nine 6-drum formations with 200-gram Pu drums only. This super unit cell formation ensures that the over mass (400-grams Pu) drums are 9 drums from each other in both the X- and Y-directions and are isolated from each other. In this infinite array, there is an over massed drum in every 300 drums. Six models are considered. The first model has all drums filled with PE. The second model have all drums filled with PE with the consideration of separation between drums because of the use of pallets, which separate the top drums from the bottom drums by 4" (10 cm). The third model has all drums filled with water. The fourth model has all drums filled with PE at 60% density. The fifth model have all drums, except the over massed drums, filled with water. The over massed drums are filled with PE. The sixth model has all drums filled with water, except for one drum filled with PE, in a six-drum formation. Again, the over massed drum is filled with PE.

Also, the 400-gram Pu drums are modeled with two fissile spheres. This is because it is incredible to have the fissile content in a drum concentrated in a sphere. In Appendix C of CSM 1087 Rev. 1 [8], it has been numerically demonstrated that the chance for the fissile content to concentrated in a single Pu sphere is far beyond incredible. The credible scenario is that some of the fissile content will be mixed with the reflectors. Since the fissile materials in the RHWM wastes are primarily in the form of contamination, which is finer than the 10-cm piece assumed in CSM 1087 Rev.1 [8] for the derivation of the distribution of fissile materials in the core and reflectors, it is concluded that 3/5 and 2/5 splits for the core and reflectors are valid for this evaluation. Therefore, of the 400 total Pu grams, 240 grams are in the core and 160 grams are dispersed in the reflectors. To maximize the effect of Pu in the reflectors, the Pu in reflectors are assumed to concentrated in a sphere in contact with the core. In the over massed drum, the core is placed in the nearest corner. The reflector Pu sphere is placed next to it in the drum along the Z direction. The radii of the Pu core and the reflector sphere as a function of the Pu volume fraction are listed in Table 10.

The KENO V.a results are summarized in Table 11 and plotted in Figure 2. All cases except for the first case with 100% dense PE moderation and reflection cases are below the subcritical limit of the KENO V.a/44-group calculations. The first case is not realistic because none of the RHWM drums is filled with 100% dense PE. Even these drums are filled with PE, it is still doubtful that the optimized neutronic condition can be reached. Without the optimized neutronic condition, it will be hard to reach critical conditions. As a matter of fact, when considered the pallets used in RHWM operations, they essentially separate the top two drums from the bottom two drums in a 4-plex configuration by the pallet thickness (height), which is about 4" (10 cm). This allows enough neutrons being absorbed in the moderator, which in this case remains to be the 100% dense PE. However, the peak k-effective value drops to 0.959, which is below the subcritical limit of 0.972.

Table 10. The radii of the Pu core and the reflector sphere as a function of Pu volume fraction for 400-gram Pu drums modeled for KENO V.a-44-Group calculations.

| Pu VF | Core Pu Mass (gram) | Core Volume (CC) | Core Radius (cm) | Reflector Pu Mass (gram) | Reflector Volume (CC) | Reflector Radius (cm) |
|---|---|---|---|---|---|---|
| 0.10% | 240 | 12097 | 14.24056 | 160 | 8065 | 12.44028 |
| 0.11% | 240 | 10997 | 13.79525 | 160 | 7331 | 12.05126 |
| 0.12% | 240 | 10081 | 13.40088 | 160 | 6720 | 11.70675 |
| 0.13% | 240 | 9305 | 13.04806 | 160 | 6203 | 11.39853 |
| 0.14% | 240 | 8641 | 12.72969 | 160 | 5760 | 11.12041 |
| 0.15% | 240 | 8065 | 12.44028 | 160 | 5376 | 10.86758 |
| 0.16% | 240 | 7560 | 12.17551 | 160 | 5040 | 10.63629 |
| 0.17% | 240 | 7116 | 11.93193 | 160 | 4744 | 10.42350 |
| 0.18% | 240 | 6720 | 11.70675 | 160 | 4480 | 10.22679 |
| 0.19% | 240 | 6367 | 11.49765 | 160 | 4244 | 10.04413 |
| 0.20% | 240 | 6048 | 11.30274 | 160 | 4032 | 9.87385 |
| 0.21% | 240 | 5760 | 11.12041 | 160 | 3840 | 9.71457 |
| 0.22% | 240 | 5499 | 10.94930 | 160 | 3666 | 9.56509 |
| 0.23% | 240 | 5259 | 10.78825 | 160 | 3506 | 9.42441 |
| 0.24% | 240 | 5040 | 10.63629 | 160 | 3360 | 9.29165 |

Table 11 $k_{eff}$ values as a function of Pu volume fraction for fissile over mass with 400 grams in 1 out of 300 drums in a 3-high infinite X-Y 200-gram drum array with various configurations from KENO V.a-44-Group calculations.

| Pu VF | 100% Dense PE | 60% Dense PE | Drum Pallet Modeled | DB Drum PE filled | 100% Water Mod/Refl | 1 of 6 Drums PE filled |
|---|---|---|---|---|---|---|
| 0.10% | 0.9203 | 0.7876 | 0.9089 | 0.9145 | 0.8828 | 0.9165 |
| 0.11% | 0.9346 | 0.7902 | 0.9219 | 0.9270 | 0.8959 | 0.9291 |
| 0.12% | 0.9491 | 0.7928 | 0.9348 | 0.9391 | 0.9008 | 0.9403 |
| 0.13% | 0.9564 | 0.7898 | 0.9392 | 0.9495 | 0.9073 | 0.9504 |
| 0.14% | 0.9652 | 0.7931 | 0.9455 | 0.9550 | 0.9113 | 0.9545 |
| 0.15% | 0.9725 | 0.7903 | 0.9496 | 0.9614 | 0.9129 | 0.9566 |
| 0.16% | 0.9761 | 0.7884 | 0.9531 | 0.9619 | 0.9162 | 0.9681 |
| 0.17% | 0.9830 | 0.7862 | 0.9575 | 0.9636 | 0.9178 | 0.9656 |
| 0.18% | 0.9839 | 0.7843 | 0.9552 | 0.9700 | 0.9158 | 0.9705 |
| 0.19% | 0.9836 | 0.7797 | 0.9584 | 0.9712 | 0.9186 | 0.9664 |
| 0.20% | 0.9836 | 0.7765 | 0.9554 | 0.9711 | 0.9188 | 0.9684 |
| 0.21% | 0.9872 | 0.7742 | 0.9601 | 0.9735 | 0.9186 | 0.9681 |
| 0.22% | 0.9792 | 0.7720 | 0.9494 | 0.9618 | 0.9179 | 0.9659 |
| 0.23% | 0.9890 | 0.7634 | 0.9588 | 0.9701 | 0.9167 | 0.9723 |
| 0.24% | 0.9912 | 0.7645 | 0.9549 | 0.9661 | 0.9154 | 0.9704 |

Having the drums moderated and reflected by PE and water combinations also reduces the peak k-effective values to slightly compared to the PE moderated and reflected case. However, when the drums are moderated and reflected by water only, the peak k-effective value significantly drops to 0.919. When the drums are moderated and reflected by 60% dense PE, the peak system k-effective value for the fissile over mass upset is even below 0.80 (or 0.793 to be exact). The 60% dense PE should bound the hydrogenous density in RHWM because the waste drums are filled with plastic materials with high porosity (or low packing factor), such as wraps, emptied plastic bottles, used gloves, and others. Furthermore, based on the average fissile drum loading , which is around 10 grams Pu, for RHWM TRU drums, the expected fissile over mass upset should involve a total fissile mass barely over 200 grams Pu. Also, the fissile contents of most of the containers in the 200-gram Pu drum arrays are less than 200 grams Pu. Based on the above discussions, the fissile over mass upset should have a peak k-effective comfortably below the subcritical limit of 0.972. Therefore, the fissile over mass upset is subcritical and critical safe for RHWM array operations. It is also noted that all TRU drums go through the segmented gamma spectroscopy (SGS), which also known as $\gamma$ scan, to confirm fissile content prior to being accepted by RHWM. Thus, a fissile over mass event with 400 grams Pu total in a drum is extremely unlikely. The scenarios analyzed here are extremely conservative but they are used as bounding scenarios for all of the fissile over mass events.

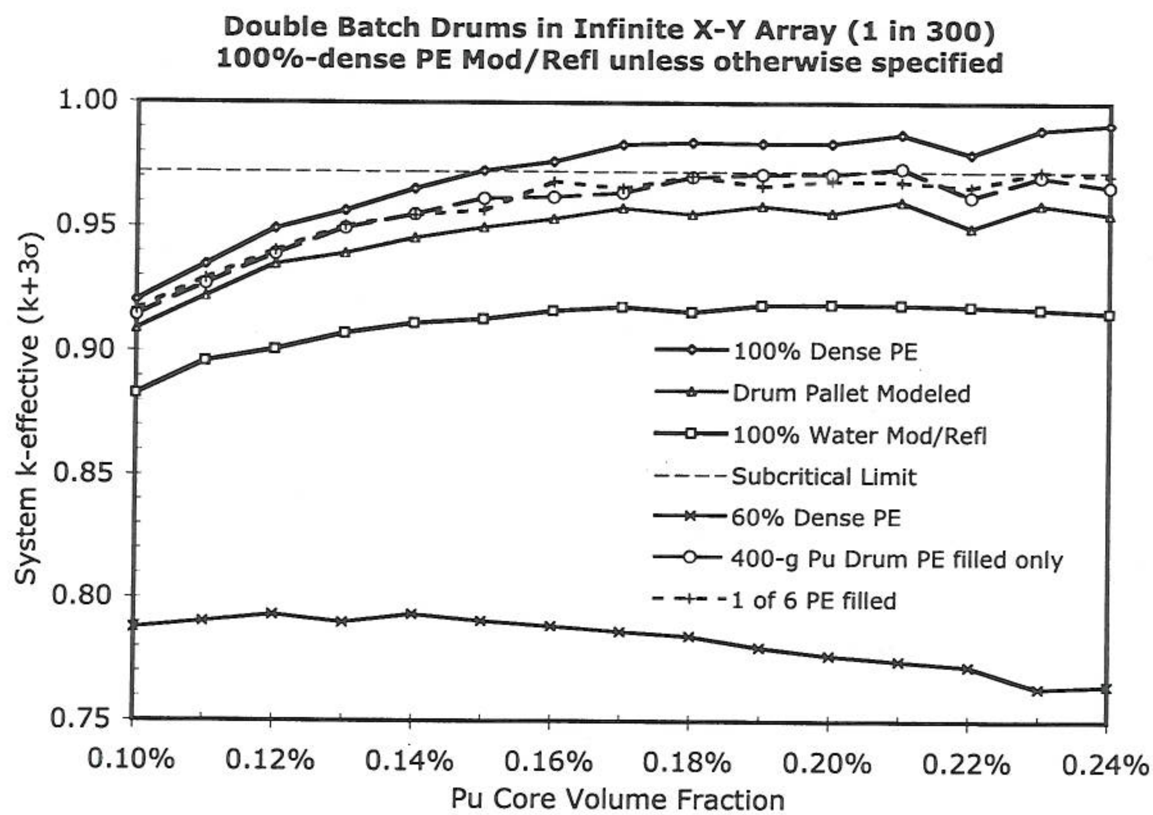



Figure 2. $k_{eff}$ values as a function of Pu volume fraction for fissile over mass with 400 grams in one out of 300 drums in a 3-high infinite X-Y 200-gram drum array with various configurations from KENO V.a-44-Group calculations.

**Bounding Scenario 3:** Reflector over mass in 200-gram Pu drums with neither beryllium nor carbon/graphite in a 3-high infinite X-Y array

As discussed in Section 4.2.2, Bounding Scenario 3 deal with one of the three credible reflector over batch scenarios for the 200-gram drum arrays:

- A drum is over batched with 300 grams beryllium
- A drum is over batched with 100 kilograms Nat-U
- A drum is over batched with 8 kilograms carbon/graphite

It should be noted that there is a 50-gram reflector waiver for RHWM waste drums. For reflector over batch, the 50-gram waiver is included in the beryllium over mass resulting an overpass of 350 grams. This is because the 50-gram waiver is relatively significant compared to the 300-gram beryllium limit. The 50-gram waivers are not included in all other cases. Based on the over mass scenarios above described, the reflector radii for Be, Nat-U and C/graphite are listed in Table 12.

Table 12. The radii of the Pu core and the reflectors as a function of Pu volume fraction for 200 grams Pu. The amount of reflectors are 350 grams, 100 kilograms and 8 kilograms for Be, Nat-U and C/graphite, respectively.

| VF | Core Volume (cc) | Core Radius (cm) | Be Radius (cm) | Nat-U Radius (cm) | C/graphite Radius (cm) |
|---|---|---|---|---|---|
| 0.10% | 10081 | 13.40088 | 13.48420 | 15.41054 | 14.82069 |
| 0.11% | 9164 | 12.98183 | 13.07055 | 15.09713 | 14.48095 |
| 0.12% | 8401 | 12.61071 | 12.70468 | 14.82564 | 14.18514 |
| 0.13% | 7754 | 12.27870 | 12.37775 | 14.58790 | 13.92484 |
| 0.14% | 7200 | 11.97910 | 12.08310 | 14.37777 | 13.69371 |
| 0.15% | 6720 | 11.70675 | 11.81559 | 14.19055 | 13.48689 |
| 0.16% | 6300 | 11.45759 | 11.57115 | 14.02258 | 13.30057 |
| 0.17% | 5930 | 11.22838 | 11.34654 | 13.87096 | 13.13172 |
| 0.18% | 5600 | 11.01647 | 11.13915 | 13.73335 | 12.97790 |
| 0.19% | 5306 | 10.81971 | 10.94681 | 13.60784 | 12.83711 |
| 0.20% | 5040 | 10.63629 | 10.76773 | 13.49287 | 12.70771 |

To assess the effect of reflector over mass for 200 grams Pu, 1-D XSDRNPM/44-group calculations are performed based on the reflector radii for Be, Nat-U, and C/graphite in Table 13. All of the configurations are moderated by PE and reflected by an outer layer of 12" (30-cm) regular PE. As a comparison, the bare core case (with no superior reflector) is included as well. The results from the XSDRNPM calculations are as listed in Table 13 below:

Table 13. The system k-effective values as a function of Pu volume fraction for 200 grams Pu reflected by 350 grams Be, or 100 kilograms Nat-U, or 8 kilograms C/graphite, or no superior reflector from XSDRNPM/44-group calculations

| VF | Be (300g) | Nat-U (100kg) | C/Graphite (8kg) | Reg PE |
|---|---|---|---|---|
| 0.10% | 0.8601 | 0.9126 | 0.9028 | 0.8529 |
| 0.11% | 0.8694 | 0.9215 | 0.9117 | 0.8624 |
| 0.12% | 0.8762 | 0.9280 | 0.9181 | 0.8694 |
| 0.13% | 0.8810 | 0.9325 | 0.9226 | 0.8743 |
| 0.14% | 0.8842 | 0.9355 | 0.9255 | 0.8778 |
| 0.15% | 0.8860 | 0.9372 | 0.9271 | 0.8799 |
| 0.16% | 0.8869 | 0.9378 | 0.9277 | 0.8809 |
| 0.17% | 0.8870 | 0.9377 | 0.9276 | 0.8812 |
| 0.18% | 0.8862 | 0.9369 | 0.9267 | 0.8807 |
| 0.19% | 0.8850 | 0.9356 | 0.9254 | 0.8797 |
| 0.20% | 0.8833 | 0.9338 | 0.9236 | 0.8782 |

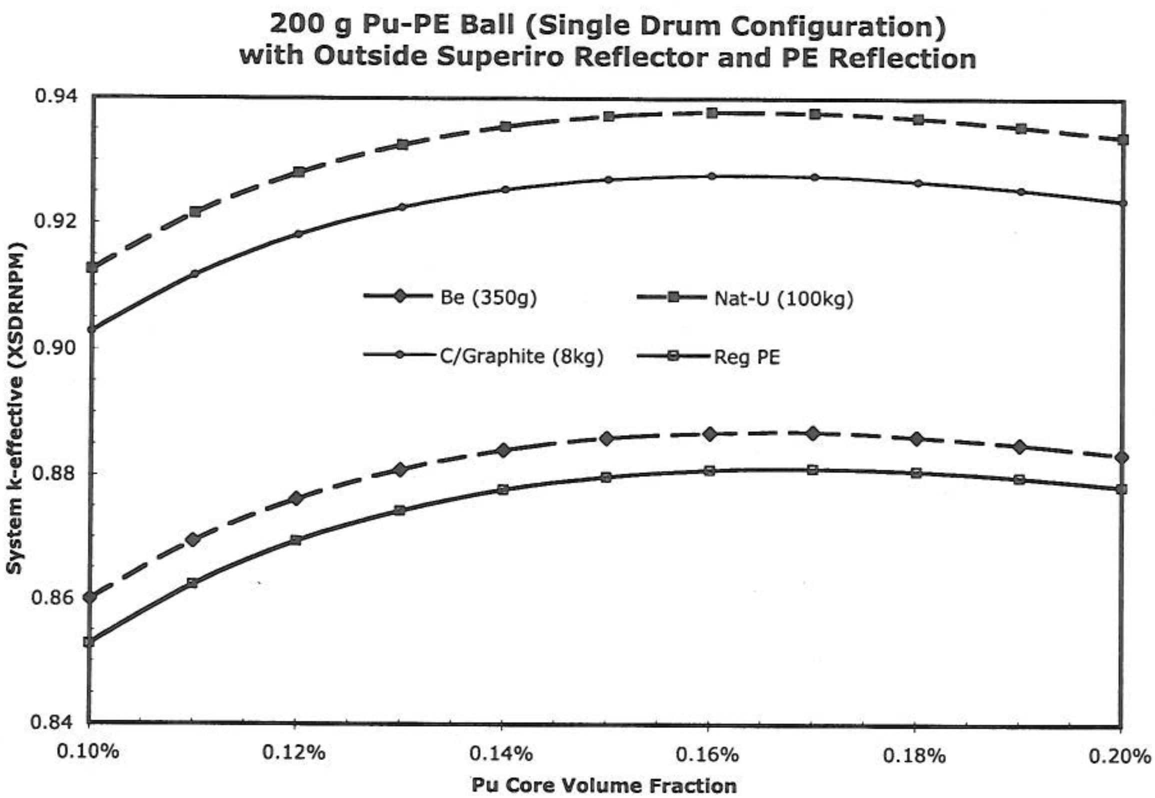



Figure 3. The system k-effective values as a function of Pu volume fraction for 200 grams Pu reflected by 350 grams Be, or 100 kilograms Nat-U, or 8 kilograms C/graphite, or no superior reflector from XSDRNPM/44-group calculations

The results in Table 13 are the bounding effects for the over mass upset in a single isolated container. These results are also plotted in Fig. 3. The Nat-U reflector has the most significant effect on the system k-effective values. It has a peak k-effective value of 0.938 at a Pu volume fraction of 0.16% for a single container. For non-superior reflector reflected container, the peak k-effective value is 0.881 for a Pu volume fraction of 0.19%. For Be and C/graphite reflected cases, their peak values are in between that of the Nat-U reflected case and the no-superior reflector case. The subcritical limit for XSDRNPM is 0.971. Therefore, it is subcritical for the reflector over mass of a single container.

