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Criticality Safety Analysis on the Mixed Be, Nat-U, and C (Graphite) Reflectors in 55-Gallon Waste Drums and Their Equivalents for HWM Applications

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CRITICALITY SAFETY ANALYSIS

On the

Mixed Be, Nat-U, and C (Graphite) Reflectors in 55-Gallon Waste Drums and Their Equivalents for HWM Applications

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1.0 INTRODUCTION

1.1 Objective

The objective of this analysis is to develop and establish the technical basis on the criticality safety controls for the storage of mixed beryllium (Be), natural uranium (Nat-U), and carbon (C)/graphite reflectors in 55-gallon waste containers and/or their equivalents in Hazardous Waste Management (HWM) facilities.

1.2 Background

This work establishes and develops a new mixed reflector criticality safety control rules for 55-gallon HWM waste drums. The new mixed reflector rules are not applicable to 5-gallon and 30-gallon waste drums. In the following paragraphs, a brief background on the current general reflector control is given. It should be noted that the general reflector control applies to all of the 5-, 30-, and 55-gallon HWM waste drums. For storage at HWM, qualified waste containers (including 5-, 30-, and 55-gallon drums) are required to meet the reflector mass limits. Current general control for reflectors in HWM waste containers is:

(a) 300 grams of beryllium, or
(b) 100 kilograms of natural and/or depleted uranium (Nat-/Dep-U), or
(c) 8 kilograms of carbon and/or graphite.

The reflector controls depict that in any qualified HWM waste container, only one of the three types of reflectors is allowed. It can be up to 300 grams of beryllium, or up to 100 kilograms of Nat-U/Dep-U, or up to 8 kilograms of carbon/graphite. Mixing of the three types of reflectors in any single waste container is not allowed for all containers in the uniform storage arrays. This general control for reflectors is also in couple with other controls on fissile, moderator, shape, and interaction.

Aside from waste container storage operations, HWM also has waste treatment operations, which include size-reduction and waste concentration processes. Some of waste treatment operations require the addition of activated carbon, which has the same nuclear characteristics as graphite, to adsorb the volatile organic compounds (VOC) so as to meet the regulatory requirements. Such operations potentially may introduce large amount of carbon into Nat-U or Be rich fissile/ fissionable containing wastes. This will result in mixed reflectors in fissionable wastes that are not compliant with the current reflector control rules for the fissionable material drums. This work derives and establishes the technical basis for the storage of mixed reflectors in fissile drums. Furthermore, the amount of carbon/graphite allowed are increased to 110 kilograms to address the fact that activated carbons are widely used for off-gas adsorption for HWM operation. The mixed reflector controls allow for reflectors in the listed amounts in any combinations,

(a) 300 grams of beryllium, and
(b) 100 kilograms of natural and/or depleted uranium (Nat-/Dep-U), and
(c) 110 kilograms of carbon and/or graphite.

The mixed reflector controls allow for the presence of three types of reflector all at once in a single 55-gallon container, unlike the general reflector controls allowing only one of the three types of reflectors in any single fissile containers. To compensate for the relaxation in the reflector control rules, the fissile mass limit is reduced from 120 grams to 65 grams Pu equivalent for the 55-gallon mixed reflector drums. For more detailed descriptions on the mixed reflector controls, please refer to Section 3 of this report.

Also, in this work, a 50-gram reflector waiver is developed as in Appendix C to allow for limited mixing in the primary reflector with other reflectors (up to a total of 50 grams). This will address the HWM concern that the major reflectors in the waste containers could be contaminated with trace amounts of the other reflectors. This 50-gram waiver will alleviate the concern that trace amounts of the other material would cause non-compliance issues for HWM operations. This 50-gram reflector waiver is not only limited to applications for 55-gallon drums and their equivalents. This waiver is also applicable to applications for 5-gallon and 30-gallon drums.

2.0 FACILITY AND OPERATIONS DESCRIPTION

2.1 Facility Description

The CS controls for the mixed reflectors in 55-gallon drums are applicable to all HWM facilities with the need for 55-gallon waste drum array storage. The applicable HWM facilities include Area 514 (A514), Area 612 (A612), which includes Building 625 (B625), Building 693 (B693), Building 169 (B169) Consolidation Waste Accumulation Area (CWAA), Building 280 (B280), and the Decontamination Waste Treatment Facility (DWTF), which includes Building 695 (B695) and Building 696 (B696).

2.2 Operations Description

The mixed reflector controls developed are only applicable to the storage operations using the uniform-size storage array composed of 55-gallon drums and their equivalents. These mixed reflector controls are not applicable to 5-gallon and 30-gallon drums and their equivalents. Nor are these mixed reflector controls applicable to the 5-gallon and 30-gallon container storage arrays.

3.0 CRITICALITY SAFETY CONTROL

The mixed array reflector controls are used with the reflector control rules in CSM 920 Rev. 2 [1], CSM 921 Rev. 2 [2], and CSM 941 [3]. They are part of the general site-wide CS controls (CSAM99-061 [4]).

Definitions and Explanations:

i. Natural uranium (Nat-U) is elemental uranium containing 0.711 percent by weight of its fissile isotope ^{235}U. Its U-235 mass equivalent is 0.711% of the total Nat-U mass.

ii. Depleted uranium (Dep-U) is elemental uranium containing less than 0.711 percent by weight of its fissile isotope ^{235}U. Its U-235 mass equivalent is its enrichment times its weight, if its enrichment is known. If the enrichment is unknown, it has to be treated as Nat-U in converting to U-235 mass equivalent.

iii. Container Equivalent

A container may be equivalent to 5-gallon, 30-gallon, and 55-gallon drums if the container has the capacity no less than the drum it is equivalent to and the smallest dimension of the container is no less than the smallest dimension of the drum it is equivalent to:

- 5-gallon drum equivalents are containers with a minimum capacity of 5 gallons (18.9 liters) each and an outer dimension of 6.44 inches (16.3 centimeters) or more on all sides.
- 30-gallon drum equivalents are containers with a minimum capacity of 30 gallons (113 liters) each and an outer dimension of 18.25 inches (46.3 centimeters) or more on all sides.
- 55-gallon drum equivalents are containers with a minimum capacity of 55 gallons (208 liters) each and an outer dimension of 22.25 inches (56.5 centimeters) or more on all sides.

iv. Container Type: The types of fissionable material contained within a container determine the container types, which can be of fissile-drum or Nat-U-drum. Fissile-drum type refers to containers containing significant amounts of fissile or Pu equivalent as well as up to 100 kilograms of Nat-U equivalents. Nat-U-drum type refers to containers containing significant amounts of Nat-U equivalent but no more than the waiver amount of fissile or Pu equivalents as specified in CSAM 98-369 Rev. 1 [5] or CSAM 99-061 [4].

v. Mixed-Size Array refers to arrays each with containers of all sizes, including different equivalent sizes, and shapes. Uniform-Size Array refers to arrays each with all of its containers in the same equivalent size.

vi. Mixed-Type Array refers to arrays each with containers of fissile-drum and Nat-U drum types intermingled together. Uniform-Type Array refers to arrays each with all of its containers being of the same type; no intermingling of fissile-drum and Nat-U drum types is allowed.

vii. Mixed Array (or Mixed-Size and Mixed-Type Array) refers to arrays that are not both uniform arrays and uniform types.

3.1 Operation Controls:

All of the currently prevailing CS controls in this category, if not overwritten, remain in effect and are unaffected by these mixed reflector controls. Therefore, operations are to follow applicable facility safety plan (FSP) and operation safety plan (OSP).)

3.2 Mass Limits (Fissile/Pu)

Fissile mass limits are controlled. The amount of fissile in each 55-gallon waste container or its equivalent is limited to 65 grams of Pu equivalent.

3.3 Moderation

The current moderation controls are not affected by the mixed control and shall remain in effect.

3.4 Enrichment

Not controlled.

3.5 Interaction

Interaction is controlled. In array formations, the 55-gallon mixed waste containers (with 300g Be, and 100kg Nat-/Dep-U, and 110kg C/graphite) may only be mixed with the 55-gallon regular fissile containers (with 300g Be, or 100kg Nat-/Dep-U, or 8 kg C/graphite). A separation distance of no-less-than 76.2 cm (or 30 in) from other arrays or containers is required. When moving a container from/to an array, this 76.2-cm (30-in) separation distance requirement is waived.

3.6 Volume

Volume is controlled. Only 55-gallon waste containers and their equivalents are applicable for these mixed reflector controls.

3.7 Reflection

Reflection is controlled. A 50-gram reflector waiver is allowed. Also, for 55-gallon drums meeting the mass limit specified in Section 3.2 Mass, reflectors are allowed in the amounts as specified below:

(a) up to 300 grams of beryllium, and/or
(b) up to 100 kilograms of natural and/or depleted uranium (Nat-/Dep-U), and/or
(c) up to110 kilograms of carbon and/or graphite.

3.8 Geometry

Not controlled

3.9 Neutron Poisons

Not applicable

3.10 Form (Concentration/Density)

Not applicable

4.0 CRITICALITY SAFETY ASSESSMENT METHODOLOGY

4.1 Introduction

This mixed reflector waiver involves specific HWM operation configurations. These operation configurations involve complicated geometry that general criticality safety handbooks and reports do not contain the appropriate information for such applications. Therefore, the one-dimensional deterministic code, XSDRNPM [6], and the three-dimensional Monte Carlo code, KENO V.a [6], of the SCALE 4.4 package have both been used for this study. XSDRNPM has been used for parametric studies and KENO V.a has been used for the detailed 3-D modeling and simulation.

4.2 Description of Calculational Method

Both XSDRNPM and KENO V.a of the SCALE4.4 package [6] were used for this analysis. All calculations were performed on a SUN workstation (Ultra 60) named *Godiva*[1]. *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].

4.2.1 The XSDRNPM Code

Two options were 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

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[1] *Godiva* referred in the Cold-Vapor Evaporator (CVE) study (CSM 944 [7]) is a HP-UX 10 dual-processor workstation, which is renamed as *Jezebel* and is not available for this analysis. The Energy Directorate workstation, *Pushkin*, referred in CSM 944 [7] suffered a catastrophic breakdown in January 1999 and is no longer available for CSG usage.

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 options allow for customizing XSDRNPM calculations. However, such calculations require the use of CSASIX [6] to preprocess and convert the cross section library into an XSDRNPM usable format. Such applications can be used for k_{eff} value, parameter search, and optimization calculations. The three driver modules, CSAS1X, CSASIX, and XSDRNPM are individually described and discussed in the following subsections.

4.2.1.1 The CSAS1X Driver

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.

4.2.1.2 The CSASIX Driver

The CSASIX driver invokes BONAMI, NITAWL, XSDRNPM, and ICE [6], in the order as specified. It acts like CSAS1X. However, the XSDRNPM run for this driver is to generate a flux distribution for the cell effect and prepares the cell-corrected working library of microscopic cross sections. ICE then creates a resonance- and cell-corrected mixing macroscopic working library from the microscopic working library. It is worth mentioning that the effect originated from the heterogeneity of the lattice cell is inherently integrated into the mixing working library through the cell-weighted correction through the XSDRNPM calculations in this CSASIX driver sequence.

4.2.1.3 XSDRNPM

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.

4.2.2 The KENO V.a Code

In this analysis, CSAS KENO V.a drivers, CSAS25 [6] and CSAS2X [6] , were 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.

4.2.2.1 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.

4.2.2.2 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.

4.3 XSDRNPM And KENO V.a Verification

Verification of XSDRNPM and KENO V.a on *Godiva* has been documented in Sections 4.3.1 and 4.3.2, respectively, of CSM 1086 (1999) [8]. 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 CSM 1086 directly [8].

4.4 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 (1999) [9]. 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 directly [9].

4.4.1 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 5. 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 [10]	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 5 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 [9].

4.4.2 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 6. 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 [10]	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 6 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.

4.5 Safety Margin and Subcriticality (as abridged from Section 4.5 of CSM 1087 [9])

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 7. 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.

Table 7. 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 this analysis and for CSM 1086 [8].

Computer System	99% Confidence Level Bias		Subcritical Limit	
	XSDRNPM	KENO V.a	XSDRNPM	KENO V.a
Godiva (this analysis)	0.009	0.008	0.971	0.972
Godiva (CSM 1086)	0.015	0.019	0.965	0.961

4.6 Material and Container Information

The materials used in this analysis and their properties are as listed in Table 8. 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 [11] because they are not available in the SCALE4.4 material database.

Table 8. 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, C15H30 at 0.129 g/cc or 15% of the theoretical density listed in the previous column. Superla is to be used with Nat-U rods to form optimized configurations (CSM 1034 [11])
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 storage of mixed reflectors. 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 upper bounded by the 55-gallon drums from a neutronic coupling viewpoint. 5-gallon and 30-gallon waste containers and their equivalents are not applicable for the storage of mixed reflectors. In this regard, Table 9 excludes the information on 5-gallon and 30-gallon containers, but includes some of the standardized waste boxes (SWB).

Table 9. 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. This is because of the larger interaction distance that the interaction between such containers and 55-gallon drum arrays is not more severe that interaction among 55-gallon drums themselves.

Table 10. Non-Exhaustive List of Waste Containers that are of 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 Standardized Waste Box (SWB) 4'x4'x7'	To pack TRU drums in a 2x2 formation	A TRUPACK 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

5.0 ANALYSIS

5.1 HWM Operation Needs

The presently prevailing criticality safety controls for the reflectors in 5-gallon, 30gallon, 55-gallon waste drums and their equivalents are (as in CSM 920 Rev.2, CSM 921 Rev.2, and CSM 940) as listed below:

*For containers (*including 55-gallon waste drums*) with fissile material, the following reflector materials are permitted in the listed amounts:*

a) 100 kilograms of natural or depleted uranium, or
b) 300 grams of beryllium, or
c) 8 kilograms of graphite.