For the effect of reflector over mass on arrays, only the case with 100 kilograms Nat-U is analyzed. The Nat-U case bounds all of the other reflector over mass scenarios. KENO V.a/44-group calculations are performed to analyze the effect on k-effective for the Nat-U case. Since it is not possible to have a single drum with reflector over mass in an infinite X-Y array, one out of 120 drums (20 six-drum formations with one formation having the reflector over mass drum) are modeled to be over massed in 100 kilograms Nat-U. Two cases are analyzed: the first case with all of the drums filled with PE and the second case with one drum out of six filled with PE and the other five filled with water. The KENO V.a results for reflector over mass with 100 kilograms Nat-U are listed in Table 14.

Table 14. The system k-effective values as a function of Pu volume fraction for 1 out of 120 drums being over massed with 100 kilograms Nat-U in a 3-high infinite X-Y array.

| Pu Mass (g) | Pu VF | All drums PE filled | | Every 6 drums, 1 PE filled | | All drum $H_2O$ filled | |
|---|---|---|---|---|---|---|---|
| | | KENO V.a Results | $k_{eff}$ ($k+3\sigma$) | KENO V.a Results | $k_{eff}$ ($k+3\sigma$) | KENO V.a Results | $k_{eff}$ ($k+3\sigma$) |
| 200 | 0.15% | 0.9483±0.0014 | 0.9525 | 0.9471±0.0014 | 0.9513 | 0.8969±0.0013 | 0.9008 |
| 200 | 0.16% | 0.9572±0.0013 | 0.9611 | 0.9481±0.0013 | 0.9520 | 0.8973±0.0014 | 0.9015 |
| 200 | 0.17% | 0.9582±0.0014 | 0.9624 | 0.9482±0.0014 | 0.9524 | 0.8978±0.0015 | 0.9005 |
| 200 | 0.18% | 0.9625±0.0013 | 0.9664 | 0.9475±0.0014 | 0.9517 | 0.8999±0.0013 | 0.9038 |
| 200 | 0.19% | 0.9636±0.0014 | 0.9678 | 0.9473±0.0014 | 0.9515 | 0.8978±0.0013 | 0.9017 |
| 200 | 0.20% | 0.9616±0.0016 | 0.9664 | 0.9452±0.0014 | 0.9494 | 0.8978±0.0017 | 0.9029 |
| 200 | 0.21% | 0.9646±0.0014 | 0.9688 | 0.9430±0.0014 | 0.9472 | 0.8948±0.0014 | 0.8990 |
| 200 | 0.22% | 0.9641±0.0013 | 0.9680 | 0.9394±0.0014 | 0.9436 | 0.8956±0.0014 | 0.8998 |
| 200 | 0.23% | 0.9641±0.0015 | 0.9686 | 0.9408±0.0013 | 0.9447 | 0.8953±0.0012 | 0.8989 |
| 200 | 0.24% | 0.9632±0.0015 | 0.9677 | 0.9377±0.0015 | 0.9422 | 0.8929±0.0016 | 0.8977 |
| 200 | 0.25% | 0.9641±0.0015 | 0.9686 | 0.9363±0.0016 | 0.9411 | 0.8891±0.0014 | 0.8933 |

The peak k-effective values are 0.969, 0.952 and 0.904 for the cases with all drums filled with PE, with one drum out of six filled with PE, and with all drums filled with water, respectively. All peak k-effective values are below the subcritical limit of 0.972 for KENO V.a/44-group calculations. Therefore, this scenario is critical safe. In reality, the average drums in RHWM are filled with hydrogenous materials with density far less than that of PE and water. With the more realistic hydrogen density taken into consideration, it is expected that the peak k-effective values be much less than 0.90. The PE-drum-only results for the reflector over mass upset are compared to the PE-drum-only results for the normal operation condition in Table 9. The reflector-over-mass results are overlapped with the normal operation results with PE filled drums. This is expected because a single over massed container with 100 kilograms Nat-U has a peak k-effective value of 0.938 and only one out of 120 drums is with excess reflectors. Therefore, the reflector over mass has no observable effects on the overall array k-effective values for the PE-drum-only case. On the other hand, when comparing the reflector over mass upset with the normal operation case for arrays with all water drums, the reflector over mass case has a peak k-effective value larger by 0.02. In Figure 4, the reflector over mass upset results are plotted as a function of Pu volume fraction for both PE-drum-only and Water-PE drum arrays. Also for comparison, the normal operation condition results are plotted in Figure 4 for both all PE and all water filled drum arrays as well. Again, the KENO V.a results for the reflector over mass upset are less than the subcritical limit of 0.972. Therefore, this reflector over mass upset scenario is subcritical and criticality safe.

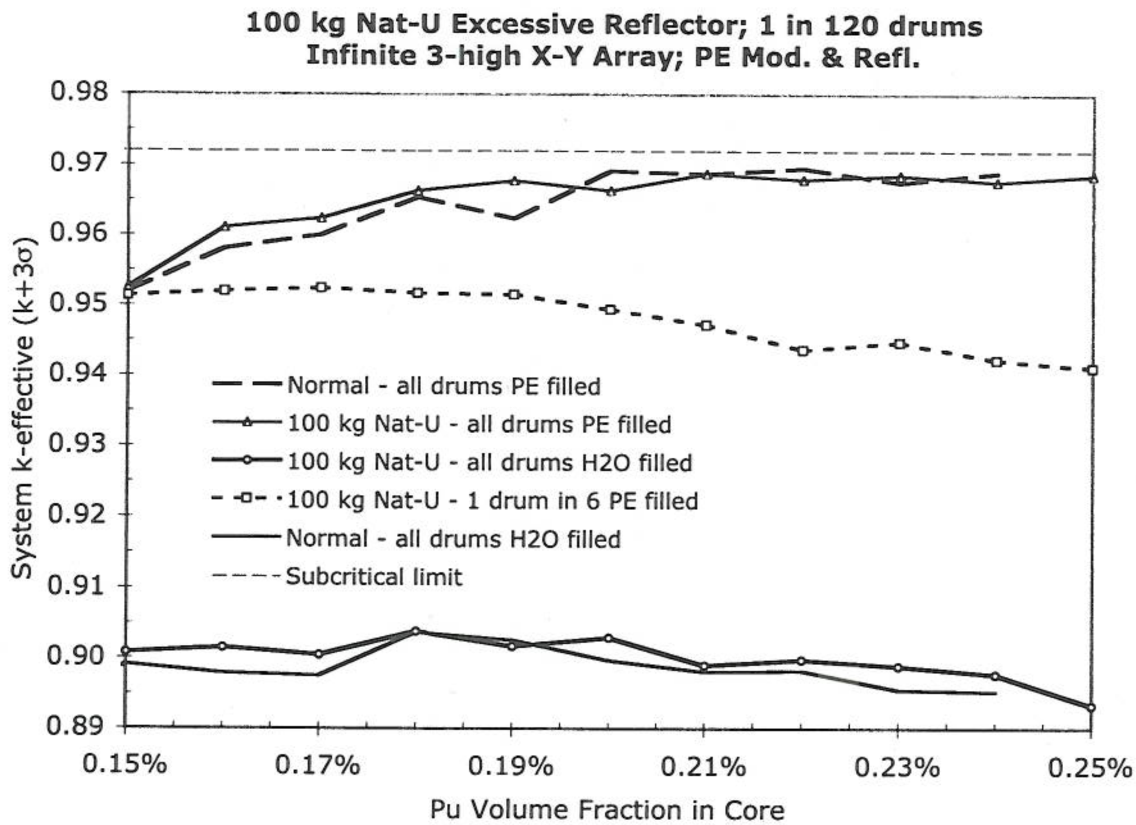



Figure 4. The system k-effective values as a function of the Pu VF for reflector over mass (100 kg Nat-U) with all PE filled, water-PE filled, and all water filled drum arrays from the KENO V.a-44 group calculations. Also, included are the normal operation cases with all PE filled and all water filled cases.

**Bounding Scenario 4:** Moderator over mass in 200-gram Pu drums with neither beryllium nor carbon/graphite in a 3-high infinite X-Y array

In this evaluation, optimized moderation is considered for all analyses. Therefore, an over mass in moderator shift the moderation configuration from the optimal condition to less optimal conditions, which result in lower system k-effective values. The system k-effective values are still bounded by the optimal value, which is bounded by the bounding normal operation scenario or Bounding Scenario 1 discussed earlier. Therefore, this scenario is subcritical and is criticality safe.

**Bounding Scenario 5:** A 200-gram Pu drum array is in contact with another fissionable material container or array with no spacing in between

Based on discussions in Section 4.2.4, the potential loss of interactions controls deal with the following scenarios:

5-1) Array spacing is not maintained between a 200-gram drum array and another 200-gram drum array.
5-2) Array spacing is not maintained between a 200-gram drum array and a 120-gram 55-gallon drum or array.
5-3) Array spacing is not maintained between a 200-gram drum array and a 65-gram 55-gallon drum or array.
5-4) Array spacing is not maintained between a 200-gram drum array and a 80-gram 30-gallon drum or array.
5-5) Array spacing is not maintained between a 200-gram drum array and a 40-gram 5-gallon container or array.
5-6) Array spacing is not maintained between a 200-gram drum array and a 120-gram mixed container or array.
5-7) Array spacing is not maintained between a 200-gram drum array and a 650-kg Nat-U 55-gallon drum or array.
5-8) Array spacing is not maintained between a 200-gram drum array and a 210-kg Nat-U 30-gallon drum array.
5-9) Array spacing is not maintained between a 200-gram drum array and a waiver drum array with excessive amount of beryllium, or graphite.

The 9 upsets dealing this scenario may be further categorized into three groups. Group 1 deals with interaction with fissile drum arrays (Upsets 5-1 through 5-6), Group 2 deals with interaction with Nat-U drum arrays (Upsets 5-7 and 5-8), and Group 3 deals with interaction with reflector drums (Upset 5-9). The analyses will be separately performed based on the group category. The bounding case for the loss of interaction control is the complete loss of the spacing control. Or the 200-gram drum array and other containers and array are in contact with each other.

**Group 1**

Group 1 deals with the interaction of a 200-gram Pu drum array with other fissile drums or arrays. Upset 5-1 deals with the interaction of a 200-gram Pu drum array with other 200-gram Pu drums or another 200-gram Pu drum array. This upset scenario is subcritical because the bounding normal operation condition (Bounding Scenario 1) involves an infinite X-Y array. In this regard, the other containers or other involves in this upset may be considered as part of a 200-gram Pu array. Upsets 5-2 and 5-3 deal with the interaction of a 200-gram Pu array with other containers and arrays of the same drum size (55-gallon drums). Although the other containers/arrays may have less fissionable materials (65 and 120 grams) inside individual drums, further analyses are required because they have superior reflectors inside. Upsets 5-4 and 5-5 deal the interaction of a 200-gram Pu array with other containers and arrays of different container sizes (5- and 30-gallon). Because of the mismatch in container size, it is hard to form the 4-plex nearest corner configuration. Therefore, the interaction between the 5- and 30-gallon drums and the 55-gallon drums are expected to be less. Furthermore, even a 4-plex nearest corner configuration is formed, the fissile materials in the 5- and 30-gallon containers are much less than those in 55-gallon fissile drums of comparable configuration (120 grams Pu vs. 40 and 80 grams Pu for 5- and 30-gallon containers, respectively.) Therefore, the interaction with 5- and 30-gallon containers is expected to be less than the interaction with 55-gallon containers. Upset 5-6 deals with the interaction of a 200-gram Pu drum array with a mix array container or a mix array.

Based on the discussions in the above, Group 1 upsets are consolidated into the following three scenarios:

1. Loss of Interaction with 120-gram 55-gallon drums/arrays with each drum containing 300 grams Be or 100 kilograms Nat-U or 8 kilograms C/graphite.
2. Loss of Interaction with 65-gram 55-gallon drums/arrays with each drum containing 300 grams Be and 100 kilograms Nat-U and 110 kilograms C/graphite.
3. Loss of Interaction with a mix array container with 120 grams Pu and 300 kilograms Nat-U or with a mix array with 120 grams Pu and 1000 kilograms Nat-U.

To reduce the analysis requirement, the first case in the above is to be bounded by having each 120-gram drum with 300 grams Be and 100 kilograms Nat-U and 8 kilograms C/graphite and the third case is to be bounded by a mix array with 120 grams Pu and 1000 kilograms Nat-U in the form of 55-gallon container to maximize interaction. It should be noted that the 50-gram reflector waiver allowance will be added to the Be mass resulting in 350 grams Be total, instead of 300 grams, in the analysis.

The dimensions of the fissile-reflector concentric spheres for 65-gram drums, 120-gram drums, and mix arrays are separately listed in Tables 15-17, respectively. These fissile-reflector concentric spheres are then modeled in the 4-plex nearest corner configuration for KENO V.a/44-group calculations.

Table 15. The radii of 65-gram Pu core, Be, Nat-U and C/graphite as a function of Pu volume fraction for a mixed-reflector 55-gallon container.

| Pu Mass (g) | VF | Pu Core Radius (cm) | Be Mass (g) | Be Radius (cm) | Nat-U Mass (kg) | Nat-U Radius (cm) | C Mass (kg) | C Radius (cm) |
|---|---|---|---|---|---|---|---|---|
| 65 | 0.10% | 9.21357 | 350 | 9.38761 | 100 | 12.76602 | 110 | 23.95818 |
| 65 | 0.11% | 8.92545 | 350 | 9.11057 | 100 | 12.61890 | 110 | 23.91682 |
| 65 | 0.12% | 8.67030 | 350 | 8.86611 | 100 | 12.49362 | 110 | 23.88224 |
| 65 | 0.13% | 8.44203 | 350 | 8.64820 | 100 | 12.38562 | 110 | 23.85290 |
| 65 | 0.14% | 8.23604 | 350 | 8.45226 | 100 | 12.29153 | 110 | 23.82770 |
| 65 | 0.15% | 8.04879 | 350 | 8.27478 | 100 | 12.20880 | 110 | 23.80581 |
| 65 | 0.16% | 7.87749 | 350 | 8.11299 | 100 | 12.13548 | 110 | 23.78663 |
| 65 | 0.17% | 7.71990 | 350 | 7.96467 | 100 | 12.07005 | 110 | 23.76968 |
| 65 | 0.18% | 7.57420 | 350 | 7.82803 | 100 | 12.01128 | 110 | 23.75459 |
| 65 | 0.19% | 7.43892 | 350 | 7.70160 | 100 | 11.95820 | 110 | 23.74107 |
| 65 | 0.20% | 7.31281 | 350 | 7.58415 | 100 | 11.91003 | 110 | 23.72889 |
| 65 | 0.21% | 7.19484 | 350 | 7.47465 | 100 | 11.86611 | 110 | 23.71786 |
| 65 | 0.22% | 7.08414 | 350 | 7.37225 | 100 | 11.82589 | 110 | 23.70783 |
| 65 | 0.23% | 6.97994 | 350 | 7.27621 | 100 | 11.78894 | 110 | 23.69866 |
| 65 | 0.24% | 6.88162 | 350 | 7.18588 | 100 | 11.75486 | 110 | 23.69024 |

Table 16. The radii of 120-gram Pu core, Be, Nat-U and C/graphite as a function of Pu volume fraction for the bounding case of a single-reflector 55-gallon container.