5.1.1 Moderator Considerations

It is established in Section 5.1.1 of CSM 944 [7] on the CVE operations that among moderators of paraffin, polyethylene, TrimSol, Superla White Oil No. 9, water, beryllium, and beryllium-polyethylene mixtures, polyethylene and paraffin are most effective in causing higher reactivities. Since hydrogen has the best neutron scattering property and a not-so-large neutron absorption cross section, materials containing the highest density for hydrogen are the better moderators. In this regard, paraffin and polyethylene are the better moderators. Polyethylene and paraffin have similar hydrogen densities. Polyethylene is a unsaturated CH_2 polymer and paraffin is made of $C_{25}H_{52}$, a saturated CH_2 polymer. Therefore, polyethylene and paraffin are interchangeable as moderators with specific densities of 0.923 g/cm^3 and 0.90 g/cm^3, respectively. Also considered in this study are oils used for the storage of Nat-U and Dep-U chips, TrimSol and Superla White Mineral Oil No.9. Below listed in Table 14 are the theoretical hydrogen densities in polyethylene, paraffin, TrimSol, Superla White Mineral Oil No.9, and water:

Table 12. The theoretical specific densities of hydrogen atoms in polyethylene (PE), paraffin, TrimSol, Superla White Mineral Oil No. 9, and water.

Material Type	Theoretical Density (g/cc)	Chemical Composition	Hydrogen Density (g/cc)
Water	0.9982	H_2O	0.1109
TrimSol*	1.0066	65.16 wt% C, 11.08 wt% H, 23.76 wt% O*	0.1115
Superla No. 9*	0.86	C15H30*	0.1229
Polyethylene (PE)	0.923	CH2 Chain	0.1318
Paraffin	0.90	C25H52	0.1330

*Chemical compositions as used in CSM 1034 [11].

It should be noted in Table 14 that polyethylene and paraffin have similar hydrogen densities, which are relatively high compared to that of water. Therefore, they will be used as the operation upper bound in hydrogen densities for mixed array operations. Because of their similarity in chemical composition and in hydrogen density content, they will be used interchangeably in this analysis. More discussions on the moderator effectiveness can be found in Section 5.1.1 of CSM 944 [7].

5.1.2 Reflector Considerations

In Figure 1, it shows that Nat-U and Dep-U are better reflectors compared to paraffin and polyethylene. At small thickness, they are also better reflectors compared to graphite. For more detail information on the effectiveness of Nat-U and Dep-U as reflectors, please refer to Section 5.1.2 Moderation Considerations in CSM 944 [7], '*Criticality Safety Analysis on the Cold-Vapor Evaporator Unit Operations.*'

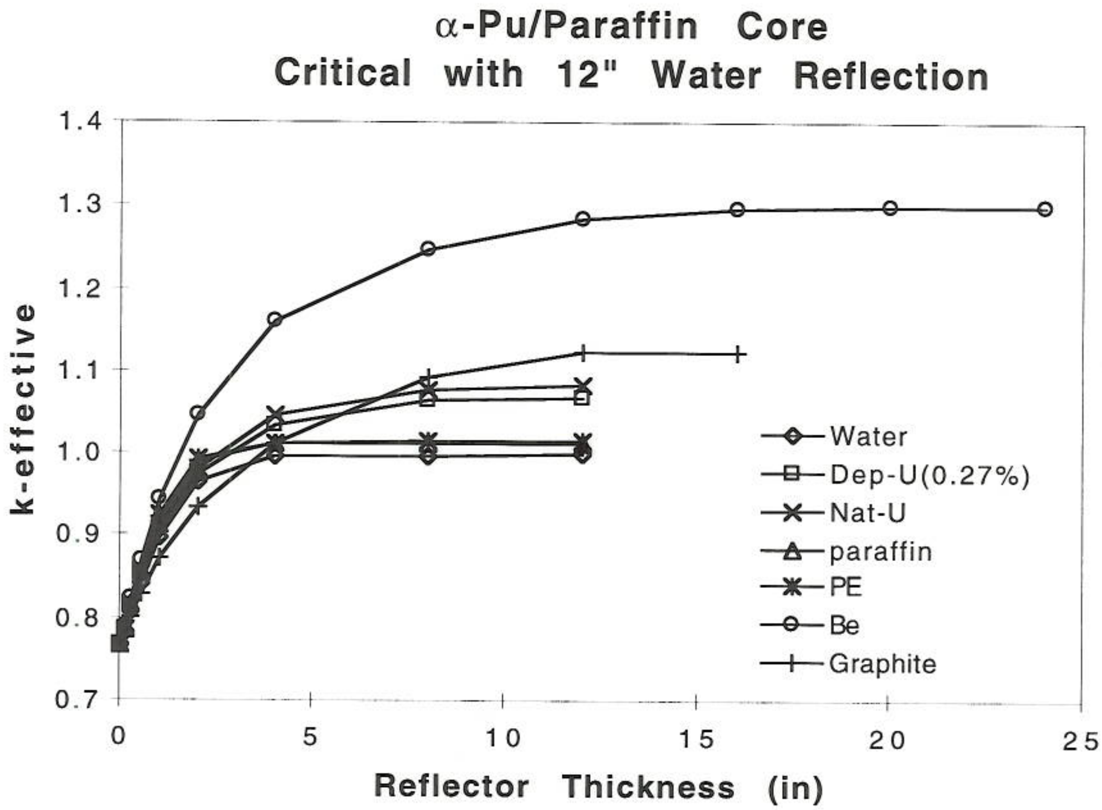
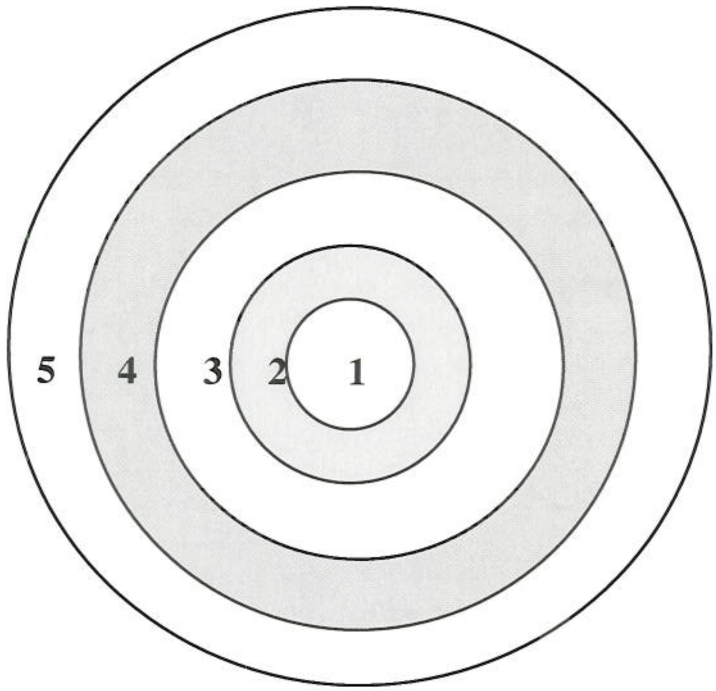


Figure 1. The system k_{eff} as a function of the thickness of different reflectors for an α-Pu/paraffin core that would be critical with 12" of water reflection (as in Figure 1 of CSM 944 [7]).

5.1.3 Configuration Considered

The spherical geometry is chosen because of its low surface to volume ratio, which allows less neutron leakage and better neutron economy, as compared to any other geometry. The spherical core is completely surrounded by layers of reflector shells. Reflector shells are the most optimized reflector configurations. The layers of reflectors are in the order of beryllium, Nat-U, carbon/graphite, and polyethylene from inside out. The optimized configuration for core and reflectors is as shown in Figure 2.

Optimized Configuration



1 denotes the plutonium (α phase)-paraffin/polyethylene core
2 denotes the beryllium reflector shell
3 denotes the natural/depleted uranium reflector shell
4 denotes the carbon (graphite) reflector shell
5 denotes an outermost polyethylene reflector shell, if available

Figure 2. The optimized core and reflector configuration used for this analysis. The arrangements for the stratified reflectors are shown in the order as modeled in all calculations.

5.1.4 Optimized Conditions

This search is to determine the optimized k_{eff} values as a function of the Pu volume fraction (VF) for the core configuration shown in Figure 2. This core is a homogeneous mixture of plutonium and polyethylene (PE) with the plutonium VF varying from 0.10% to 0.20%. The core is first reflected by a Be shell, then by a Nat-U shell and finally by a C (graphite) reflector. Each reflector shell is also modeled with the inclusion of 50 grams of trace-amount material. The mass limits are 300 grams for Be, 100 kilograms for Nat-U, and 110 kilograms for C (graphite). In other words, in all modelings dealing with the reflector mass limits, 50 grams of trace amount are added to each type of reflectors.

Table 13. The system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a 65-gram plutonium core moderated by PE and reflected first by a 350-gram Be (beryllium) shell, then by a 100050-gram Nat-U shell, and finally by a 110050-gram C (carbon/graphite) shell. Two types of systems are considered: One with the outer radius of the PE reflector shell at 30 cm and the other with the thickness of the outmost PE reflector shell at 1 foot (30.48cm)

Pu VF	Pu Mass (g)	Pu-PE Core Radius (cm)	Be Mass (g)	Be Shell Outer Radius (cm)	Nat-U Mass (g)	Nat-U Outer Shell Radius (cm)	Carbon Mass (g)	Graphite Outer Shell Radius (cm)	k_{eff} for 30-cm Outer PE Radius	k_{eff} for 1'-PE Reflection
0.10%	65	9.21357	350	9.38761	100050	12.76730	110050	24.43637	0.790492	0.792600
0.11%	65	8.92545	350	9.11057	100050	12.62021	110050	24.39662	**0.791193**	**0.793191**
0.12%	65	8.67030	350	8.86611	100050	12.49496	110050	24.36339	0.790318	0.792312
0.13%	65	8.44203	350	8.64820	100050	12.38698	110050	24.33520	0.788502	0.790341
0.14%	65	8.23604	350	8.45226	100050	12.29291	110050	24.31099	0.785758	0.787539
0.15%	65	8.04879	350	8.27478	100050	12.21020	110050	24.28996	0.782390	0.784120
0.16%	65	7.87749	350	8.11299	100050	12.13690	110050	24.27154	0.778543	0.780232
0.17%	65	7.71990	350	7.96467	100050	12.07148	110050	24.25526	0.774375	0.776003
0.18%	65	7.57420	350	7.82803	100050	12.01272	110050	24.24076	0.769916	0.771513
0.19%	65	7.43892	350	7.70160	100050	11.95966	110050	24.22778	0.765273	0.766844
0.20%	65	7.31281	350	7.58415	100050	11.91150	110050	24.21609	0.760499	0.762048
								Input:	db65x	db65xw

Table 13 above lists the optimized results for the cases that all of the mixed reflector cases (including the reflector waiver) are singly batched in the amount of fissile. Two types of systems are considered. One is with PE reflection up to a outer radius of 30 cm. The other is with 1-foot (30.48-cm) PE reflection on the outside. The optimized Pu volume fraction is 0.11% for both systems.

Table 14 lists the optimized results for the cases that all of the mixed reflector cases (including the reflector waiver) are doubly batched in the fissile. Two types of systems are considered. One is with PE reflection up to a outer radius of 30 cm. The other is with 1-foot (30.48-cm) PE reflection on the outside. The optimized Pu volume fraction is 0.14% and 0.15% for the two systems. In this analysis, the optimized Pu volume fraction is chosen to be 0.15%, because the 30-cm radius system is in closer order to the diameter of the 55-gallon drums. The difference in the keff value is less than 0.0001 between 0.14% and 0.15% Pu volume fractions. In Table 5, it show that with a confidence level of 99%, the statistical uncertainty is about 0.0090, which is 90 times of this difference. In this regard, both 0.14% and 0.15% can be considered as optimized when factoring in the statistical uncertainty derived from the critical experiments. Therefore, the selection of 0.14% or 0.15% is really a toss-up and will not matter much in the analysis results.

Table 14. The system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a 130-gram plutonium core moderated by PE and reflected first by a 350-gram Be (beryllium) shell, then by a 100050-gram Nat-U shell, and finally by a 110050-gram C (carbon/graphite) shell. Two types of systems are considered: One with the outer radius of the PE reflector shell at 30 cm and the other with the thickness of the outmost PE reflector shell at 1 foot (30.48cm)

Pu VF	Pu Mass (g)	Pu-PE Core Radius (cm)	Be Mass (g)	Be Shell Outer Radius (cm)	Nat-U Mass (g)	Nat-U Outer Shell Radius (cm)	Carbon Mass (g)	Graphite Outer Shell Radius (cm)	k_{eff} for 30-cm Outer PE Radius	k_{eff} for 1'-PE Reflection
0.10%	130	11.60837	350	11.71903	100050	14.19995	110050	24.86540	0.905948	0.909083
0.11%	130	11.24537	350	11.36318	100050	13.96086	110050	24.78850	0.912720	0.915649
0.12%	130	10.92389	350	11.04863	100050	13.75517	110050	24.72404	0.917429	0.919903
0.13%	130	10.63629	350	10.76773	100050	13.57620	110050	24.66924	0.919953	0.922350
0.14%	130	10.37676	350	10.51474	100050	13.41894	110050	24.62207	0.921104	**0.923378**
0.15%	130	10.14084	350	10.28518	100050	13.27961	110050	24.58105	**0.921116**	0.923287
0.16%	130	9.92501	350	10.07556	100050	13.15525	110050	24.54504	0.920125	0.922970
0.17%	130	9.72646	350	9.88306	100050	13.04353	110050	24.51318	0.918510	0.920594
0.18%	130	9.54290	350	9.70543	100050	12.94260	110050	24.48479	0.916295	0.918316
0.19%	130	9.37245	350	9.54080	100050	12.85093	110050	24.45933	0.913613	0.915574
0.20%	130	9.21357	350	9.38761	100050	12.76730	110050	24.43637	0.910654	0.912464

Table 15 lists the optimized results for the cases that all of the mixed reflector cases (including the reflector waiver) are doubly batched in the reflectors. Two types of systems are considered. One is with no PE reflection on the outside at all. The other is with 1-foot (30.48-cm) PE reflection on the outside. This is because the reflector doubly-batched mixed reflector systems have a radius larger than 30 cm, which is larger than the radius of a typical 55-gallon waste drum. There is no space for PE in the optimized cases. The optimized Pu volume fraction is 0.11% for both systems.

Table 15. The system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a 65-gram plutonium core moderated by PE and reflected first by a 700-gram Be (beryllium) shell, then by a 200.1-kilogram Nat-U shell, and finally by a 220.1-kilogram C (carbon/graphite) shell. Two types of systems are considered: One with no PE reflector on the outside and the other with a 1-foot (30.48-cm) PE reflector shell.