| Pu Mass (g) | VF | Pu Core Radius (cm) | Be Mass (g) | Be Radius (cm) | Nat-U Mass (kg) | Nat-U Radius (cm) | C Mass (kg) | C Radius (cm) |
|---|---|---|---|---|---|---|---|---|
| 120 | 0.10% | 11.30274 | 350 | 11.41938 | 100 | 13.99711 | 8 | 15.31359 |
| 120 | 0.11% | 10.94930 | 350 | 11.07346 | 100 | 13.77011 | 8 | 15.12468 |
| 120 | 0.12% | 10.63629 | 350 | 10.76773 | 100 | 13.57506 | 8 | 14.96357 |
| 120 | 0.13% | 10.35625 | 350 | 10.49476 | 100 | 13.40553 | 8 | 14.82449 |
| 120 | 0.14% | 10.10356 | 350 | 10.24894 | 100 | 13.25672 | 8 | 14.70316 |
| 120 | 0.15% | 9.87385 | 350 | 10.02592 | 100 | 13.12500 | 8 | 14.59637 |
| 120 | 0.16% | 9.66371 | 350 | 9.82230 | 100 | 13.00753 | 8 | 14.50162 |
| 120 | 0.17% | 9.47038 | 350 | 9.63535 | 100 | 12.90210 | 8 | 14.41699 |
| 120 | 0.18% | 9.29165 | 350 | 9.46286 | 100 | 12.80691 | 8 | 14.34091 |
| 120 | 0.19% | 9.12569 | 350 | 9.30301 | 100 | 12.72052 | 8 | 14.27215 |
| 120 | 0.20% | 8.97099 | 350 | 9.15429 | 100 | 12.64175 | 8 | 14.20969 |
| 120 | 0.21% | 8.82627 | 350 | 9.01544 | 100 | 12.56964 | 8 | 14.15271 |
| 120 | 0.22% | 8.69046 | 350 | 8.88540 | 100 | 12.50335 | 8 | 14.10050 |
| 120 | 0.23% | 8.56264 | 350 | 8.76325 | 100 | 12.44220 | 8 | 14.05250 |
| 120 | 0.24% | 8.44203 | 350 | 8.64820 | 100 | 12.38562 | 8 | 14.00820 |

Table 17. The radii of 120-gram Pu core and Nat-U as a function of Pu volume fraction for a mix array in the form of a 55-gallon container.

| Pu Mass (g) | VF | Core Volume (cc) | Radius (cm) | Nat-U Mass (kg) | Nat-U Radius (cm) |
|---|---|---|---|---|---|
| 120 | 0.10% | 6048 | 11.30274 | 1000 | 24.08755 |
| 120 | 0.11% | 5499 | 10.94930 | 1000 | 24.01190 |
| 120 | 0.12% | 5040 | 10.63629 | 1000 | 23.94849 |
| 120 | 0.13% | 4653 | 10.35625 | 1000 | 23.89457 |
| 120 | 0.14% | 4320 | 10.10356 | 1000 | 23.84817 |
| 120 | 0.15% | 4032 | 9.87385 | 1000 | 23.80780 |
| 120 | 0.16% | 3780 | 9.66371 | 1000 | 23.77236 |
| 120 | 0.17% | 3558 | 9.47038 | 1000 | 23.74101 |
| 120 | 0.18% | 3360 | 9.29165 | 1000 | 23.71307 |
| 120 | 0.19% | 3183 | 9.12569 | 1000 | 23.68802 |
| 120 | 0.20% | 3024 | 8.97099 | 1000 | 23.66542 |
| 120 | 0.21% | 2880 | 8.82627 | 1000 | 23.64494 |
| 120 | 0.22% | 2749 | 8.69046 | 1000 | 23.62629 |
| 120 | 0.23% | 2630 | 8.56264 | 1000 | 23.60924 |
| 120 | 0.24% | 2520 | 8.44203 | 1000 | 23.59359 |

For the interaction of 200-gram Pu drums with 65-gram and 120-gram Pu drums, each 6-drum formation consists of three 200-gram Pu drum and three 65-gram Pu drums or 120-gram Pu drums in the modeling of the infinite array. For the interaction of 200-gram Pu drums with a 120-gram Pu mix array, a 6-drum formation consisting of one mix array and five 200-gram Pu drums is used. This 6-drum formation is then mixed with 49 regular 6-drum formations with 200-gram Pu drums only to form a super unit cell a 5x10 formation. This ensures that the mix array drums are isolated from each other by 9 drums in both X- and Y-direction. The infinite array for interaction with the mix array is based on this super unit cell. Therefore, half of the drums are 65-gram or 120-gram containers in the interacting infinite arrays while only one out of 300 is a mix array in the associated infinite array. The reason for disparity in the numbers between 65- and 120-gram drum and the mix array in the infinite array lies with the fact that there are far more 65- and 120-gram containers and arrays compared to mix array and mix array containers at RHWM facilities. Also, all drums are filled with 100% dense PE.

The KENO V.a results are as listed in Table 18. Also, included in Table 18 are the normal operation results from the infinite arrays with 200-gram Pu drums only and because these results bound the interaction between 200-gram Pu drum arrays.

Table 18. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with 120-gram Pu drum arrays, 65-gram Pu drum arrays, 120-gram mix arrays, and other 200-gram Pu drum arrays from KENO V.a/44-group calculations.

| Pu VF | 120-g Pu Drums | 65-g Pu Drums | 120-g Pu Mix Array | 200-g Pu PE Drums Only | 200-g Pu $H_2O$-PE* Drums | 200-g Pu $H_2O$ Drums |
|---|---|---|---|---|---|---|
| 0.10% | 0.9023 | 0.8811 | 0.9050 | 0.9076 | 0.8852 | 0.8719 |
| 0.11% | 0.9094 | 0.8896 | 0.9198 | 0.9205 | 0.8955 | 0.8797 |
| 0.12% | 0.9179 | 0.8992 | 0.9289 | 0.9317 | 0.9068 | 0.8841 |
| 0.13% | 0.9243 | 0.9061 | 0.9408 | 0.9384 | 0.9127 | 0.8901 |
| 0.14% | 0.9259 | 0.9102 | 0.9423 | 0.9458 | 0.9168 | 0.8924 |
| 0.15% | 0.9332 | 0.9141 | 0.9536 | 0.9519 | 0.9187 | 0.8991 |
| 0.16% | 0.9328 | 0.9181 | 0.9589 | 0.9581 | 0.9228 | 0.8979 |
| 0.17% | 0.9349 | 0.9212 | 0.9590 | 0.9600 | 0.9268 | 0.8975 |
| 0.18% | 0.9365 | 0.9176 | 0.9648 | 0.9654 | 0.9292 | 0.9037 |
| 0.19% | 0.9372 | 0.9185 | 0.9664 | 0.9624 | 0.9280 | 0.9026 |
| 0.20% | 0.9346 | 0.9211 | 0.9657 | 0.9692 | 0.9321 | 0.8997 |
| 0.21% | 0.9347 | 0.9207 | 0.9657 | 0.9688 | 0.9295 | 0.8981 |
| 0.22% | 0.9341 | 0.9170 | 0.9701 | 0.9696 | 0.9273 | 0.8982 |
| 0.23% | 0.9344 | 0.9179 | 0.9688 | 0.9676 | 0.9233 | 0.8955 |
| 0.24% | 0.9325 | 0.9156 | 0.9677 | 0.9690 | 0.9269 | 0.8953 |

* Of every six drums in the array, one is filled with PE and the other five are filled with water.

All of the Group 1 results are below the subcritical limit of 0.972 for KENO V.a/44-group calculations. Therefore, these scenarios are subcritical and criticality safe. It should be noted that in realistic RHWM applications, the hydrogen density of the hydrogenous materials in waste drums is much less than that of 100% dense PE due to the packing factor. Furthermore, Pu contents are relatively more uniformly distributed throughout the waste drums, instead of having all of the fissile materials inside being conservatively modeled as a sphere as used in this evaluation. When factoring this into considerations, the results should be around 0.90 or less. This would ensure that the loss of interaction control upsets with other fissile containers/arrays in 200-gram Pu drum array operations are subcritical and criticality safe.

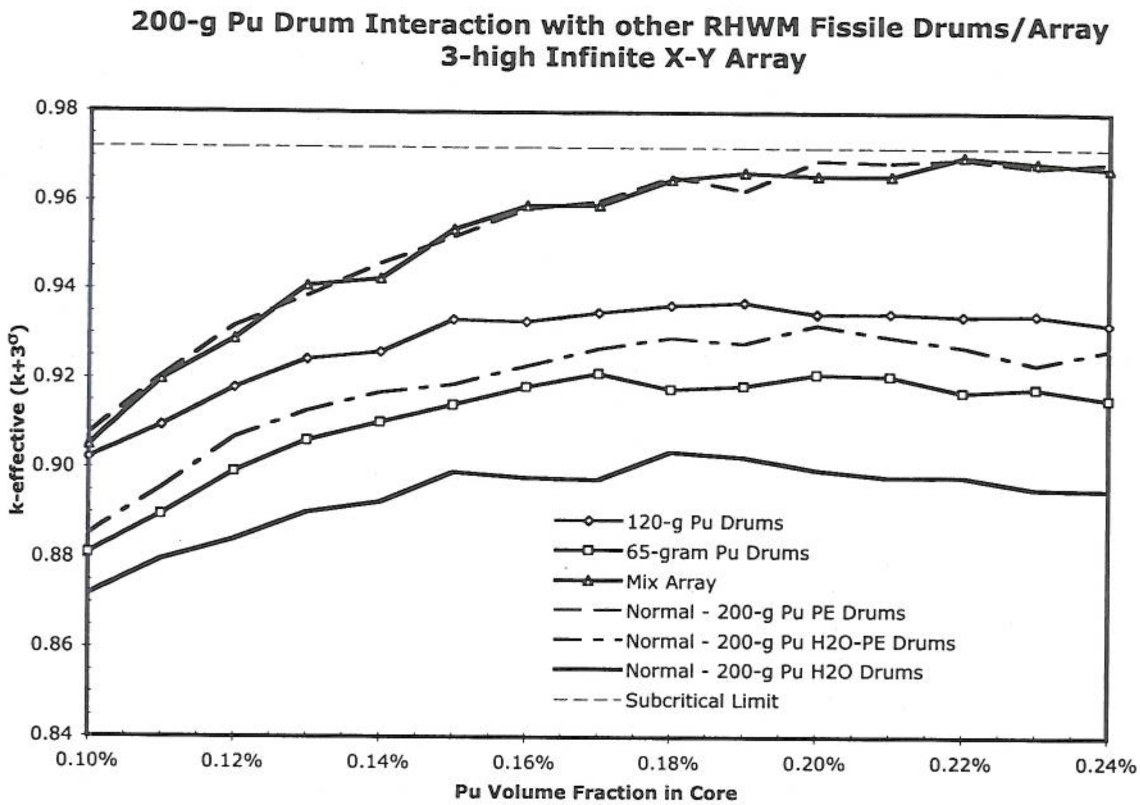



Figure 5. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with 120-gram Pu drum arrays, 65-gram Pu drum arrays, mix arrays, and other 200-gram Pu drum arrays from KENO V.a/44-group calculations.

**Group 2**

Group 2 deals with the interaction of a 200-gram Pu drum array with Nat-U drums. Upset 5-7 deals with the interaction of a 200-gram Pu drum array with other Nat-U containers and arrays of the same drum size (55-gallon drums). Upsets 5-8 deals the interaction of a 200-gram Pu array with other containers and arrays of different container sizes (30-gallon). Because of the mismatch in container size, it is hard to form the 4-plex nearest corner configuration with 30-gallon drums.

To bound the interaction of 200-gram Pu drum array with Nat-U drums, latticed Nat-U structures are used. In CSM 1034, it has been derived that the optimized lattice drum conditions based on the RHWM Nat-U drum controls are as listed in Table 19 below:

Table 19. The optimized Nat-U lattice in a PE/Superla matrix for 30-gallon and 55-gallon RHWM Nat-U drum (the information are from CSM 1034 Table A.2 [10])

| Optimized Conditions | 30-gallon Nat-U Drums | 55-gallon Nat-U Drums |
|---|---|---|
| Nat-U Mass (kg/drum) | 210 | 650 |
| Lattice Pitch (cm) | 8.27871 | 5.63586 |
| Rod Diameter (cm) | 2.6 | 2.4 |
| PE or Superla Density (g/cc) | 0.129 | 0.258 |
| k-infinity | 0.9858 | 0.9816 |

Superla in the above table refers to the Superla White Mineral Oil. It has the same chemical compositions as PE, but with a lower density (0.86 g/cc compared to PE density of 0.923 g/cc). It should be noted that the optimized moderator (PE & Superla) density is very low, 0.129 and 0.258 g/cc for 30- and 55-gallon drums. Full-density PE or Superla will cause neutrons being severely over-moderated resulting in lower system k-effective values and safer configurations. Because of the low PE& Superla density, neutron leakage is large. Therefore, these optimized condition may not result in the most conservative estimation on the loss of interaction control upset. In this regards, other denser Nat-U configurations need to be considered. For Nat-U homogeneously mixed with full-density PE, the k-infinity value is 0.8849 with a Pu volume fraction of 0.3219, which corresponding to Nat-U double batch with 1300 kilograms each 55-gallon drum as from CSM 1309 Table 1 [11]. This configuration conservatively bounds the single batch configuration for typical RHWM operations.

Table 20. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with optimized 55- and 30-gallon drums, homogenized Nat-U/PE drums, solid Nat-U drums and 200-gram PE drum array moderated by PE and Water from KENO V.a/44-group calculations.

| Pu VF | 55-gallon latticed Nat-U Drums | 30-gallon latticed Nat-U Drums | Homogenized Nat-U/PE | Solid Nat-U |
|---|---|---|---|---|
| 0.15% | 0.9258 | 0.9208 | 0.9296 | 0.9345 |
| 0.16% | 0.9280 | 0.9180 | 0.9314 | 0.9364 |
| 0.17% | 0.9255 | 0.9216 | 0.9306 | 0.9401 |
| 0.18% | 0.9322 | 0.9219 | 0.9300 | 0.9417 |
| 0.19% | 0.9302 | 0.9241 | 0.9348 | 0.9435 |
| 0.20% | 0.9305 | 0.9264 | 0.9333 | 0.9436 |
| 0.21% | 0.9302 | 0.9201 | 0.9324 | 0.9418 |
| 0.22% | 0.9322 | 0.9196 | 0.9368 | 0.9378 |
| 0.23% | 0.9275 | 0.9204 | 0.9356 | 0.9400 |
| 0.24% | 0.9251 | 0.9183 | 0.9352 | 0.9414 |

* Of every six drums in the array, one is filled with PE and the other five are filled with water.

The other configuration considered is with the Nat-U drum filled with uranium, which corresponds to 4000 kilograms per 55-gallon drum. Again, this case also conservatively bounds the typical RHWM Nat-U drum storage operations. Again, half of the drums in the 6-drum unit cell are Nat-U

drums. Therefore, half of the drums in the 3-high infinite X-Y array are Nat-U drums. The rest of the drums are, of course, the 200-gram Pu drums, which are filled with full-density PE. Also, to simplify the analysis on loss of control for 30-gallon Nat-U drums, 55-gallon drums are used but with the content corresponding to the optimized lattice structure for 30-gallon drums.
The KENO V.a results are listed in Table 20 and plotted in Fig. 6.

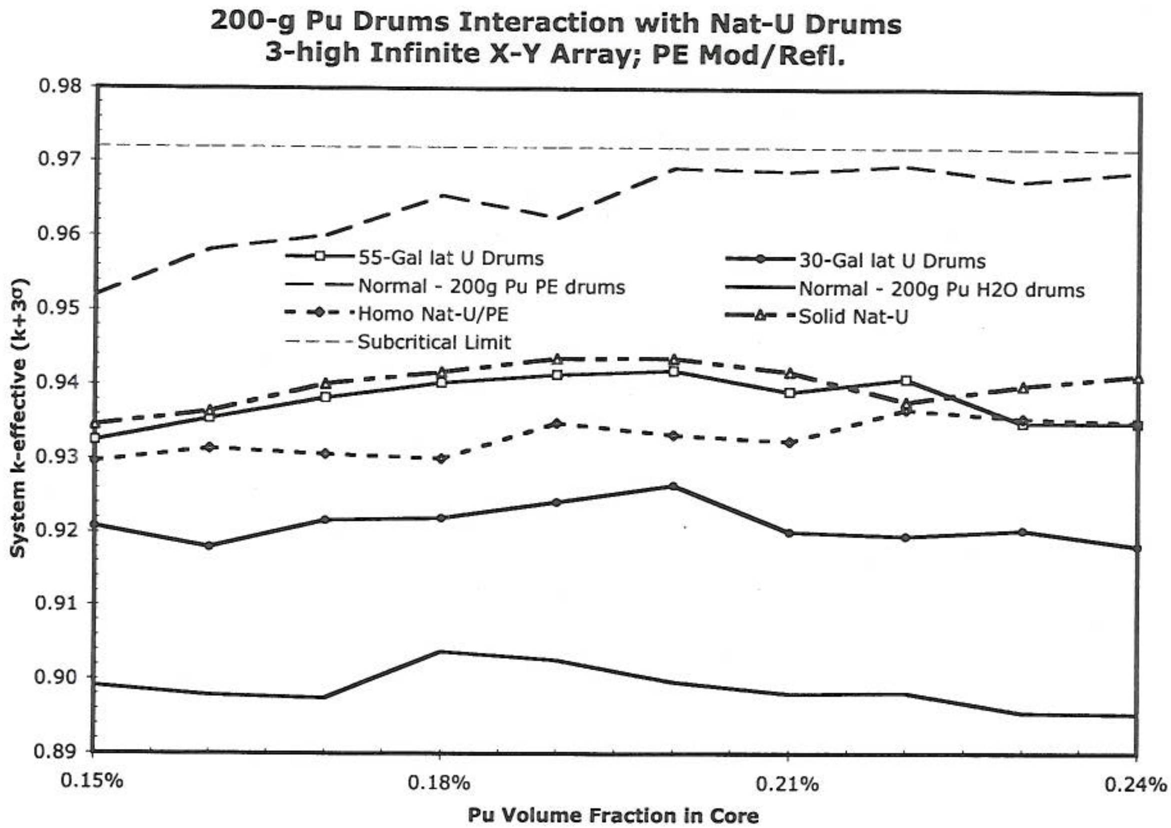



Figure 6. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with optimized 55- and 30-gallon drums, homogenized Nat-U/PE drums, solid Nat-U drums and 200-gram PE drum array moderated by PE and Water from KENO V.a/44-group calculations.