Pu VF	Pu Mass (g)	Pu-PE Core Radius (cm)	Be Mass (g)	Be Shell Outer Radius (cm)	Nat-U Mass (g)	Nat-U Outer Shell Radius (cm)	Carbon Mass (g)	Graphite Outer Shell Radius (cm)	k_{eff} for no PE Reflection	k_{eff} for 1'-PE Reflection
0.10%	65	9.21357	700	9.55543	200100	15.00755	220100	30.51036	0.773949	0.804995
0.11%	65	8.92545	700	9.28846	200100	14.90158	220100	30.48488	**0.774365**	**0.805003**
0.12%	65	8.67030	700	9.05364	200100	14.81209	220100	30.46361	0.773363	0.803681
0.13%	65	8.44203	700	8.84498	200100	14.73552	220100	30.44559	0.771303	0.801371
0.14%	65	8.23604	700	8.65795	200100	14.66926	220100	30.43013	0.768447	0.798320
0.15%	65	8.04879	700	8.48906	200100	14.61133	220100	30.41672	0.764994	0.794717

0.16%	65	7.87749	700	8.33556	200100	14.56027	220100	30.40497	0.761093	0.790704
0.17%	65	7.71990	700	8.19526	200100	14.51492	220100	30.39460	0.756860	0.786392
0.18%	65	7.57420	700	8.06639	200100	14.47437	220100	30.38538	0.752433	0.781953
0.19%	65	7.43892	700	7.94748	200100	14.43789	220100	30.37712	0.747727	0.777173
0.20%	65	7.31281	700	7.83734	200100	14.40490	220100	30.36968	0.742951	0.772385

The results in Table 16 upper bound the results for the singly batched 55-gallon fissile drums, which can only contain, aside the 50-gram reflector waiver (Appendix C), one type of the below listed reflectors, up to 300 grams of Be, or up to 100 kilograms of Nat-U, or up to 8 kilograms of C. 50 grams of trace amounts are also included for all of the reflectors. The amount of fissile, 120 grams of Pu, corresponds to the maximum normal batch (single batch) scenarios. By mixing the reflector for the typical fissile drums (120 grams Pu maximum), the cases with individual reflector of one of the three types can be categorically upper bounded by this mixed reflector configuration. The optimized Pu volume fraction is 0.14%.

Table 16. The system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a 120-gram plutonium core moderated by PE and reflected first by a 350-gram Be (beryllium) shell, then by a 100.05-kilogram Nat-U shell, and finally by a 8.05-kilogram C (carbon/graphite) shell. Outside of this Pu/reflector core is a 1-foot (30.48-cm) PE reflector shell.

Pu VF	Pu Mass (g)	Pu-PE Core Radius (cm)	Be Mass (g)	Be Shell Outer Radius (cm)	Nat-U Mass (g)	Nat-U Outer Shell Radius (cm)	Carbon Mass (g)	Graphite Outer Shell Radius (cm)	k_{eff} for 30-cm Outer PE Radius
0.10%	120	11.30274	350	11.41938	100050	13.99818	8050	15.40816	0.850957
0.11%	120	10.94930	350	11.07346	100050	13.77122	8050	15.22160	0.856778
0.12%	120	10.63629	350	10.76773	100050	13.57620	8050	15.06257	0.860506
0.13%	120	10.35625	350	10.49476	100050	13.40669	8050	14.92534	0.862614
0.14%	120	10.10356	350	10.24894	100050	13.25791	8050	14.80566	**0.863453**
0.15%	120	9.87385	350	10.02592	100050	13.12621	8050	14.70036	0.863288
0.16%	120	9.66371	350	9.82230	100050	13.00877	8050	14.60696	0.862316
0.17%	120	9.47038	350	9.63535	100050	12.90335	8050	14.52355	0.860700
0.18%	120	9.29165	350	9.46286	100050	12.80818	8050	14.44860	0.858575
0.19%	120	9.12569	350	9.30301	100050	12.72181	8050	14.38086	0.856040
0.20%	120	8.97099	350	9.15429	100050	12.64306	8050	14.31936	0.853171

The results in Table 17 upper bound the results for the reflector doubly batched 55-gallon fissile drums, which can only contain one type of the below listed reflectors, up to 700 grams of Be, or up to 200.1 kilograms of Nat-U, or up to 16.1 kilograms of C. The waiver amounts are double to 100 grams as well. The amount of fissile, 120 grams of Pu, corresponds to the maximum normal batch (single batch) scenarios. By mixing the reflector for the typical fissile drums (120 grams Pu maximum), the cases with individual reflector of one of the three types can be categorically upper bounded by this mixed reflector configuration. The optimized Pu VF for this case is 0.14%.

Table 17. The system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a 120-gram plutonium core moderated by PE and reflected first by a 700-gram Be (beryllium) shell, then by a 200.1-kilogram Nat-U shell, and finally by a 16.1-kilogram C (carbon/graphite) shell Outside of this Pu/reflector core is a 1-foot (30.48-cm) PE reflector shell.

Pu VF	Pu Mass (g)	Pu-PE Core Radius (cm)	Be Mass (g)	Be Shell Outer Radius (cm)	Nat-U Mass (g)	Nat-U Outer Shell Radius (cm)	Carbon Mass (g)	Graphite Outer Shell Radius (cm)	k_{eff} for 30-cm Outer PE Radius
0.10%	120	11.30274	700	11.53368	200100	15.92926	16100	18.04126	0.873356
0.11%	120	10.94930	700	11.19490	200100	15.75491	16100	17.90581	0.878834
0.12%	120	10.63629	700	10.89605	200100	15.60662	16100	17.79135	0.882264
0.13%	120	10.35625	700	10.62971	200100	15.47891	16100	17.69334	0.884099
0.14%	120	10.10356	700	10.39031	200100	15.36773	16100	17.60846	**0.884684**
0.15%	120	9.87385	700	10.17351	200100	15.27006	16100	17.53422	0.884276
0.16%	120	9.66371	700	9.97594	200100	15.18357	16100	17.46875	0.883084
0.17%	120	9.47038	700	9.79486	200100	15.10642	16100	17.41057	0.881262
0.18%	120	9.29165	700	9.62809	200100	15.03718	16100	17.35852	0.878941
0.19%	120	9.12569	700	9.47381	200100	14.97468	16100	17.31169	0.876219
0.20%	120	8.97099	700	9.33053	200100	14.91798	16100	17.26932	0.873177

Table 18 shows that the most optimized configuration involving 240-g Pu and 300-g Be is at a Pu volume fraction of 0.17%. This scenario involves the double batch of fissile, 240 grams, instead of 120 grams. Please note that 50 grams in Be, Nat-U, and C/graphite are included to cover the consideration for the reflector waivers.

Table 18. The system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a doubly batched 240-gram plutonium core moderated by PE and reflected first by a 350-gram Be (beryllium) shell, then by a 50-gram Nat-U shell, and finally by a 50-gram C (carbon/graphite) shell. Outside of this Pu/reflector core is a 1-foot (30.48-cm) PE reflector shell.