The KENO V.a results are less than the subcritical limit of 0.972. Therefore, these upset events are subcritical and criticality safe. The peak k-effective value on the interaction of 200-gram Pu drum array with RHWM Nat-U drums or arrays is 0.944 for solid uranium drums, which contain 6 times of the allowable amount of 650 kilograms. The next most reactive configuration deals with the homogenized Pu/PE drums, which have a peak k-effective value of 0.942. However, these homogenized drums contain twice of the allowable Nat-U amount. Furthermore, the 200-gram Pu drums are filled with full-density PE. Factoring in the actual hydrogenous density in the RHWM waste streams, the peak k-effective value should be dropped to about 0.90 or less.

**Group 3**

Group 3 deals with the interaction of a 200-gram Pu drum array with Nat-U drums. Upset 5-9 deals with the interaction of a 200-gram Pu drum array with reflector containers with large amounts of Be and C/graphite. To maximize the loss of control effect, 55-gallon reflector drums are used. The 3-high infinite X-Y array is analyzed. The 6-drum unit cell included three 200-gram Pu drums and three Be or C/graphite drums. The KENO V.a results are listed in Table 21.

Table 21. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with reflector drums and arrays from KENO V.a/44-group calculations.

| Pu VF | Solid Beryllium Reflector | | Solid Carbon/Graphite Reflector | |
|---|---|---|---|---|
| | KENO V.a Results | $k_{eff}$ (k+3σ) | KENO V.a Results | $k_{eff}$ (k+3σ) |
| 0.15% | 0.9202±0.0012 | 0.9238 | 0.9183±0.0015 | 0.9228 |
| 0.16% | 0.9239±0.0014 | 0.9281 | 0.9237±0.0012 | 0.9273 |
| 0.17% | 0.9220±0.0014 | 0.9262 | 0.9238±0.0015 | 0.9283 |
| 0.18% | 0.9251±0.0015 | 0.9296 | 0.9211±0.0014 | 0.9253 |
| 0.19% | 0.9240±0.0013 | 0.9279 | 0.9264±0.0014 | 0.9306 |
| 0.20% | 0.9261±0.0015 | 0.9306 | 0.9241±0.0013 | 0.9280 |
| 0.21% | 0.9232±0.0017 | 0.9283 | 0.9212±0.0015 | 0.9257 |
| 0.22% | 0.9252±0.0019 | 0.9309 | 0.9214±0.0014 | 0.9256 |
| 0.23% | 0.9254±0.0014 | 0.9296 | 0.9214±0.0014 | 0.9256 |
| 0.24% | 0.9213±0.0014 | 0.9255 | 0.9202±0.0015 | 0.9247 |

In Figure 7, as a comparison, the Be and C/graphite reflector drum results from the KENO V.a calculations are plotted with the Table 9 results from the dry normal operation conditions, 1) all drums are filled with full-density PE and 2) one sixth of the drums are filled with PE and the rest with water.

The KENO V.a Be and C/graphite reflector drum results are less than the subcritical limit of 0.972. Therefore, these upset events are subcritical and criticality safe. The peak k-effective value on the interaction of 200-gram Pu drum array with RHWM reflector drums or arrays is 0.931. Furthermore, the 200-gram Pu drums are filled with full-density PE. Factoring in the actual hydrogenous density in the RHWM waste streams, the peak k-effective value should be dropped to about 0.90 or less.

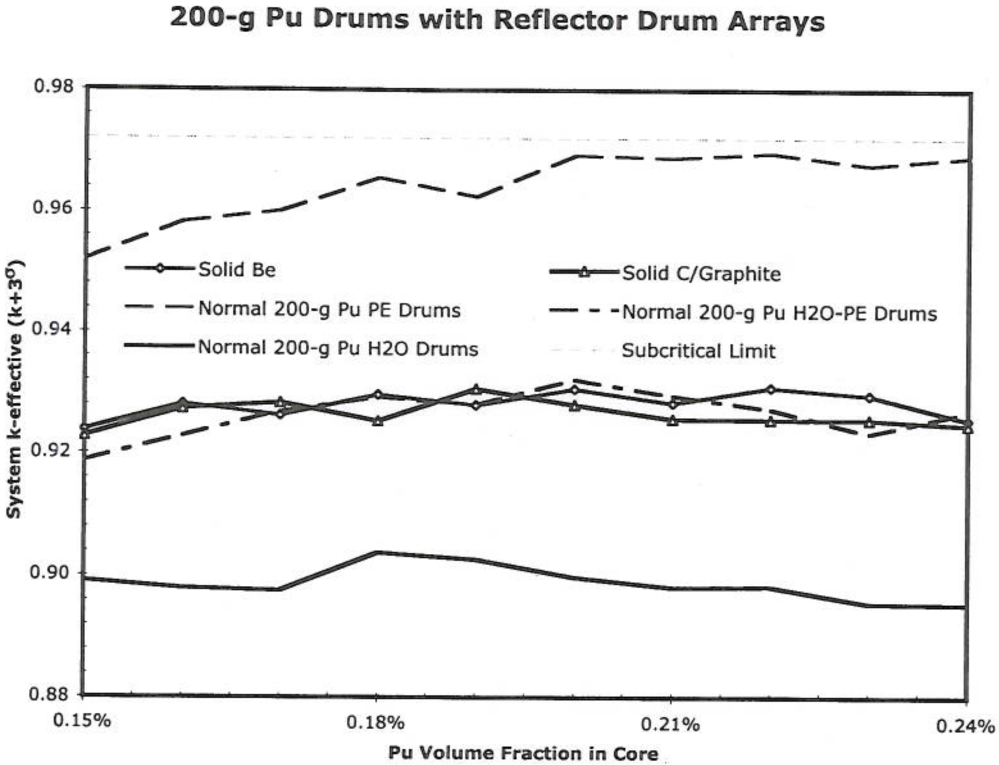



Figure 7. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with reflector drums and arrays from KENO V.a/44-group calculations.

*Conclusion on Bounding Scenario 5: Loss of Interaction Controls*

All upset scenarios in Groups 1-3 are subcritical. Therefore, the loss of interaction controls is criticality safe for 200-gram Pu drum array operations.

**Bounding Scenario 6:** Loss of Stacking Controls – the drums in an infinite X-Y 200-gram Pu drum array are stacked with 4-high, instead of 3-high.

This bounding upset scenario deals with an infinite X-Y array composed of 200-gram Pu drums. The only deviation from the bounding normal operation condition is that the drums are stacked 4-high, instead of 3-high. The analysis is based on a 8-drum configuration made of two 4-plex formations, with one on top of the other. One drum in the 4-plex formation is filled with PE and the others are filled with water. Therefore, one in every four drums is filled with PE. The results from the KENO V.a calculations are listed in Table 22 and plotted in Figure 8. In Figure 8, the KENO V.a 4-high stacking results, as a comparison, are plotted with the Table 9 results from the dry normal operation conditions, 1) all drums are filled with full-density PE and 2) one sixth of the drums are filled with PE and the rest with water.

Table 22. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with 4-high stacking and 3-high stacking from KENO V.a/44-group calculations.

| | 4-high<br>1 Drum in 6 PE Filled | | 4-high<br>All Drums Water Filled | |
|---|---|---|---|---|
| Pu VF | KENO V.a Results | $k_{eff}$ (k+3σ) | KENO V.a Results | $k_{eff}$ (k+3σ) |
| 0.10% | 0.8820±0.0012 | 0.8856 | 0.8652±0.0013 | 0.8691 |
| 0.11% | 0.8943±0.0015 | 0.8988 | 0.8756±0.0012 | 0.8792 |
| 0.12% | 0.9044±0.0014 | 0.9086 | 0.8809±0.0012 | 0.8845 |
| 0.13% | 0.9097±0.0012 | 0.9133 | 0.8875±0.0015 | 0.8920 |
| 0.14% | 0.9153±0.0013 | 0.9192 | 0.8900±0.0014 | 0.8942 |
| 0.15% | 0.9166±0.0013 | 0.9205 | 0.8961±0.0013 | 0.9000 |
| 0.16% | 0.9242±0.0013 | 0.9281 | 0.8959±0.0016 | 0.9007 |
| 0.17% | 0.9262±0.0013 | 0.9301 | 0.8969±0.0013 | 0.9008 |
| 0.18% | 0.9257±0.0015 | 0.9302 | 0.8977±0.0016 | 0.9025 |
| 0.19% | 0.9268±0.0014 | 0.9310 | 0.8990±0.0013 | 0.9029 |
| 0.20% | 0.9239±0.0014 | 0.9281 | 0.8966±0.0016 | 0.9014 |
| 0.21% | 0.9254±0.0014 | 0.9296 | 0.8972±0.0015 | 0.9017 |
| 0.22% | 0.9248±0.0014 | 0.9290 | 0.8961±0.0015 | 0.9006 |
| 0.23% | 0.9258±0.0014 | 0.9300 | 0.8901±0.0013 | 0.8940 |
| 0.24% | 0.9235±0.0014 | 0.9277 | 0.8916±0.0015 | 0.8961 |

The results show that the upset with 4-high stacking has a peak k-effective value of 0.931 and 0.903 fro water-PE and water-only filled drum cases, respectively. Both peak values are less than the subcritical limit of 0.972 for KENO V.a/44-group calculations. Therefore, this 4-high stacking upset scenario is subcritical safe. It should be noted that in realistic RHWM waste storage operations, the hydrogen density would be much less than 100% dense PE or water. Therefore, under realistic conditions, the actual peak k-effective value would be much less than 0.90.

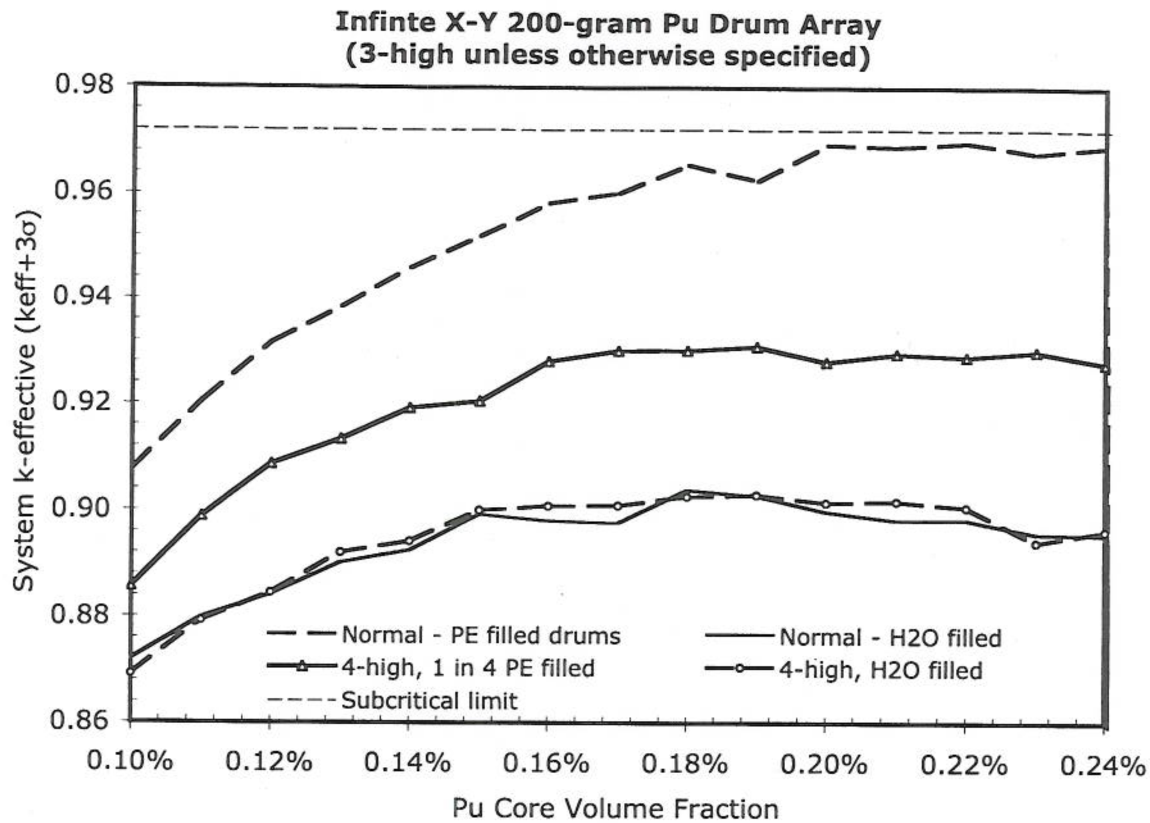



Figure 8. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with 4-high stacking and 3-high stacking from KENO V.a/44-group calculations.

**Bounding Scenario 7:** Flooding –an infinite 3-high X-Y 200-gram Pu drum array is flooded with full water reflection on the top of the array

This bounding upset scenario deals with an infinite X-Y array composed of 200-gram Pu drums. The only deviation from the bounding normal operation condition is that the array is flooded with water completely. Furthermore, there is full water reflection on the top of the array. This upset condition bounds all scenarios from the floods, rain, and firewater. It should be noted that all RHWM facilities are above the 500-year flood level. Therefore, the actual flooding situations are expected to be less severe compared to the bounding flooding scenario. The analysis is based on a 6-drum configuration with one drum filled with PE and the rest filled with water. Therefore, one in every six drums is filled with PE. The results from the KENO V.a calculations are listed in Table 23 and plotted in Figure 9.

Table 23. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with a flood from KENO V.a/44-group calculations.

| | Flooded 1 Drum in 6 PE Filled | | Flooded all Drums Water Filled | |
|---|---|---|---|---|
| Pu VF | KENO V.a Results | $k_{eff}$ (k+3σ) | KENO V.a Results | $k_{eff}$ (k+3σ) |
| 0.10% | 0.8820±0.0012 | 0.8856 | 0.8651±0.0013 | 0.8690 |
| 0.11% | 0.8834±0.0012 | 0.8870 | 0.8758±0.0012 | 0.8794 |
| 0.12% | 0.9044±0.0013 | 0.9083 | 0.8839±0.0012 | 0.8875 |
| 0.13% | 0.9087±0.0015 | 0.9132 | 0.8883±0.0012 | 0.8919 |
| 0.14% | 0.9158±0.0013 | 0.9197 | 0.8891±0.0011 | 0.8924 |
| 0.15% | 0.9179±0.0013 | 0.9218 | 0.8954±0.0014 | 0.8996 |
| 0.16% | 0.9252±0.0014 | 0.9294 | 0.8987±0.0014 | 0.9029 |
| 0.17% | 0.9261±0.0012 | 0.9297 | 0.8978±0.0014 | 0.9020 |
| 0.18% | 0.9292±0.0012 | 0.9328 | 0.8996±0.0014 | 0.9038 |
| 0.19% | 0.9279±0.0014 | 0.9321 | 0.9015±0.0015 | 0.9060 |
| 0.20% | 0.9274±0.0013 | 0.9313 | 0.8996±0.0014 | 0.9038 |
| 0.21% | 0.9314±0.0015 | 0.9359 | 0.9011±0.0014 | 0.9053 |
| 0.22% | 0.9266±0.0015 | 0.9311 | 0.8989±0.0017 | 0.9040 |
| 0.23% | 0.9276±0.0015 | 0.9321 | 0.8982±0.0014 | 0.9024 |
| 0.24% | 0.9270±0.0014 | 0.9312 | 0.8967±0.0014 | 0.9009 |

In Figure 9, the KENO V.a flooding results, as a comparison, are plotted with the Table 9 results from the dry normal operation conditions, 1) all drums are filled with full-density PE and 2) one sixth of the drums are filled with PE and the rest with water.

The flooding results show that the upset with 4-high stacking has a peak k-effective value of 0.936 and 906 for water-PE and water-only filled drum cases, respectively. Both peak values are less than the subcritical limit of 0.972 for KENO V.a/44-group calculations. Therefore, these 4-high stacking upset scenarios are subcritical and criticality safe. It should be noted that in realistic RHWM waste storage operations, the hydrogen density would be much less than 100% dense PE or water. Therefore, under realistic conditions, the peak k-effective value would be much less than 0.90.