Pu VF	Pu Mass (g)	Pu-PE Core Radius (cm)	Be Mass (g)	Be Shell Outer Radius (cm)	Nat-U Mass (g)	Nat-U Outer Shell Radius (cm)	Carbon Mass (g)	Graphite Outer Shell Radius (cm)	k_{eff} for 30-cm Outer PE Radius
0.13%	240	13.04806	350	13.13590	50	13.13711	50	13.14808	0.915008
0.14%	240	12.72969	350	12.82193	50	12.82320	50	12.83471	0.919424
0.15%	240	12.44028	350	12.53681	50	12.53813	50	12.55018	0.922417
0.16%	240	12.17551	350	12.27623	50	12.27762	50	12.29017	0.924351
0.17%	240	11.93193	350	12.03676	50	12.03820	50	12.05126	0.925333
0.18%	240	11.70675	350	11.81559	50	11.81708	50	11.83064	**0.925564**
0.19%	240	11.49765	350	11.61043	50	11.61198	50	11.62601	0.925175
0.20%	240	11.30274	350	11.41938	50	11.42098	50	11.43549	0.924276

Table 19 shows that the most optimized configuration involving 240-g Pu and 100-kg Nat-U is at a volume fraction of 0.17%. This scenario involves the double batch of fissile, 240 grams, instead of 120 grams.

Table 19. The system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a doubly batched 240-gram plutonium core moderated by PE and reflected first by a 50-gram Be (beryllium) shell, then by a 100050-gram Nat-U shell, and finally by a 50-gram C (carbon/graphite) shell. Outside of this Pu/reflector core is a 1-foot (30.48-cm) PE reflector shell.

Pu VF	Pu Mass (g)	Pu-PE Core Radius (cm)	Be Mass (g)	Be Shell Outer Radius (cm)	Nat-U Mass (g)	Nat-U Outer Shell Radius (cm)	Carbon Mass (g)	Graphite Outer Shell Radius (cm)	k_{eff} for 30-cm Outer PE Reflection
0.13%	240	13.04806	50	13.06068	100050	15.15647	50	15.16472	0.962663
0.14%	240	12.72969	50	12.74295	100050	14.92264	50	14.93114	0.966540
0.15%	240	12.44028	50	12.45416	100050	14.71388	50	14.72263	0.969068
0.16%	240	12.17551	50	12.19000	100050	14.52623	50	14.53521	0.970492
0.17%	240	11.93193	50	11.94702	100050	14.35654	50	14.36573	**0.971027**
0.18%	240	11.70675	50	11.72242	100050	14.20226	50	14.21165	0.970847
0.19%	240	11.49765	50	11.51390	100050	14.06132	50	14.07089	0.970038
0.20%	240	11.30274	50	11.31955	100050	13.93201	50	13.94176	0.968736

Table 20 shows that the most optimized configuration involving 240-g Pu and 8-kg C/graphite is at a volume fraction of 0.19%. Again, this scenario involves the double batch of fissile, 240 grams, instead of 120 grams.

Table 20. The system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a doubly batched 240-gram plutonium core moderated by PE and reflected first by a 50-gram Be (beryllium) shell, then by a 50-gram Nat-U shell, and finally by a 8050-gram C (carbon/graphite) shell. Outside of this Pu/reflector core is a 1-foot (30.48-cm) PE reflector shell.

Pu VF	Pu Mass (g)	Pu-PE Core Radius (cm)	Be Mass (g)	Be Shell Outer Radius (cm)	Nat-U Mass (g)	Nat-U Outer Shell Radius (cm)	Carbon Mass (g)	Graphite Outer Shell Radius (cm)	k_{eff} for 30-cm Outer PE Radius
0.13%	240	13.04806	50	13.06068	50	13.06191	8050	14.64916	0.936968
0.14%	240	12.72969	50	12.74295	50	12.74423	8050	14.39842	0.942661
0.15%	240	12.44028	50	12.45416	50	12.45550	8050	14.17383	0.946901
0.16%	240	12.17551	50	12.19000	50	12.19141	8050	13.97129	0.949920
0.17%	240	11.93193	50	11.94702	50	11.94848	8050	13.78758	0.951961
0.18%	240	11.70675	50	11.72242	50	11.72394	8050	13.62007	0.953137
0.19%	240	11.49765	50	11.51390	50	11.51548	8050	13.46661	**0.953618**
0.20%	240	11.30274	50	11.31955	50	11.32118	8050	13.32545	0.953514

Table 21 shows system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a doubly batched 240-gram plutonium core moderated by PE and reflected first by a 350-gram Be (beryllium) shell, then by a 100050-gram Nat-U shell, and finally by a 8050-gram C (carbon/graphite) shell.. Outside the C shell, there is a 1-foot (30.48-cm) PE reflector shell. The optimized Pu VF is 0.18%. However, this configuration is larger than the subcritical limit of 0.971 (Table 7) for the XSDRNPM/44-Group calculations. This implies that the analysis for the fissile double batch scenarios involving the one-reflector drums need to be individually investigated.

Table 21. The system k_{eff} values, core/reflector radii, and masses as a function of plutonium VF for a doubly batched 240-gram plutonium core moderated by PE and reflected first by a 350-gram Be (beryllium) shell, then by a 100050-gram Nat-U shell, and finally by a 8050-gram C shell. Outside the C shell, there is a 1-foot (30.48-cm) PE reflector shell.

Pu VF	Pu Mass (g)	Pu-PE Core Radius (cm)	Be Mass (g)	Be Shell Outer Radius (cm)	Nat-U Mass (g)	Nat-U Outer Shell Radius (cm)	Carbon Mass (g)	Graphite Outer Shell Radius (cm)	k_{eff} for 30-cm Outer PE Radius
0.13%	240	13.04806	350	13.13590	100050	15.21244	8050	16.43048	0.979752
0.14%	240	12.72969	350	12.82193	100050	14.98036	8050	16.23217	0.984321
0.15%	240	12.44028	350	12.53681	100050	14.77325	8050	16.05629	0.987446
0.16%	240	12.17551	350	12.27623	100050	14.58713	8050	15.89918	0.989416
0.17%	240	11.93193	350	12.03676	100050	14.41888	8050	15.75792	0.990436
0.18%	240	11.70675	350	11.81559	100050	14.26595	8050	15.63020	**0.990681**
0.19%	240	11.49765	350	11.61043	100050	14.12628	8050	15.51413	0.990283
0.20%	240	11.30274	350	11.41938	100050	13.99818	8050	15.40816	0.989354

The input decks for the parametric and optimizing calculations performed in this Section are listed in Appendix B. In summary, the optimized Pu VFs are as listed in Table 22 as a function of the fissile and reflector masses. The specific fissile and reflector masses considered in this table are related to the HWM normal and off-normal scenarios for drum and array storage operations and are within the scope of the requirements for the double-contingency principle (DOE Order 420.1, Facility Safety).

Table 22. The optimized Pu VF as a function of Pu and reflector masses.