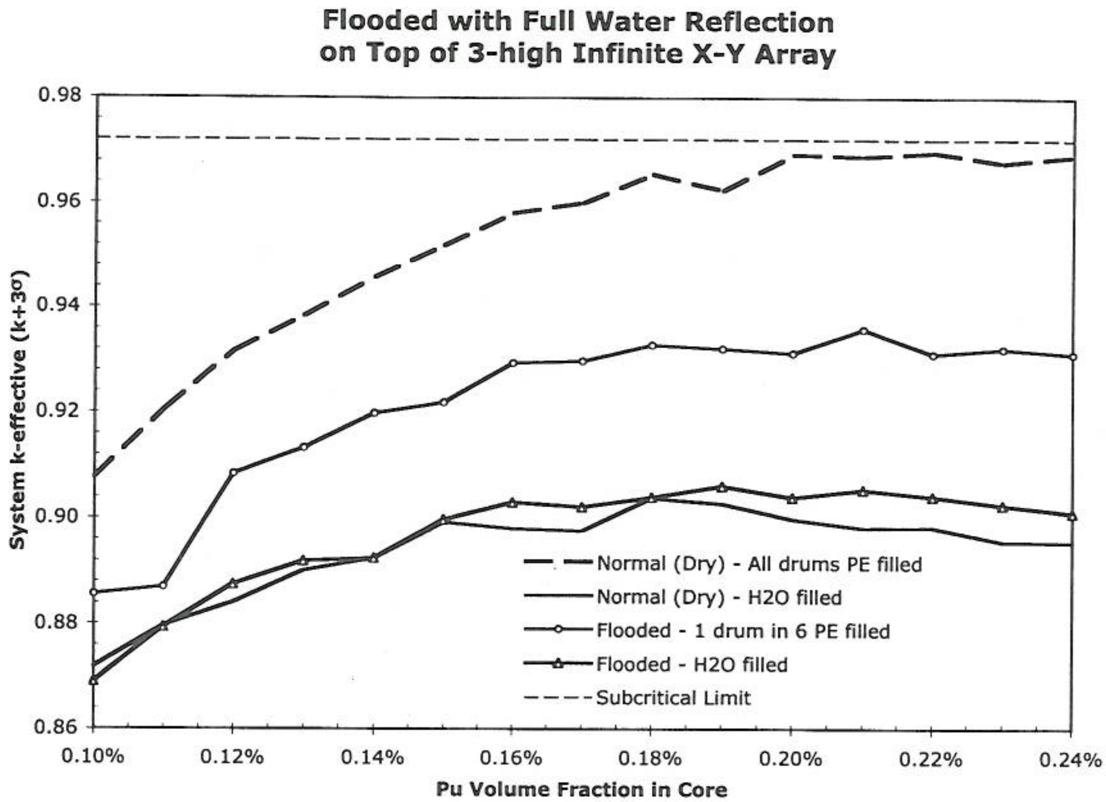



Figure 9. The system k-effective values as a function of Pu volume fraction for the interaction of 200-gram Pu drum arrays with flooding and dry (normal operation) conditions from KENO V.a/44-group calculations.

Fire may cause additional damage to drums resulting in spills. However, the fire loadings in RHWM facilities are minimized, in particular, near the TRU drum storage. The presence of fire sprinkler systems is also expected to reduce the fire damage. Fire alarms would alert RHWM and the on-site Fire House to respond to the fire events. Furthermore, RHWH personnel may fight the fire with fire extinguisher and firemen may provide additional fire fighting capability. Therefore, it is expected that only the contents of few drums would be affected. Typical 200-gram Pu containers have a fissile material density on the order of 1 gram/liter. Firewater is expected to disperse the fissile material further. ANSI/ANS8.1-1998 [5] has a subcritical fissile concentration limit of 7.5 grams/liter for Pu. Therefore, fire damage to drums is expected to be criticality safe as well.

**Bounding Scenario 8:** Spills

Multiple spills are not credible because RHWM procedure requires that the spills be cleaned up. Therefore, the credible scenario dealing with this upset condition is the single drum spill. When a 200-gram Pu drum is spilled, the maximum amount of fissile that could be involved is 200 grams. Based on ANSI/ANS8.1-1998 [5], the minimum critical mass for a Pu-water mixture is 450 grams.

Therefore, the amount of fissile material involved is less than 0.45 of a subcritical mass with water moderation and reflection. With concrete reflection in the sumps, the critical mass is expected to be 10% less with close fitting reflection (Page 80, Nuclear Criticality Safety Guide, LA-12808 [12]). This increases the amount of fissile involved to slightly less than 50% of the subcritical mass with water based system. With PE, the critical mass is 300 grams Pu as determined by Heinrichs in CSM 936A [13], 200 grams Pu are 0.67 of the critical mass. All of the situations discussed involve fissile material mass less that that of a critical mass. Therefore, this upset scenario remains subcritical and is criticality safe.

**Bounding Scenario 9:** Seismic Consideration

All RHWM facilities are designed meeting the PC-2 criteria, which include a design base earthquake (DBE) with an acceleration of 0.57 g and a frequency of $10^{-3}$/yr. The RHWM fissile drums are Type A containers and can remain intact with a drop of 4 ft (122 cm). Therefore, no spill of fissionable materials when drums are dropped to the ground during earthquakes. The drums would be scattered throughout the RHWM facilities. Interactions between drums of different types and sizes would be possible. However, such interactions are bounded by Bounding Scenario 5.

## 5.1 Summary of Criticality Safety Analysis Results on Bounding Scenarios for the 200-gram Pu Drum Storage Operations

The criticality safety analysis results are summarized in the Table 24 for Bounding Scenarios 1-9. The subcritical limits for XSDRNPM and KENO V.a calculations with the 44-Group ENDF/B-V library the are 0.971 and 0.972, respectively.

Table 24. Lists of Criticality Safety Analysis Results of Bounding Scenarios A-I for Tank Farm Normal Operation and Upset Conditions

| Bounding Scenario ID | Description of Normal/ Off-Normal Conditions | Maximum $k_{eff}$ value or Critical Mass (CM) |
|---|---|---|
| 1 | Normal Operation: 200-gram Pu drums with no beryllium or carbon/graphite in a storage array. The drums are stacked 3-high. | Water/PE Moderated $k_{eff}$ < 0.94<br>Water Moderated $k_{eff}$ < 0.91 |
| 2 | Fissile Over Batch: A single 400-gram Pu drum in a 200-gram Pu drum array. No beryllium and carbon/graphite are in drums. The drums are stacked 3-high | PE Moderated (with pallets) $k_{eff}$ < 0.961<br>Water Moderated (no pallets) $k_{eff}$ < 0.92 |
| 3 | Reflector Over Batch: A single 200-gram Pu drum with 350 grams Be, or 100 kilograms Nat-U, or 8 kilograms C/Graphite in a 200-gram Pu drum array. No beryllium and carbon/graphite are in all other drums. The drums are stacked 3-high | Water/PE Moderated $k_{eff}$ < 0.96<br>Water Moderated $k_{eff}$ < 0.91 |
| 4 | Moderator Over Batch: 200 Pu drum array with each drum filled with unlimited amount of PE or hydrogenous materials superior to water | Water/PE Moderated $k_{eff}$ < 0.94 |
| 5 | Loss of Interaction Control: Array spacing of 30" (76 cm) is not maintained | Water Moderated $k_{eff}$ < 0.94 |
| 6 | Loss of Stacking Control: Stacking limit of 3-high is not maintained. | Water/PE Moderated $k_{eff}$ < 0.93<br>Water Moderated $k_{eff}$ < 0.91 |

| | | |
|---|---|---|
| 7 | Flooding/Moisture/Fire Water: A 200-gram Pu drum array is submerged in water and is fully reflected from the top. | Water/PE Moderated $k_{eff} < 0.94$<br>Water Moderated Only $k_{eff} < 0.91$<br>Fire Damage: Fissile Concentration << 1 g Pu/liter |
| 8 | Spills: Spill of the content of a single 200-gram Pu drum | Water system < 0.45 CM<br>Concrete Close Fit Reflection < 0.5 CM<br>PE system < 0.67 CM |
| 9 | Seismic Consideration | Water/PE Moderated $k_{eff} < 0.93$ |

# 6.0 DESIGN FEATURES AND ADMINISTRATIVE CONTROLS

## 6.1 Operation Controls:

The following operation controls are required for all RHWM waste drum storage operations:

**Spill Controls:**

- In the event of major spills involving fissionable materials, all active operations in the same general area of the storage facility shall be suspended or stopped if they can be safely achieved. For operations that can not be safely suspended immediately, they may be allowed to proceed to a point when they may be safely suspended or to finish, whichever that can be achieved first. In any events, no new operations other than the clean up operations are allowed to start. Suspended/stopped treatment operations may be resumed or new operations may be started after the spills are cleaned up.

## 6.2 Criticality Safety Controls for 200-gram Pu Drums

### 6.2.1 Mass (Fissile/Pu)

Each 55-gallon drum or its equivalent shall be limited to 200 gram Pu or Pu equivalent.

Note: Pu Equivalent is defined in CSAM99-061 Rev. 1 [2].

### 6.2.2 Moderation

Hydrogen materials with a hydrogen density greater than that (0.133 g H/cc) of polyethylene and paraffin are not allowed. Hydrogen materials with a hydrogen density no greater than that of polyethylene and paraffin are allowed with unlimited amounts.

### 6.2.3 Interaction

- A spacing of 30" (76 cm) is required between arrays.
- 200-gram Pu drums shall be placed in arrays for 200-gram Pu drums only. (No mingling of 200-gram Pu drums with other drums not meeting the drum controls associated with the 200-gram mass limit.)

### 6.2.4 Reflection

No beryllium and carbon/graphite (other than the 50-gram waiver amount) is allowed. (Note: Nat-U exceeding the waiver amount is allowed when its U-235 content is included in the fissile mass limit of 200 grams.)

### 6.2.5 Geometry

- Drum Geometry: Only 55-gallon drum or its equivalent shall be used.
- Array Geometry: 55-gallon drums are allowed for 2-high stacking. Steel waste boxes may be stacked 3-high if constraint.

## 7.0 CRITICALITY HAZARD TYPE

The Criticality Hazard Type of 1 is assigned for RHWM 200-gram waste drum storage operations.

***Fire Fighting Guidance:*** In the event of fire, water may be used.

## 8.0 CRITICALITY BARRIERS AND CONTINGENCY ASSESSMENTS

The following contingency table (Table 25) outlines the credible upset conditions (events) for the RHWM 200-gram drum storage operations and the associated administrative and physical barriers in place to provide double contingency (at a minimum) for such operations:

Table 25. Contingency Table for RHWM 200-gram Pu Drum Storage Operations

| Description | Barrier | Controls |
|---|---|---|
| Fissile Over Mass: fissionable material exceeds the fissile mass limit. Increase fissile material in a single RHWM waste storage container | 1. Fissile mass limits for containers<br>2. RHWM fissile materials are in low concentrations as contaminations in the wastes. Fissile materials in such a form do not cause criticality concern<br>3. Most of the RHWM operations deal with few or no fissionable materials.<br>4. All TRU drums generated in Pu Facility are subject to $\gamma$ scan to confirm their fissile contents. | 200-gram Pu drum limit |
| Reflector Over Mass: Banned superior reflectors are placed inside a 200-gram Pu drum. | No Be, Nat-U, and C/graphite are allowed. | No Be and C/graphite are allowed. Nat-U is allowed when its U-235 content is included in the 200-gram Pu drum mass limit |

Table 25 Continued

| Description | Barrier | Controls |
|---|---|---|
| Moderator Over Mass: | 1. Moderator controls<br>2. TRU drums do not have free fluid<br>3. The plastic content in TRU drums are mostly from clothes, covers, gloves, and wraps. The packing factor is much lower than the theoretical density of PE. | No hydrogenous materials with hydrogen density greater than 0.133 g/cc. See CSAM99-061 Rev. 1. |
| Loss of Interaction Controls: The 30" (76 cm) spacing between arrays is not maintained. | 1. 30" (76 cm) spacing control<br>2. No mingling of 200-gram Pu drums with containers with different fissile mass limit<br>3. Access is required between arrays to allow personnel access<br>4. Allow movement of drums in and out of arrays | 1. 30" (76 cm) spacing control<br>2. 200-gram Pu drums shall be in its own array; no intermingling with containers with other fissile mass limit |
| Loss of Stacking Control: drums are stacked 4-high (or more than 3-high) | 1. Stacking height control<br>2. Type A drums can only sustain a 4-foot drop or can only be safely stored 2-high | 55-gallon drums are not to be stacked 2-high. When constraint, 3-high is allowable. |
| Spills: simultaneous spills of fissionable materials by Tank Farm tanks and other equipment or containers | Prevention of multiple spills: suspend all operations using the same secondary containment until after clean up | RHWM Facility Safety Plans (FSPs) |
| Flood/Rain: the 200-gram drum array are merged in water | 1. RHWM facilities are located above the 500-year flood level.<br>2. The established 200-gram drum limit is safe with superior moderator, PE. | 1. RHWM Facility Documented Safety Analyses (DSAs) |
| Fires: Damage to Tank Farm tanks and other equipment and containers resulting in loose fissionable materials | 1. Limited fire loadings (for fissile drum storage)<br>2. Fire alarm/facility personnel/fire extinguisher<br>3. NFPA Compliant Sprinkler system<br>4. LLNL Fire Department Response | RHWM FSPs<br>RHWM Facility DSAs |
| Earthquake: 200-gram drums dropped | Building seismic design meets DOE-STD-1020 PC-2 requirements. | RHWM Facility DSAs |

**Criticality Safety Barriers**

A summary of the available criticality barriers for 200-gram Pu drum storage operations is as listed in Table 26:

Table 26. List of available criticality safety barriers for 200-gram Pu drum storage operations

| Barrier Parameters | Barriers Formally Claimed (BFC; yes=1; no=0) | Remarks |
|---|---|---|
| Neutronic Coupling | 1 | 30" (76 cm) array spacing; no intermingling of 200-gram containers with other containers with different fissile mass limit; array drum stacking limit |
| Poison | 0 | Not Used |
| Density | 0 | Not Used |
| Reflection (Albedo) | 1 | Optimized Reflection/Reflector Controls |
| Shape (Geometry) | 1 | Optimized stratified shelled spherical geometry |
| Volume | 1 | Type A drum; optimized geometry |
| Material Form | 1 | Pure Pu-239 with no contaminant |
| Concentration | 0 | Not Used |
| Enrichment/Fissile Composition | 1 | Pure Pu-239 is assumed for Weapon-Grade Plutonium (WGPu); Pu equivalent is conservatively used in RHWM operations |
| Moderation | 1 | Optimized Moderation |
| Mass | 1 | Mass Limits: 200 grams Pu-239 per 55-gallon drum or equivalent |
| Sum: | BFC=8 | |

## 9.0 CONCLUSIONS

Based on the criticality safety limits and controls in Section 6.0, all normal operation and credible upset conditions are subcritical for the RHWM storage operations with 200-gram Pu drums. Therefore, an inadvertent criticality event is incredible (or beyond extremely unlikely). Based on this, the use of 200-gram Pu drums in RHWM waste storage operations is criticality safe satisfying the double-contingency principle as required by DOE Order 420.1 [1].

Any deviation from the CS controls listed in Section 6.0 requires a criticality safety analysis on a case-by-case basis and Criticality Safety Section approval before implementation.

## 10.0 REFERENCES


1. DOE Order 420.1, 'Facility Safety,' Change Note 3, November 22, 2000.
2. P. Chou, CSAM99-061, Rev. 1, January 2000.
3. TRUPACT-II, TRAMPAC, Rev. 19C, WIPP, Carlsbad, New Mexico, April 2003.
4. NRC Certificate of Compliance, No. 9218, U.S. Nuclear Regulatory Commission, Washington, D.C., April 2003.
5. American National Standard, ANSI/ANS-8.1, 'Nuclear Criticality Safety in Operations with Fissionable Materials Reactors," American Nuclear Society, 1998.
6. SCALE Package, "Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation for Workstations and Personal Computers," CCC-545, Radiation Safety Information Computational Center, Oak Ridge National Laboratory, 1998.
7. R. Evarts, CSAM99-074, 1999.
8. P. Chou, "Criticality Safety Analysis on Use of Mixed-Size and Mixed-Type Arrays for the Storage of Containers of Different Sizes and Types at Hazardous Waste Management Facilities," CSM 1087, Rev. 1, September 2001.
9. M. Ben-Horim and H. Levy, "Business Statistics: Fundamentals and Applications," Random House, NY, NY, 1983.
10. P. Chou, "Criticality Safety Analysis on 30- and 55-Gallon Drum Nat-U and Dep-U u, "Beryllium and Graphite in Nat- and Dep-U Storage at Radioactive and Hazardous Waste Management Facilities," CSM 1309, February 2003.
11. N.L. Pruvost and H.C. Paxton, "Nuclear Criticality Safety Guide," LA-12808, Los Alamos National Laboratory, September 1996.
12. D. Heinrichs, CSM 936A, February 1998.
13. LLNL Environment, Safety and Safety (ES&H) Manual, Document 20.6, "Criticality Safety," (latest version).

# APPENDIX A

## Neutron Transport Analysis Modeling of the RHWM 200-gram Pu Drum Storage Configuration

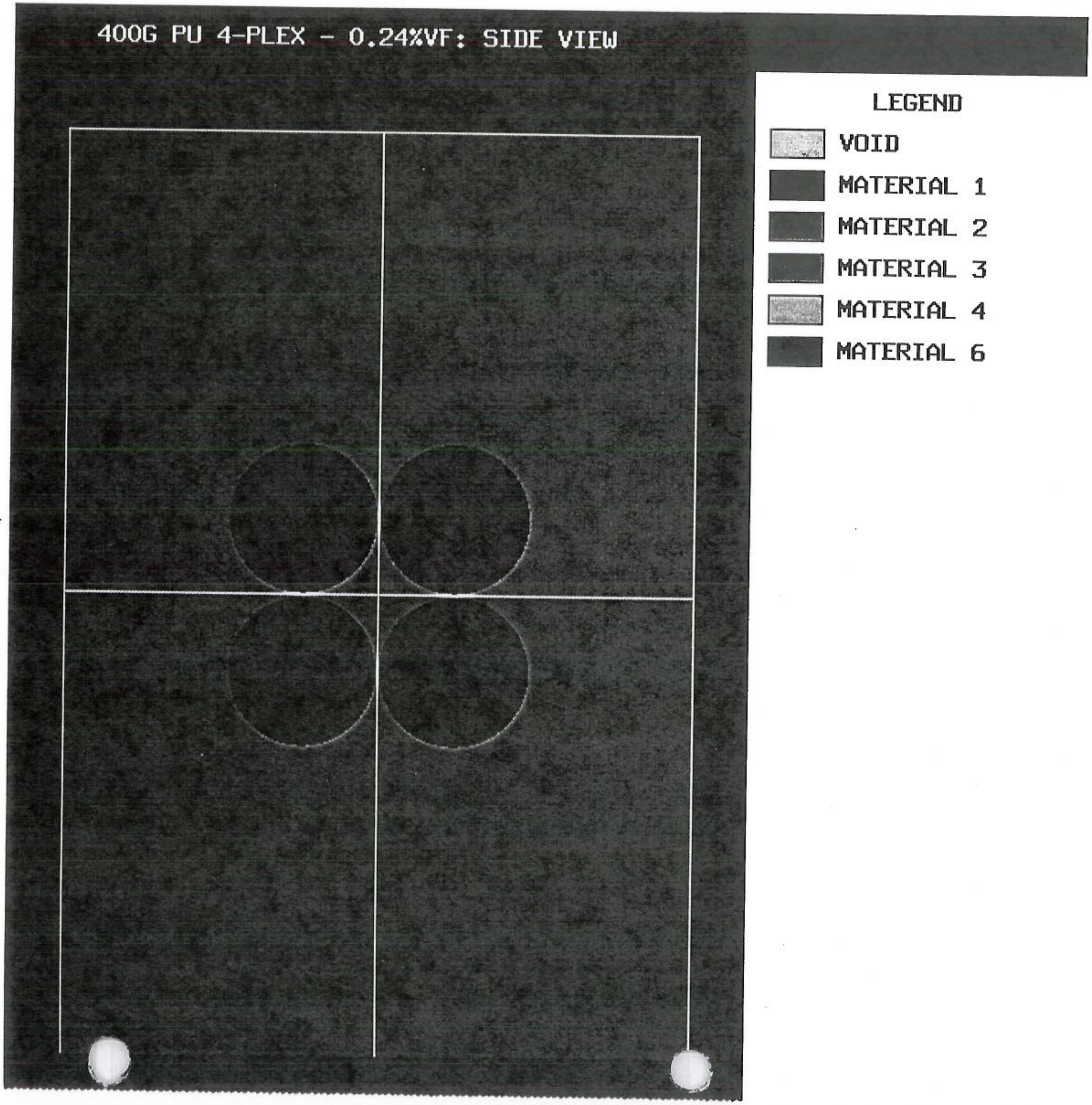
The neutron transport analysis performed for this evaluation is based on the bounding drum and array models. An infinite X-Y array is always used. Typically, the array is 3-high conforming to the current RHWM storage practices. There is an exception to this. The array is 4-hgih when drums are over stacked. A four-drum 4-plex configuration is normally used to bound the interaction between fissile materials in drums. The 4-plex configuration is 1-drum long , 2-drum wide, and 2-drum high. The fissile materials and their moderators in these drums are assumed to be clustered in spheres in the nearest corners.

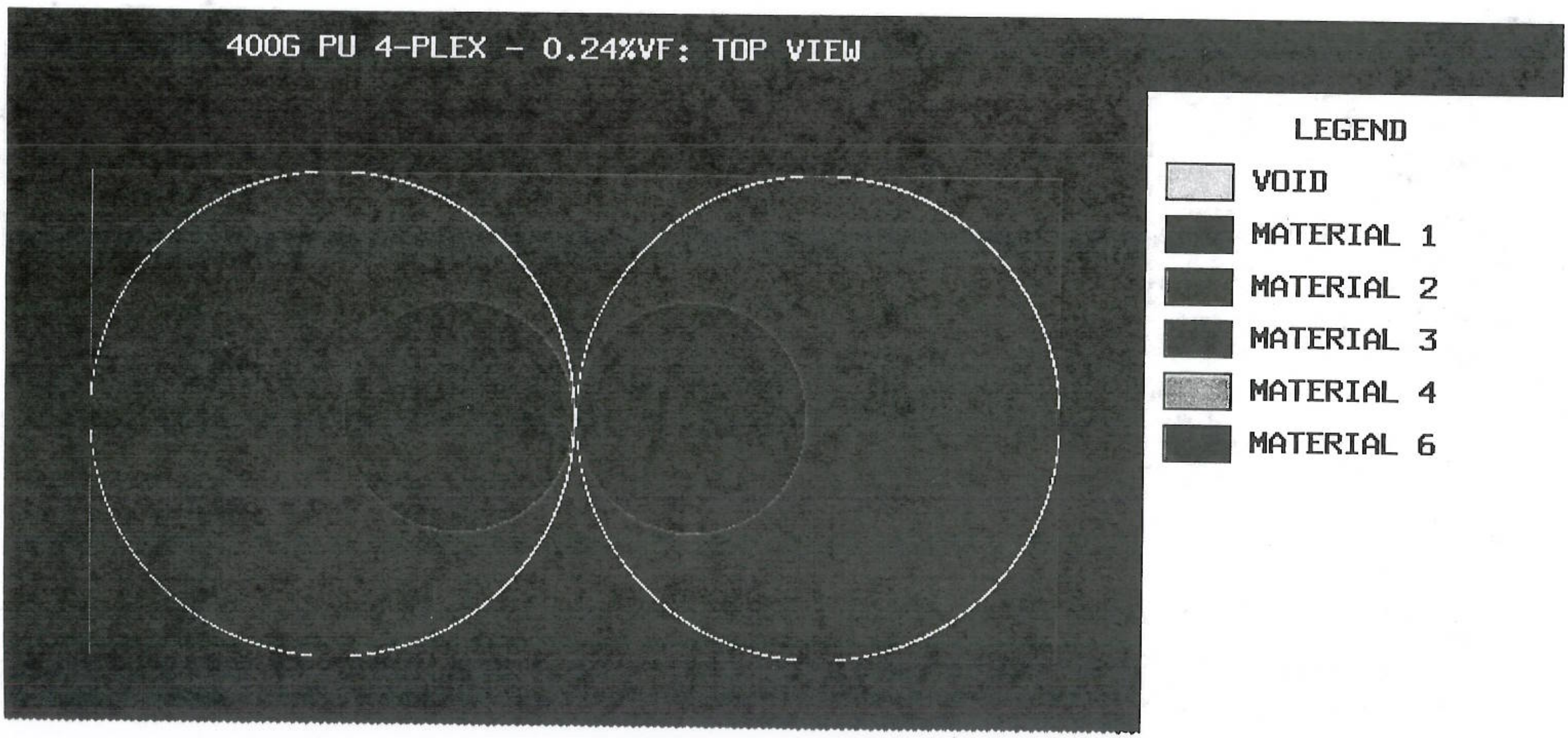
The 4-plex configurations and its variations are used as the unit cell to form arrays. Two 4-plexes with one on top of the other form the unit cell in the 4-high array models. The top two drums (or the top half) of a 4-plex on top of a 4-plex form the unit cell in the 3-high array models.

The four-plex configuration maximizes the neutronic interaction in drum array storage because of the following reasons:

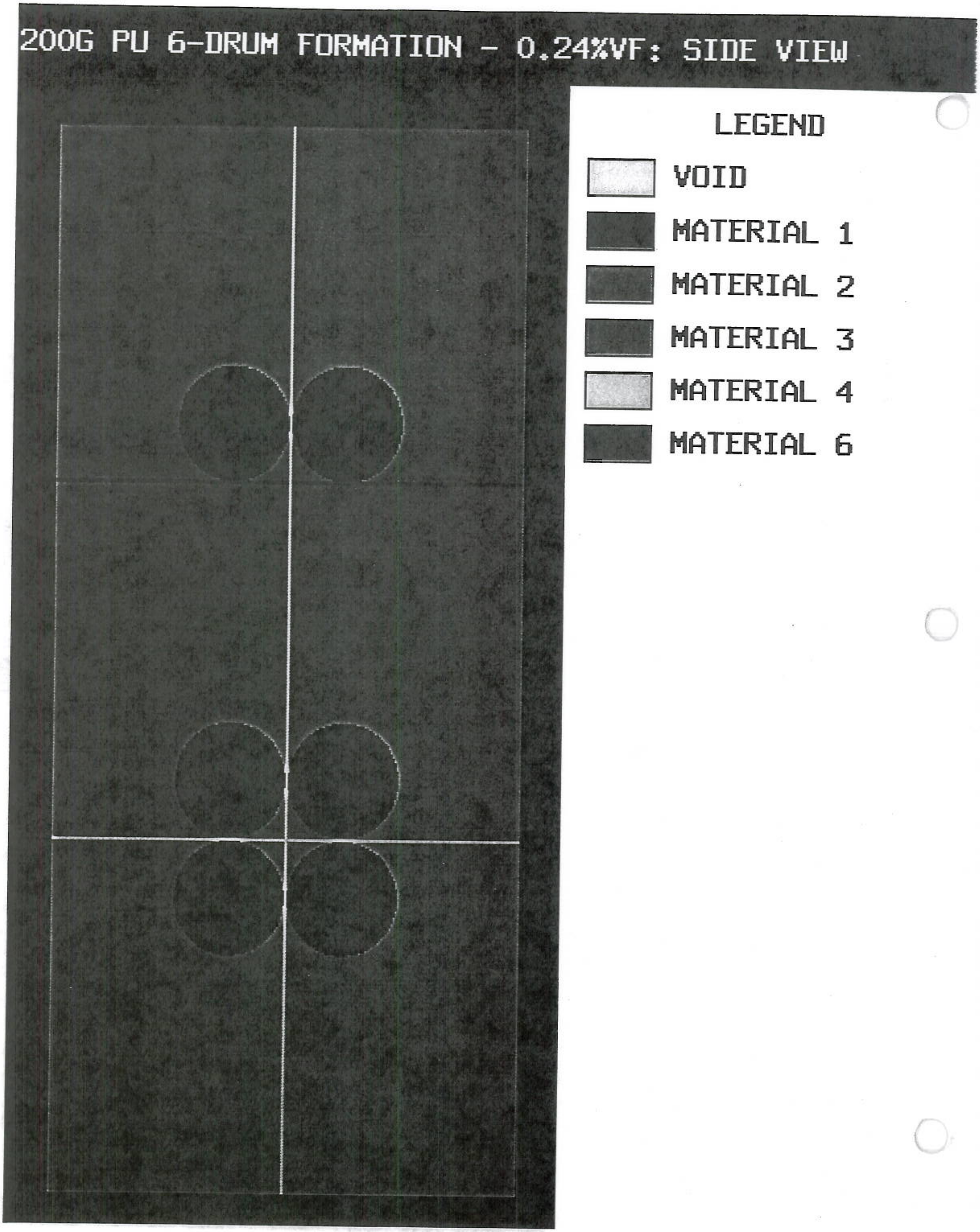
The fissile materials in all drums are modeled as spheres clustered in the nearest corners. In reality, the fissile materials are distributed throughout the drums, not limiting to the nearest corner. Furthermore, the fissile materials are not concentrated in spheres and do not assume the form of favorable neutronic geometry. Also, the balls have the same moderation behavior with the same amount of moderator and the same H/X ratio so that they may have better neutronic coupling among them. In reality, the moderating behaviors for individual drums are different even with the same content. The relative positions for fissile and moderator/reflector materials determine the true moderating behavior. Therefore, the 4-plex configuration is high unrealistic compared to the actual fissile configuration in actual RHWM storage operations. However, the configuration serves as a good bounding condition for drum behaviors. Also, the 4-plex configuration and its variations as the unit cell and the building element of the RHWM storage arrays are not very realistic. The RHWM drum arrays consist of drums with different fissile contents. Therefore, an organized order in the form of unit cells does not exist for RHWM drum array. The organized order enhances the system reactivity in drum storages. Therefore, the use of 4-plex and its variation as the unit cell for arrays provide a bounding condition for array drum interaction.

The plot on Pages A-2 shows the side view of a 4-plex formation and the plot on Page A-3 shows the top view of a 4-plex formation. The plots on Pages A-4 and A-5 show the side views of a 6-drum and 8-drum formations, respectively. It should be noted that the 6-drum and 8-drum formations have the same top view as the 4-plex formation. Therefore, they are not individually plotted.

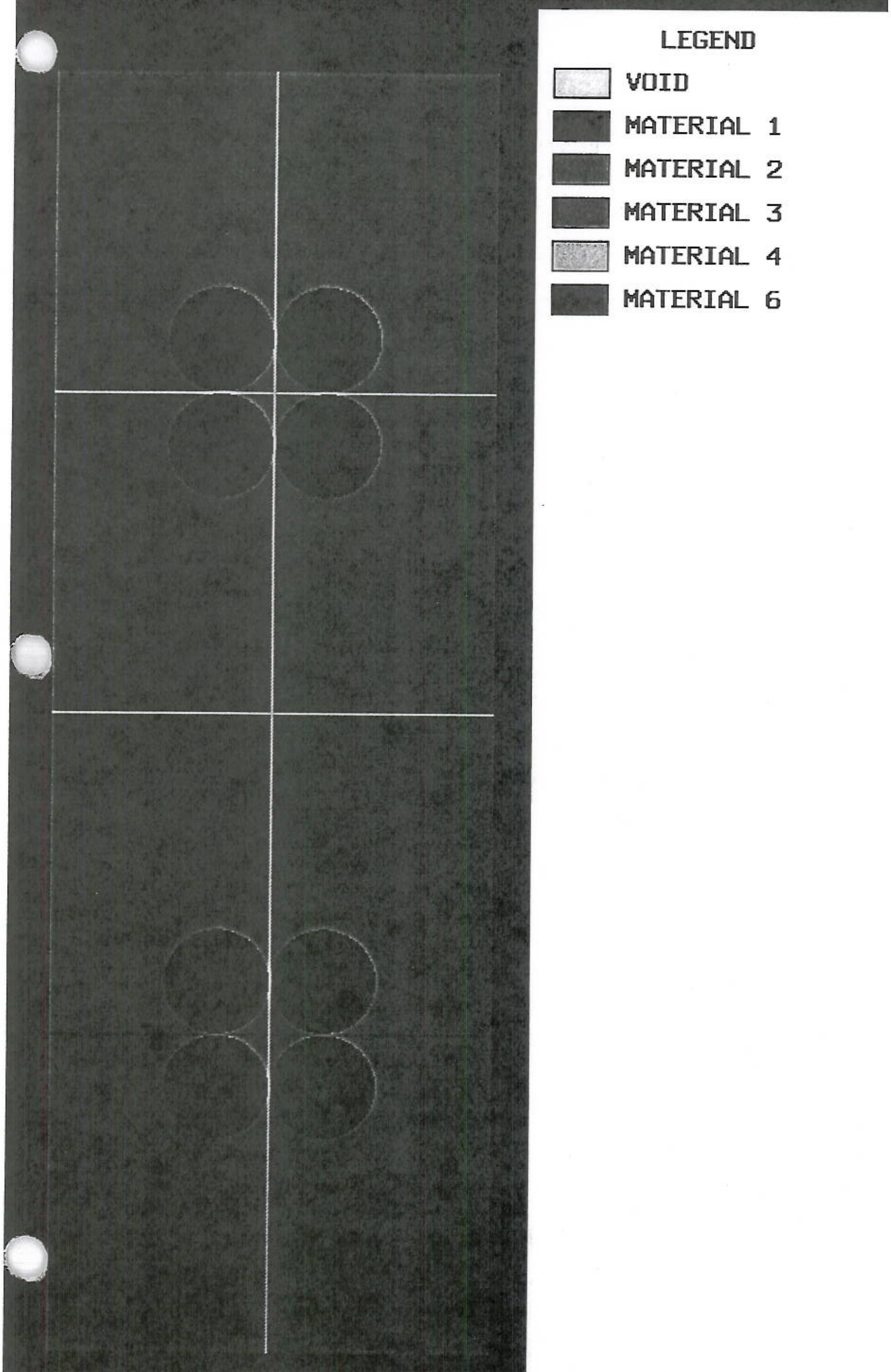

400G PU 4-PLEX - 0.24%VF: SIDE VIEW
LEGEND
VOID
MATERIAL 1
MATERIAL 2
MATERIAL 3
MATERIAL 4
MATERIAL 6


400G PU 4-PLEX - 0.24%VF: TOP VIEW
LEGEND
VOID
MATERIAL 1
MATERIAL 2
MATERIAL 3
MATERIAL 4
MATERIAL 6

A-3


200G PU 6-DRUM FORMATION - 0.24%VF: SIDE VIEW
LEGEND
VOID
MATERIAL 1
MATERIAL 2
MATERIAL 3
MATERIAL 4
MATERIAL 6

200G PU 8-DRUM FORMATION - 0.24%VF: SIDE VIEW




A-5

# APPENDIX B

## Input Decks for Criticality Safety Evaluation on Normal and Credible Upset Conditions for 200-gram Pu Drum Storage at RHWM Facilities

The input decks used in Section 5.0 of this criticality safety evaluation on the RHWM 200-gram Pu drum storage are present in this Appendix. The input decks are listed in for the following order for calculations performed in Section 5.0 of the main text:

1. **Bounding Scenario 1 (Table 9)**
2. **Bounding Scenario 2 (Table 11)**
3. **Bounding Scenario 3 (Tables 13 and 14)**
4. **Bounding Scenario 5 (Tables 18, 20 and 21)**
5. **Bounding Scenario 6 (Table 22), and**
6. **Bounding Scenario 7 (Table 23)**

## B.1. Bounding Scenario 1 – Normal Operation Conditions

The input desks listed in Section B.1 are used to evaluate Bounding Scenario 1 (or the normal operation conditions) for 200-gram Pu drum storage with PE and water/PE moderation and reflection. The input file for the PE moderated and reflected cases is named **dr200sb,** the input file for the water moderated and reflected cases is named **dr200sbh2o**, and the input file for the water/PE moderated and reflected cases is named **dr200sbw**. These two files contain the input files for 200-gram Pu drums with the Pu core volume fraction ranging from 0.10% to 0.24%. The results from calculations using these two input files are listed in Table 9 of the main text. A sample input deck is included here for each of input files. The listed decks are for KENO V.a calculations using the SCALE4.4 ENDF/B-V 44-Group cross section library. KENO V.a is driven by the SCALE criticality safety analysis sequence (CSAS) drive, CSAS25.