Pu Mass (g)	Be Mass (g)	Nat-U Mass (g)	C/Graphite Mass (g)	Pu Volume Fraction
65	350	100050	110050	0.11%
130	350	100050	110050	0.15%
65	700	200100	220100	0.11%
120	350	100050	8050	0.14%
120	700	200100	16100	0.14%
240	350	50	50	0.18%
240	50	100050	50	0.17%
240	50	50	8050	0.19%
240	350	100050	8050	0.18%

Although individual amounts of fissile involved for 55-gallon drums are less than the allowable workstation mass limit of 220 grams as given in Table 31.2 of the LLNL Environment Health &

Safety (EH&S) manual [16]. However, the interaction of 55-gallon fissile drum arrays may potentially involve many times of this 220-gram limit and may also be in excess of 450 grams of Pu which is the minimum amount subcritical in ANSI/ANS 8.1-1998 [17]. Furthermore, superior moderators and reflectors, such as PE, paraffin, oils (namely, TrimSol and Superla), Be, C/graphite and Nat-U are expected to be present in abundant amounts in the drums in arrays. Because of the complexity in individual drum and array configurations, criticality safety handbooks [18] do not contain enough information to demonstrate the safety for such drum and array storage operations. Therefore, to demonstrate and to ensure that such operations are criticality safe, 3-D KENO V.a are used.

5.2 Normal and Off-Normal Conditions Covered

The normal and off-normal operation scenarios covered in this analysis are as listed in Table 14. In Table 14, each of the covered normal and off-normal operation scenarios are briefly described. Also listed in Table 14 are the number of failures and the number of contingencies lost for each covered scenario. The reason that the contingencies lost and the failures are listed together is for the purpose of easy identifying for double-contingency principle compliance for the covered operation scenarios.

Table 23. Lists of Failures and Contingencies for All Operation Scenarios Considered

Case	Description of Normal/ Off-Normal Conditions	No. of Failure	Number of Lost Contingency	Remarks
1	Normal operation conditions	0	0	Single batch mixed reflector drum arrays
2	Fissile over-batch: mixed reflector drums in mixed-reflector-drums-only arrays	1	1	Fissile double batch for mixed reflector drums Section 5.4.1
2a	Fissile over-batch: fissile drums in mixed-reflector-and-fissile-drum arrays	1	1	Fissile double batch for fissile drums; Section 5.4.1
3	Reflector over-batch	1	1	Reflector double batch for mixed reflector drums Section 5.4.2
3a	Moderator over-batch	1	1	Section 5.4.2
4	Loss of Interaction Control: with fissile drum arrays	1	1	Section 5.4.3
4a	Loss of Interaction Control: with Nat-U drum arrays	1	1	Section 5.4.3
4b	Loss of Interaction Control: with mixed container array	1	1	Section 5.4.3
5	Flooding	1	0	Section 5.4.4
5a	Fire water/fire damage	2^+	1	Section 5.4.4; $^+$common-mode failures
6	Spill	1	1	Section 5.4.5
7	seismic consideration	1	1	Section 5.4.6

The normal storage configurations assumed for this analysis are infinite 3-D arrays. Unless otherwise specified, all of the storage arrays considered are infinite in the 3-D space. The drums in arrays are arranged in units of the optimized 4-plex configuration. For more details on the drum and array configurations, please refer to Appendix A of this report.

In this report, unless otherwise specified, all of the KENO V.a/44-Group calculations use the following calculations parameters: 1000 particles/generation, 215 generations/calculation, and the first 15 generations skipped.

5.3 Normal Conditions

Normal operation scenarios for the 55-gallon mixed-reflector waste drums are:

7.0 The 65-gram Pu mixed-reflector waste drums are stored in arrays made of them only.

8.0 The 65-gram Pu mixed-reflector waste drums are stored in arrays together with the 120-gram Pu one-reflector fissile drums.

For the operation viewpoint, the 65-gram Pu mixed-reflector-waste-drums-only array storage is simple and straightforward, is a no-brainer to the HWM operation personnel, and should be the preference for the storage of mixed-reflector waste drums. To mix the mixed-reflector waste drums and the one-reflector waste drums in the same arrays may have some benefits on HWM operations when short-term needs arise. The results in Sections 5.3.1 and 5.3.2 demonstrate that both normal-operation configurations are criticality safe.

5.3.1 Normal Operation Scenario for Mixed-Reflector-Drum-Only Arrays

In this normal-operation scenario, arrays are made of mixed-reflector drums only. Each mixed array drum has a Pu-reflector core made of 65 grams of Pu, 350 grams of Be, 100.05 kilograms of Nat-U, and 110.05 kilograms of C/graphite with PE filling up the rest of drum as described in Appendix A. The drums are arranged in the 4-plex configuration. The two array configurations are analyzed: one is an infinite 3-D array and the other is an infinite XY array with the drums stacked 6-high and a 16" (40.64-cm)-thick concrete floor underneath it.

The optimized maximum k_{eff} value is no greater than 0.891 (0.8864±0.0014) for this mixed drum array. The value is below the subcritical limit of 0.972 for the KENO V.a/44-group calculations. In this regard, this scenario is criticality safe. It is noted that the peaks occur at the PE reflector volume fraction of 0%. This is not surprising because there is no neutron leakage in an infinite array system and there would be no parasitic absorption by the PE reflector.

Table 23. The system k_{eff} as a function of the PE reflector volume fraction inside the mixed-reflector drums in two array formations

PE Reflector Volume Fraction	Infinite 3-D Mixed-Reflector-Drum-Only Array; Input file: sb65p			Infinite XY 6-high Mixed-Reflector-Drum-Only Array; Input file: sb65p6		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
100%	0.8080	0.0017	0.8131	0.8053	0.0017	0.8104
90%	0.8063	0.0018	0.8117	0.8073	0.0015	0.8118
80%	0.8074	0.0017	0.8125	0.8089	0.0017	0.8140
60%	0.8071	0.0019	0.8128	0.8100	0.0018	0.8154
40%	0.8118	0.0016	0.8166	0.8103	0.0016	0.8151
20%	0.8265	0.0016	0.8313	0.8233	0.0016	0.8281
10%	0.8371	0.0016	0.8419	0.8351	0.0017	0.8402
5%	0.8505	0.0016	0.8553	0.8456	0.0017	0.8507
3%	0.8595	0.0014	0.8637	0.8541	0.0014	0.8583
2%	0.8677	0.0014	0.8719	0.8572	0.0015	0.8617
1%	0.8750	0.0014	0.8792	0.8615	0.0015	0.8660
0%	0.8864	0.0014	0.8906	0.8682	0.0015	0.8727

5.3.2 Normal Operation Scenario for Mixed Mixed-Reflector Drum and One-Reflector Drum Arrays

In this scenario, arrays are made of mixed-reflector drums and one-reflector drums. Each mixed array drum has a Pu-reflector core made of 65 grams of Pu, 350 grams of Be, 100.05 kilograms of Nat-U, and 8.05 kilograms of C/graphite with PE filling up the rest of drum as described in Appendix A. The one-reflector drum has a Pu-reflector core made of 120 grams of Pu, 350 grams of Be, 100.05 kilograms of Nat-U, and 8.05 kilograms of C/graphite, with PE filling up the rest of drum. The mixed-reflector drums and the one-reflector drums are arranged in the 4-plex configurations with drums of one type. There is no mixing of drum types in the 4-plex configuration. The mixed-reflector 4-plex is then placed next to a one-reflector 4-plex to form a unit cell from which the mixed-drum arrays are constructed. It should be noted that the one-reflector drums are not really modeled as having a reflector only. Rather, the one-reflector drums are modeled as three-reflector drums that inherently include and upper bound all of the one-reflector drum configurations. That is, if the three-reflector configuration can be demonstrated to be criticality safe, all of the one-drum reflector configurations will be upper bound by the three-drum reflector case and be deduced as criticality safe. (This method works only for the normal operation scenario. For fissile double batch of the one-reflector drums in Table 21, the three-reflector configuration can not be demonstrated to be criticality safe. This upper bounding method therefore can not be used and each of the three one-reflector configurations needs to be individually demonstrated that it is criticality safe.)