A sample case for the PE moderated and reflected cases, **dr200sb**, is listed below. It corresponds to a Pu volume fraction of 0.24% with a $k_{eff}$ value of 0.9690.

```
=csas25
dr200sb: 200g Pu 0.24%VF;100%PE Mod&Refl;3-high
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
poly(h2o)    1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o         6 0.0001 293 end
end comp
spherical reflected reflected 0.0 end
1 10.00913 2 28.267 3 28.495 4 28.630 end zone
dr200sb: 200g Pu 0.24%VF;100%PE Mod&Refl;3-high
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
```

```
read geom
unit 91
sphere   1 1 10.00913
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f51 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

The input deck for the water moderated and reflected cases is named, **dr200sbh2o**. For the sample case, it corresponds to a Pu volume fraction of 0.24% with a $k_{eff}$ value of 0.8953. The sample input deck is very similar to, **dr200db**, with the following cards modified:

```
poly(h2o)    1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
```

by replacing them with the following cards (water volume fraction in Material Card 1 depends on the Pu VF) :

```
h2o          1 den=0.9982 0.9976 293 end
h2o        2 den=0.9982 1.0 293 end
```

The sample case for the water/PE moderated and reflected cases, **dr200sbw**, is listed below. The water/PE cases have one drum filled with PE and five drums filled with water in a 6-drum formation, which is the basis of a 3-high infinite X-Y array. The sample case corresponds to a Pu volume fraction of 0.24% with a $k_{eff}$ value of 0.9269.

```
=csas25
dr200sbw: 200g Pu 0.24%VF;H2O 4-plex Reg. PE Mod&Refl;3-high;1 drum in 6 PE
filled
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
h2o          1            0.9976 293 end
h2o        2 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o          6 0.0001 293 end
plutoniumalp 7 den=19.84 0.0024 293 end
poly(h2o)     7 den=0.923 0.9976 293 end
poly(h2o)     8 den=0.923 1.0 293 end
end comp
spherical reflected reflected 0.0 end
7 10.00913 8 28.267 3 28.495 4 28.630 end zone
dr200sbw: 200g Pu 0.24%VF;H2O 4-plex Reg. PE Mod&Refl;3-high;1 drum in 6 PE
filled
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 92
sphere   7 1 10.00913
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 8 1 28.267 82.65 0.0
```

```
hole    92   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3, Pu balls in nearest corners'
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 3 4 3 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f52 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

## B.2. Bounding Scenario 2 – Fissile Over Mass (Table 11)

The input desks listed in Section C.2 are used to evaluate the fissile overpass in a 3-high infinite X-Y arrays with 200-gram Pu drums. The fissile over mass deals the double batch for a single container. The infinite array is derived based on two six-drum formations. One of the 6-drum formation consists of 200-gram drums only. The other 6-drum formation consists of one fissile over massed 400-gram Pu drum and 5 200-gram Pu drum. The two–drum formations are then used to create the super unit cell consisting of 50 6-drum formations in a 5x10 formation. This corresponds to 1 over massed drum in every 300 drums. Six cases have been included. They are:

1. all drums including the over massed on are filled with 100% dense PE.
2. all drums are filled with 100% dense PE with the consideration of pallet spacing
3. all drum are filled with 60% dense PE.
4. all drum are filled with water
5. the over massed formation have one drum filled with PE and the other five drums filled with water. The over massed drum is filled with water.
6. both over massed formation have one drum filled with PE and the other five drums filled with water. The over massed drum is filled with water

The input file for Case 1 is named, **dr200db**. The sample input has a 0.24% Pu volume fraction with a $k_{eff}$ value of 0.9912.

```
=csas25
dr200db:1 400gDB+299 200gPu Drums;0.24%VF;100%PE Mod&Refl;3-high
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
poly(h2o)    1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
```

```
orconcrete  5 1.0 293 end
h2o         6 0.0001 293 end
end comp
spherical reflected reflected 0.0 end
1 10.63629 2 28.267 3 28.495 4 28.630 end zone
dr200db:1 400gDB+299 200gPu Drums;0.24%VF;100%PE Mod&Refl;3-high
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 93
sphere   1 1 10.63629
unit 94
sphere   1 1  9.29165
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 2 1 28.267 82.65 0.0
hole     93   17.63070 0.0 72.01370
hole     94   18.97534 0.0 52.13117
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3, Pu balls in nearest corners, 1DB'
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.96 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 3 4 3 4 end fill
```

```
ara=99 nux=5 nuy=10 nuz=1 fill 52 f51 end fill end array
read bounds xyf=periodic end bounds
read start nst=5 nbx=52 end start
end data
end
```

The input file for Case 2 is named, **dr200dbpal**. The sample deals with the configuration with 0.24% Pu volume fraction with a $k_{eff}$ value of 0.9548. The input deck is very similar to, **dr200db**, with the following card modified (5 replacements):

```
cuboid   6 1 4p28.630 83.005 -0.355
```

by replacing it with the following card:

```
cuboid   6 1 4p28.630 83.005 -10.515g
```

The input file for Case 3 is named, **dr200dbp60**. The sample deals with the configuration with 0.24% Pu volume fraction with a $k_{eff}$ value of 0.7645. The input deck is very similar to, **dr200db**, with the following cards modified:

```
poly(h2o)     1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
```

by replacing them with the following cards (water volume fraction in Material Card 1 depends on the Pu VF) :

```
poly(h2o)     1 den=0.554 0.9976 293 end
poly(h2o) 2 den=0.554 1.0 293 end
```

The input file for Case 4 is named, **dr200dbwww3**. The sample deals with the configuration with 0.24% Pu volume fraction with a $k_{eff}$ value of 0.9154. The input deck is very similar to, **dr200db**, with the following cards modified:

```
poly(h2o)     1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
```

by replacing them with the following cards (water volume fraction in Material Card 1 depends on the Pu VF) :

```
h2o        1 0.9976 293 end
h2o        2 1.0 293 end
```

The input file for Case 5 is named, **dr200dbwp**. The sample deck deals with the configuration with 0.24% Pu volume fraction with a $k_{eff}$ value of 0.9616. This input deck has the over massed drum filled with PE, while the rest of the drums are filled with water.

```
=csas25
dr200dbwp:1 400gDB+299 200gPu;0.24%VF;H2O+PE Mod&Refl;3-high;DB Drm with PE
44groupndf5 multiregion
```

```
plutoniumalp 1 den=19.84 0.0024 293 end
h2o          1 den=0.9982 0.9976 293 end
h2o       2 den=0.9982 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o          6 0.0001 293 end
poly(h2o)    7 den=0.923 1.0 293 end
plutoniumalp 8 den=19.84 0.0024 293 end
poly(h2o)     8 den=0.923 0.9976 293 end
end comp
spherical reflected reflected 0.0 end
8 10.63629 7 28.267 3 28.495 4 28.630 end zone
dr200dbwp:1 400gDB+299 200gPu;0.24%VF;H2O+PE Mod&Refl;3-high;DB Drm with PE
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 93
sphere   8 1 10.63629
unit 94
sphere   8 1  9.29165
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 7 1 28.267 82.65 0.0
hole     93   17.63070 0.0 72.01370
hole     94   18.97534 0.0 52.13117
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3, Pu balls in nearest corners, 1DB'
```

```
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.96 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 3 4 3 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill 52 f51 end fill end array
read bounds xyf=periodic end bounds
read start nst=5 nbx=52 end start
end data
end
```

The input file for Case 6 is named, **dr200dbwp6**. The sample deals with the configuration with 0.24% Pu volume fraction with a $k_{eff}$ value of 0.9548. This input deck has one of the drums in the 6-drum formations filled with PE and the rest filled with water. The over massed drum is one of the two drums filled with PE (in the two formations used to create the super unit cell).

```
=csas25
dr200dbwp6:1 400gDB+299 200gPu;0.24%VF;H2O+PE Mod&Refl;3-high;1 PE drum in 6
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
h2o          1 den=0.9982 0.9976 293 end
h2o       2 den=0.9982 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o          6 0.0001 293 end
poly(h2o)    7 den=0.923 1.0 293 end
plutoniumalp 8 den=19.84 0.0024 293 end
poly(h2o)     8 den=0.923 0.9976 293 end
end comp
spherical reflected reflected 0.0 end
8 10.63629 7 28.267 3 28.495 4 28.630 end zone
dr200dbwp6:1 400gDB+299 200gPu;0.24%VF;H2O+PE Mod&Refl;3-high;1 PE drum in 6
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 92
sphere   8 1 10.00913
unit 93
sphere   8 1 10.63629
unit 94
sphere   8 1  9.29165
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
```

```
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 7 1 28.267 82.65 0.0
hole     93   17.63070 0.0 72.01370
hole     94   18.97534 0.0 52.13117
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 6
cylinder 7 1 28.267 82.65 0.0
hole     92   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, u balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3, u balls in nearest corners, 1DB'
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.96 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 6 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 3 4 3 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill 52 f51 end fill end array
read bounds xyf=periodic end bounds
read start nst=5 nbx=52 end start
end data
end
```

## B.3. Bounding Scenario 3 – Reflector Over Mass (Tables 13 and 14)

Both KENO V.a and XSDRNPM are used for the analysis on the bounding scenarios. The XSDRNPM is used to bound the effect of reflectors. The KENO V.a is used to perform array simulation.

Four XSDRNPM input decks, **pr200be**, **pr200u**, **pr200c8** and **pr200pr** have been used to assess the superior reflector effect o 350 grams Be, 100 kilograms Nat-U, 8 kilograms C/graphite, and no reflector, respectively, with a 12" (30-cm) layer of PE on the outside. A Nat-U reflection deck is listed below as a sample input deck. The sample deck corresponds to a Pu volume fraction of 0.20% and has a $k_{eff}$ value of 0.9339.

```
=csas1x
200g Pu 0.20%VF 100kg Nat-U Reg. PE Mod.-Refl.
44groupndf5 multiregion
plutoniumalp 1 0.0020 293 end
poly(h2o)     1 0.9980 293 end
uranium   2 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
end comp
spherical vacuum reflected 0.0 end
1 10.63629 2 13.49287 3 43.97287 end zone
end data
end
```

The radii of the concentric sphere, which are specified as zones in the sample deck, are given in Table 12 of the main text. This XSDRNPM parametric analysis identifies 100 kilograms Nat-U bound the effect of all reflectors. The Nat-U reflector is further analyzed in array formations. The input file for PE-filled-drum-only arrays with the 100-kiligram Nat-U reflector-over-mass drum is named, **dr200sbu**. The sample deals with the configuration with 0.25% Pu volume fraction with a $k_{eff}$ value of 0.9686.

```
=csas25
dr200sbu: 200gPu;0.25%VF;100%PE Mod&Refl;3-high;100kg Nat-U (1 in 120)
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0025 293 end
poly(h2o)     1 den=0.923 0.9975 293 end
poly(h2o) 2 den=0.923 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o         6 0.0001 293 end
uranium     7 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.87385 7 13.03702 2 28.267 3 28.495 4 28.630 end zone
dr200sbu: 200gPu;0.25%VF;100%PE Mod&Refl;3-high;100kg Nat-U (1 in 120)
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1  9.87385
unit 92
sphere   1 1  9.87385
sphere   7 1 13.03702
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.39314 0.0 72.77614
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
```

```
cylinder 2 1 28.267 82.65 0.0
hole     91   -18.39314 0.0 72.77614
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.39314 0.0 9.87386
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91   -18.39314 0.0 9.87386
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 2 1 28.267 82.65 0.0
hole     92   15.22997 0.0 69.61297
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 3 4 3 4 end fill
ara=99 nux=2 nuy=10 nuz=1 fill 52 f51 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

The input deck for the water moderated and reflected cases is named, **dr200sbuh2o**. For the sample case, it corresponds to a Pu volume fraction of 0.25% with a $k_{eff}$ value of 0.8891. The sample input deck is very similar to, **dr200sbu**, with the following cards modified:

```
poly(h2o)    1 den=0.923 0.9975 293 end
poly(h2o) 2 den=0.923 1.0 293 end
```

by replacing them with the following cards (water volume fraction in Material Card 1 depends on the Pu VF) :

```
h2o         1 den=0.9982 0.9975 293 end
h2o      2 den=0.9982 1.0 293 end
```

The input file for water-and-PE-filled drum arrays (for every six drums in the arrays, one drum is filled with PE and five are filled with water) with the 100-kiligram Nat-U reflector-over-mass drum is named, **dr200sbuw**. The sample deals with the configuration with 0.25% Pu volume fraction with a $k_{eff}$ value of 0.9411.

```
=csas25
dr200sbuw:200gPu;0.25%VF;PE-H2O Mod&Refl;3-high;100kg Nat-U (1 in 120);1 PE drm
in 6
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0025 293 end
h2o           1 den=0.9982 0.9975 293 end
h2o        2 den=0.9982 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o          6 0.0001 293 end
uranium      7 1.0 293 end
poly(h2o) 8 den=0.923 1.0 293 end
plutoniumalp 9 den=19.84 0.0025 293 end
poly(h2o)     9 den=0.923 0.9975 293 end
end comp
spherical reflected reflected 0.0 end
9 9.87385 7 13.03702 2 28.267 3 28.495 4 28.630 end zone
dr200sbuw: 200gPu;0.25%VF;PE-H2O Mod&Refl;3-high;100kg Nat-U (1 in 120);1 PE drm
in 6
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1  9.87385
unit 92
sphere   9 1  9.87385
sphere   7 1 13.03702
unit 93
sphere   9 1  9.87385
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.39314 0.0 72.77614
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.39314 0.0 72.77614
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.39314 0.0 9.87386
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.39314 0.0 9.87386
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
```

```
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 8 1 28.267 82.65 0.0
hole     92   15.22997 0.0 69.61297
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 6
cylinder 8 1 28.267 82.65 0.0
hole     93   18.39314 0.0 72.77614
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 6 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 3 4 3 4 end fill
ara=99 nux=2 nuy=10 nuz=1 fill 52 f51 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

## B.4. Bounding Scenario 5 – Loss of Interaction Controls (Tables 18, 20 and 21)

The input desks listed in Section C.4 are used to the upset scenario dealing with the loss of interaction controls. The upset scenarios can be categorized into 3 groups: Group 1 deals with the loss of interaction controls with fissile drums/arrays, Group 2 deals the Nat-U drum interactions, and Group 3 deals with reflector drum interaction.

Group 1 consists of three bounding upset scenarios: 1-1) the interaction with 65-gram fissile drums, 1-2) the interaction with 120-gram fissile drums and 1-3) the interaction with 120-gram mix array/containers.

***Case 1-1:*** The input deck used to investigate the interaction of 200-gram Pu drums with 65-gram fissile drums. The 6-drum formation consists of three 200-gram Pu drums and three 65-gram fissile drums. The input deck name is **dr200sb65**. The concentric spherical radii of the 65-gram fissile core and reflector shells are listed in Table 15. It should be noted that all drums are filled with PE. A sample deck, which corresponds to a Pu volume fraction of 0.24% and has a $k_{eff}$ value of 0.9156, is listed below:

```
=csas25
dr200sb65:200gPu;0.24%VF;PE Mod&Refl;1 65g drum in 2
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
```

```
poly(h2o)    1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o        6 0.0001 293 end
beryllium 7 den=1.85 1.0 293 end
uranium   8 den=19.05 1.0 293 end
c 9 den=2.25 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.00913 2 28.267 3 28.495 4 28.630 end zone
dr200sb65:200gPu;0.24%VF;PE Mod&Refl;1 65g drum in 2
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 92
sphere   1 1  6.88162
sphere   7 1  7.18588
sphere   8 1 11.75486
sphere   9 1 23.69024
unit 1
cylinder 2 1 28.267 82.65 0.0
hole    91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole    91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole    91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355 vi
unit 4
cylinder 2 1 28.267 82.65 0.0
hole    91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 2 1 28.267 82.65 0.0
hole    92    4.57675 0.0 58.95975
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 6
cylinder 2 1 28.267 82.65 0.0
hole    92    4.57675 0.0 23.69025
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
```

```
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3 unit with 120-gram drum'
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 6 4 6 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f52 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

***Case 1-2:*** The input deck used to investigate the interaction of 200-gram Pu drums with 120-gram fissile drums. The 6-drum formation consists of 3 200-gram Pu drums and 3 120-gram fissile drums. The input deck name is **dr200sb120**. The concentric spherical radii of the 120-gram fissile core and reflector shells are listed in Table 16. It should be noted that all drums are filled with PE. A sample deck, which corresponds to a Pu volume fraction of 0.24% and has a $k_{eff}$ value of 0.9325, is listed below:

```
=csas25
dr200sb120:200gPu;0.24%VF;100%PE Mod&Refl;3-high;one 120g drum in 2
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
poly(h2o)    1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o        6 0.0001 293 end
beryllium 7 den=1.85 1.0 293 end
uranium   8 den=19.05 1.0 293 end
c 9 den=2.25 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.00913 2 28.267 3 28.495 4 28.630 end zone
dr200sb120:200gPu;0.24%VF;100%PE Mod&Refl;3-high;one 120g drum in 2
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 92
sphere   1 1  8.44203
sphere   7 1  8.64820
sphere   8 1 12.38562
sphere   9 1 14.00820
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91    18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
```

```
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 2 1 28.267 82.65 0.0
hole     92   14.25879 0.0 68.64179
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 6
cylinder 2 1 28.267 82.65 0.0
hole     92   14.25879 0.0 14.00821
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3 unit with 120-gram drum'
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 6 4 6 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f52 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

***Case 1-3:*** The input deck used to investigate the interaction of 200-gram Pu drums with 120-gram mix array/container. Because of the paucity of mix array in RHWM operations, it is expect that no more than one mix array/container may interact with the 200-gram drum array. Two 6-drum formations are used. One consists of 200-gram Pu drums only. The other consists of one mix array/container and 5 200-gram Pu drums. The two 6-drum formations are used to form a 5x10 super unit cell, with one mix array/container 6-drum formation and forty-nine all 200-gram Pu drum formations. This results in one out of 300 drums is a mix array/container. The input deck name is **dr200sbmx**. The concentric spherical radii of the 120-gram fissile core and reflector shells are listed in Table 17. It should be noted that all drums are filled with PE. A sample deck, which corresponds to a Pu volume fraction of 0.24% and has a $k_{eff}$ value of 0.9677, is listed below:

```
=csas25
dr200sbmx:200gPu;0.24%VF;100%PE Mod&Refl;3-high;1 mix array drum in 300
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
poly(h2o)     1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o         6 0.0001 293 end
uranium     7 den=19.05 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.00913 2 28.267 3 28.495 4 28.630 end zone
dr200sbmx:200gPu;0.24%VF;100%PE Mod&Refl;3-high;1 mix array drum in 300
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 92
sphere   1 1  8.44203
sphere   7 1 23.59359
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 2 1 28.267 82.65 0.0
hole     92   4.67340 0.0 59.05640
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
```

```
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3 unit with mix array'
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 3 4 3 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill 52 f51 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

Group 2 consists of four bounding upset scenarios: 2-1) the interaction with optimized 55-gallon latticed Nat-U drums, 2-2) the interaction with optimized 30-gallon latticed Nat-U drums, 2-3) the interaction with optimized homogenized Nat-U drums and 2-4) the interaction with solid Nat-U drums.

***Case 2-1:*** The input deck used to investigate the interaction of 200-gram Pu drums with 55-gallon latticed Nat-U drums. The 6-drum formation consists of 5 200-gram Pu drums and 1 Nat-U drum. The input deck name is **dr200sb55us**. The optimized Nat-U lattice structure, corresponding to a pitch of 5.63586 cm and a Nat-U rod diameter of 2.4 cm, is derived in CSM 1034. The 200-gram drum has a Pu volume fraction of 0.24%. A sample deck, which has a $k_{eff}$ value of 0.9251, is listed below:

```
=csas2x   param=(size=4000000)
dr200sb55us:200gPu;0.24%VF;100%PE Mod&Refl;3-high;one lat U SB 55-gal drum in 2
44groupndf5 latticecell
plutoniumalp 1 den=19.84 0.0024 293 end
poly(h2o)    1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o         6 0.0001 293 end
uranium   7 1.0 293 end
arbmsuper 0.86 2 0 1 0 1000 30 6012 15 8 0.3 293 end
end comp
triangpitch 5.63586 2.4 7 8 end
dr200sb55us:200gPu;0.24%VF;100%PE Mod&Refl;3-high;one lat U SB 55-gal drum in 2
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 1
cylinder 2 1 28.267 82.65 0.0
hole    91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
```

```
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 500 1 28.267 82.65 0.0
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3 unit: 3 Pu drums&3 Solid U drums'
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 1 5 3 5 3 5 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f52 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

***Case 2-2:*** The input deck used to investigate the interaction of 200-gram Pu drums with 30-gallon latticed Nat-U drums. The 6-drum formation consists of 5 200-gram Pu drums and 1 Nat-U drum. The input deck name is **dr200sb30us**. The optimized lattice structure, corresponding to a pitch of 8.27871 cm and a Nat-U rod diameter of 2.6 cm, is derived in CSM 1034. The sample deck, which has a $k_{eff}$ value of 0.9183, is similar to the one listed for Case 2-1. The following two cards should replace the corresponding card in the sample deck Case 2-1:

Material Card

```
arbmsuper 0.86 2 0 1 0 1000 30 6012 15 8 0.15 293 end
```

Latticecell Card

```
triangpitch 8.27871 2.6 7 8 end
```

***Case 2-3:*** The input deck used to investigate the interaction of 200-gram Pu drums with optimized homogenized Nat-U/PE drums. The 6-drum formation consists of 3 200-gram Pu drums and 3 Nat-U drums. The input deck name is **dr200sbhu**. The optimized homogenized structure, corresponding to a volume fraction of 32.19%, is derived in CSM 1309. The sample deck, which has a $k_{eff}$ value of 0.9351. The input deck listed corresponds to a Pu volume fraction of 0.24% for the 200-gram Pu drums.

```
=csas25
dr200sbhu: 200gPu;0.24%VF;PE Mod&Refl;3-high;One homo U Drum in 2
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
poly(h2o)    1 den=0.923 0.9976 293 end
poly(h2o) 2 den=0.923 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o         6 0.0001 293 end
uranium     7 1.0 293 end
uranium   8 den=19.05 0.3219 293 end
poly(h2o) 8 den=0.923 0.6781 293 end
beryllium  9 1.0 293 end
c 10 den=2.25 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.00913 2 28.267 3 28.495 4 28.630 end zone
dr200sbhu: 200gPu;0.24%VF;PE Mod&Refl;3-high;One homo U Drum in 2
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 1
cylinder 2 1 28.267 82.65 0.0
hole    91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole    91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole    91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole    91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
```

```
cylinder 7 1 28.267 82.65 0.0
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 6
cylinder 8 1 28.267 82.65 0.0
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 7
cylinder 9 1 28.267 82.65 0.0
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 8
cylinder 10 1 28.267 82.65 0.0
cylinder  3 1 28.495 82.878 -0.228
cylinder  4 1 28.630 83.005 -0.355
cuboid    6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3 unit: 3 Pu drums&3 Solid U drums'
array 52 3*0.0
unit 53
com='2x3 unit: 3 Pu drums&3 homo U-PE drums-CSM1309'
array 53 3*0.0
unit 54
com='2x3 unit: 3 Pu drums&3 Solid Be drums'
array 54 3*0.0
unit 55
com='2x3 unit: 3 Pu drums&3 Solid carbon drums'
array 55 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 1 5 3 5 3 5 end fill
ara=53 nux=2 nuy=1 nuz=3 fill 1 6 3 6 3 6 end fill
ara=54 nux=2 nuy=1 nuz=3 fill 1 7 3 7 3 7 end fill
ara=55 nux=2 nuy=1 nuz=3 fill 1 8 3 8 3 8 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f53 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

***Case 2-4:*** The input deck used to investigate the interaction of 200-gram Pu drums with solid Nat-U/PE drums. The 6-drum formation consists of 3 200-gram Pu drums and 3 Nat-U drum. The input deck name is **dr200sbsu**. The optimized homogenized structure, corresponding to a volume fraction of 32.19%, is derived in CSM 1309. The sample deck, which has a $k_{eff}$ value of 0.9414. The 200-gram Pu drums have a Pu volume fraction of 0.24%. The input deck is the same as in Case2-3. The only difference is that '`f53`' in Array Card for Array 99 should be changed to '`f52`.'

Group 3 consists of two bounding upset scenarios: 3-1) the interaction with solid beryllium drums and 3-2) the interaction with solid carbon/graphite drums.

***Case 3-1:*** The input deck used to investigate the interaction of 200-gram Pu drums with solid beryllium drums. The 6-drum formation consists of 3 200-gram Pu drums and 3 beryllium drums. The input deck name is **dr200sbbe**. The sample deck, which has a $k_{eff}$ value of 0.9255. The 200-gram Pu drums have a Pu volume fraction of 0.24%. The input deck is the same as in Case2-3. The only difference is that '`f53`' in Array Card for Array 99 should be changed to '`f54`.'

***Case 3-2:*** The input deck used to investigate the interaction of 200-gram Pu drums with solid carbon/graphite drums. The 6-drum formation consists of 3 200-gram Pu drums and 3 carbon/graphite drums. The input deck name is **dr200sbc**. The sample deck, which has a $k_{eff}$ value of 0.9247. The 200-gram Pu drums have a Pu volume fraction of 0.24%. The input deck is the same as in Case2-3. The only difference is that '`f53`' in Array Card for Array 99 should be changed to '`f55`.'

## B.5. Bounding Scenario 6 – Loss of Stacking Controls (Table 22)

The input desks listed in Section B.5 are used to evaluate Bounding Scenario 6 (or the upset dealing with loss of stacking controls) for 200-gram Pu drum storage with water/PE moderation and reflection. The input files for the water/PE and water-only moderated and reflected cases are named **dr200sbw4h** and **dr200sb4hh2o**. They contain the input decks for 200-gram Pu drums with the Pu core volume fraction ranging from 0.10% to 0.24%. The results from calculations using these input files are listed in Table 22 of the main text. The input files are for KENO V.a calculations using the SCALE4.4 ENDF/B-V 44-Group cross section library. KENO V.a is driven by the SCALE criticality safety analysis sequence (CSAS) driver, CSAS25.

A sample case for the water/PE moderated and reflected cases, **dr200sbw4h,** is listed here. The water/PE cases have one drum filled with PE and the 3 drums filled with water in a 4-plex formation, which is the basis of a 4-high infinite X-Y array. The sample case corresponds to a Pu volume fraction of 0.24% with a $k_{eff}$ value of 0.9277.

```
=csas25
dr200sbw4h: 200gPu;0.24%VF;H2O+PE Mod&Refl;4-high
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
h2o          1           0.9976 293 end
h2o        2 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o         6 0.0001 293 end
plutoniumalp 7 den=19.84 0.0024 293 end
poly(h2o)     7 den=0.923 0.9976 293 end
poly(h2o)     8 den=0.923 1.0 293 end
end comp
spherical reflected reflected 0.0 end
7 10.00913 8 28.267 3 28.495 4 28.630 end zone
```

```
dr200sbw4h: 200gPu;0.24%VF;H2O+PE Mod&Refl;4-high
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 92
sphere   7 1 10.00913
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 8 1 28.267 82.65 0.0
hole     92   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3, Pu balls in nearest corners'
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=4 fill 1 2 3 4 2i 1 4 end fill
ara=52 nux=2 nuy=1 nuz=4 fill 5 2 3 4 2i 1 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f52 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

For the sample case with water-only moderation and reflection from **dr200sb4hh2o**, it has a $k_{eff}$ value of 0.8961 with a Pu volume fraction 0f 0.24%.

```
=csas25
dr200sb4hh2o:200gPu 0.24%VF;100%H2O Mod&Refl;4-high
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
h2o          1 den=0.9982 0.9976 293 end
h2o       2 den=0.9982 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o         6 0.0001 293 end
end comp
spherical reflected reflected 0.0 end
1 10.00913 2 28.267 3 28.495 4 28.630 end zone
dr200sb4hh2o:200gPu 0.24%VF;100%H2O Mod&Refl;4-high
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 0 1 4*0.0 100.0 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=4 fill 1 2 3 4 1q4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f51 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

## B.6. Bounding Scenario 7 – Flooding (Table 23)

The input desks listed in Section B.6 are used to evaluate Bounding Scenario 7 (or the flooding upset) for 200-gram Pu drum storage with water/PE moderation and reflection. The input files for the water/PE and water-only moderated and reflected cases are named **dr200sbwf** and **dr200sbfh2o**. They contain the input decks for 200-gram Pu drums with the Pu core volume fraction ranging from 0.10% to 0.24%. The results from calculations using these input files are listed in Table 23 of the main text. These input files are for KENO V.a calculations using the SCALE4.4 ENDF/B-V 44-Group cross section library. KENO V.a is driven by the SCALE criticality safety analysis sequence (CSAS) driver, CSAS25.

A sample case for the water/PE moderated and reflected cases, **dr200sbwf**, is listed here. The water/PE cases have one drum filled with PE and the 5 drums filled with water in a 6-drum formation, which is the basis of a 3-high infinite X-Y array. The sample case corresponds to a Pu volume fraction of 0.24% with a $k_{eff}$ value of 0.9270.

```
=csas25
dr200sbwf: 200gPu;0.24%VF;H2O+PE Mod&Refl;3-high;fully flooded
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
h2o          1             0.9976 293 end
h2o        2 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o          6 1.0 293 end
plutoniumalp 7 den=19.84 0.0024 293 end
poly(h2o)     7 den=0.923 0.9976 293 end
poly(h2o)     8 den=0.923 1.0 293 end
end comp
spherical reflected reflected 0.0 end
7 10.00913 8 28.267 3 28.495 4 28.630 end zone
dr200sbwf: 200gPu;0.24%VF;H2O+PE Mod&Refl;3-high;fully flooded
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
sphere   1 1 10.00913
unit 92
sphere   7 1 10.00913
unit 1
cylinder 2 1 28.267 82.65 0.0
hole     91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole     91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
```

```
unit 3
cylinder 2 1 28.267 82.65 0.0
hole     91    18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole     91   -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 5
cylinder 8 1 28.267 82.65 0.0
hole     92    18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
unit 52
com='2x3, Pu balls in nearest corners'
array 52 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 6 1 4*0.0 30.48 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=52 nux=2 nuy=1 nuz=3 fill 5 2 3 4 3 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f52 end fill end array
read bounds xyf=periodic end bounds
end data
end
```

For the sample case with water-only moderation and reflection from **dr200sbfh2o**, it has a $k_{eff}$ value of 0.9009 with a Pu volume fraction 0f 0.24%.

```
=csas25
dr200sbfh2o:200gPu 0.24%VF;100%H2O Mod&Refl;3-high;fully flooded
44groupndf5 multiregion
plutoniumalp 1 den=19.84 0.0024 293 end
h2o          1 den=0.9982 0.9976 293 end
h2o       2 den=0.9982 1.0 293 end
poly(h2o) 3 den=0.965 1.0 293 end
carbonsteel 4 1.0 293 end
orconcrete  5 1.0 293 end
h2o         6 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.00913 2 28.267 3 28.495 4 28.630 end zone
dr200sbfh2o:200gPu 0.24%VF;100%H2O Mod&Refl;3-high;fully flooded
read param npg=2000 gen=225 nsk=25 nub=yes fdn=yes end param
read geom
unit 91
```

```
sphere   1 1 10.00913
unit 1
cylinder 2 1 28.267 82.65 0.0
hole    91   18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 2
cylinder 2 1 28.267 82.65 0.0
hole    91  -18.25786 0.0 72.64086
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 3
cylinder 2 1 28.267 82.65 0.0
hole    91   18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 4
cylinder 2 1 28.267 82.65 0.0
hole    91  -18.25786 0.0 10.00914
cylinder 3 1 28.495 82.878 -0.228
cylinder 4 1 28.630 83.005 -0.355
cuboid   6 1 4p28.630 83.005 -0.355
unit 51
com='array: 2x3, Pu balls in nearest corners, all SB'
array 51 3*0.0
global unit 99
array 99 0.0 0.0 0.0
replicate 6 1 4*0.0 30.48 0.0 1
replicate 5 1 5*0.0 40.64 1
end geom
read array ara=51 nux=2 nuy=1 nuz=3 fill 1 2 3 4 3 4 end fill
ara=99 nux=5 nuy=10 nuz=1 fill f51 end fill end array
read bounds xyf=periodic end bounds
end data
end
```