Table 24. The system k_{eff} as a function of the PE reflector volume fraction inside the mixed-reflector drums in two array formations

PE Reflector Volume Fraction	Infinite 3-D Mixed-Reflector/One-Reflector Drum Array; Input file: sbfiss			Infinite XY 6-high Mixed-Reflector/One Reflector-Drum Array; Input file: sbfiss6		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
100%	0.8989	0.0019	0.9046	0.9030	0.0019	0.9087
90%	0.9010	0.0018	0.9064	0.9017	0.0016	0.9065
80%	0.8980	0.0016	0.9028	0.9022	0.0016	0.9070
60%	0.9015	0.0017	0.9066	0.9035	0.0021	0.9098
40%	0.9029	0.0016	0.9077	0.9057	0.0017	0.9108
20%	0.8997	0.0016	0.9045	0.8983	0.0021	0.9046
10%	0.9012	0.0015	0.9057	0.9003	0.0016	0.9051
5%	0.9091	0.0017	0.9142	0.9029	0.0019	0.9086
3%	0.9186	0.0016	0.9234	0.9168	0.0017	0.9219
2%	0.9319	0.0019	0.9376	0.9249	0.0015	0.9294
1%	0.9473	0.0016	0.9521	0.9456	0.0016	0.9504
0%	0.9699	0.0018	0.9753	0.9577	0.0016	0.9625

The optimized maximum k_{eff} value is no greater than 0.963 (0.9577±0.0016) for this mixed drum array stacked to 6-high. The value is below the subcritical limit of 0.972 for the KENO V.a/44-group calculations. In this regard, this scenario is criticality safe. Although for infinite 3-D arrays, it shows that the optimized keff value at a PE reflector volume fraction of 0% would be greater than the subcritical limit of 0.972. However, this operation scenario does not exist for HWM operations for several reasons: 1) at HWM, 55-gallon drums are limited to 2-high, which is upper bounded by the 6-high case analyzed in the above, 2) HWM does not have infinite XY arrays, and 3) a volume fraction of 0% PE reflector means that the drum is mostly empty with the exception of the optimized fissile and moderator mixture and the reflectors. Such scenarios of empty drums, if ever existing at HWM, would occur to a few drums only. It should be noted that when the PE reflector volume fraction is increased to 1% and beyond, the reactivity is drastically curtailed. The reason for this is with the waste in the drums, the neutronic coupling between the nearby drums is reduced because of the absorption of neutrons by the waste.

5.4 Off Normal Conditions

Off normal conditions, such as fissile double batch, loss of interaction control, flooding, seismic consideration, and spilling are discussed. Optimized moderation and reflection conditions are assumed for all off-normal events.

5.4.1 Fissile Double/Over Batch

The prerequisite for the occurrence of a criticality event is that an adequate amount of fissionable materials has to be made available. Therefore, the effects of the double batch, which can potentially result in excessive accumulations of fissionable materials, need to be investigated. The k_{eff} values of double-batch systems are at the maximum if the cores are optimally moderated and fully reflected.

For this analysis, double batch is assumed for 1 out of every 8 drums in an array (see Appendix A). Or one double-batch drum in a dual 4-plex configuration. The double-batch drum is always in a fixed corner of the dual 4-plex configuration. This would allow as many double-batch drums as possible, while preventing the direct contact of all nearby double-batch drums. In other words, there will always be a single-batch drum between two nearby double-batch drums.

5.4.1.1 Fissile Double Batch in Mixed-Reflector Containers

This scenario deals with the interaction of the fissile double batch in mixed-reflector drums. All of the drums in the array are of the mixed-reflector type. Three array configurations are considered:

Configuration 1: An infinite XY array with the drums stacked 6-high: The array is neutronically reflected by a 16"(40.64 cm)-thick concrete floor. There is a double batch drum in individual 4-plex units (one drum in 4).

Configuration 2: An infinite 3-D array constructed by individual 4-plex units: There is a double batch drum in each 4-plex (one drum in 4).

Configuration 3. An infinite 3-D array constructed by dual 4-plex units: There is a double batch drum in each 4-plex (one drum in 8).

For information on the single 4-plex and dual 4-plex, please refer to Section A.2 in Appendix A of this report. The double batch configuration is made of a single ball with 130 grams of fissile.

Table 25. Array k_{eff} values as a function of PE reflector VF for a double-batch mixed-reflector core (130 grams Pu) moderated by PE, reflected first by a 350-gram Be shell, then by a 100.05-kilogram Nat-U shell, and finally by a 8.05-kilogram C/graphite shell. The core is then placed inside a 55-gallon drum with PE of different volume fractions as the bulk filling for three different mixed-reflector drum configurations.

PE Volume Fraction	6-drum-high dual 4-plex Input file: db130db46			inf-high single 4-plex Input file: db130db4			inf-high dual 4-plex Input file: db130db8		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
0%	0.9271	0.0016	0.9319	0.9543	0.0017	0.9594	0.9312	0.0024	0.9384
1%	0.9168	0.0019	0.9225	0.9428	0.0017	0.9479	0.9186	0.0019	0.9243
2%	0.9156	0.0017	0.9207	0.9388	0.0019	0.9445	0.9223	0.0021	0.9286
3%	0.9154	0.0017	0.9205	0.9320	0.0019	0.9377	0.9148	0.0020	0.9208
5%	0.9078	0.0018	0.9132	0.9295	0.0016	0.9343	0.9136	0.0020	0.9196
10%	0.9042	0.0020	0.9102	0.9274	0.0019	0.9331	0.9037	0.0018	0.9091
20%	0.9121	0.0020	0.9181	0.9213	0.0019	0.9270	0.9127	0.0016	0.9175
40%	0.9193	0.0018	0.9247	0.9210	0.0017	0.9261	0.9143	0.0021	0.9206
60%	0.9193	0.0016	0.9241	0.9226	0.0018	0.9280	0.9202	0.0018	0.9256
80%	0.9188	0.0014	0.9230	0.9247	0.0020	0.9307	0.9228	0.0017	0.9279
90%	0.9204	0.0017	0.9255	0.9288	0.0019	0.9345	0.9265	0.0018	0.9319
100%	0.9222	0.0017	0.9273	0.9302	0.0021	0.9365	0.9245	0.0016	0.9293

The results in the above indicate that the k_{eff} values for the credible fissile double batch scenarios are not greater than 0.960 for the three mixed-reflector drum array configurations considered. Since all of the results are less than the subcritical limit of 0.972 for the KENO V.a/44-Group calculations, these three configurations are all criticality safe. It should be noted that, for the case of an infinite XY array with the drums stacked 6-high, the keff value is less than 0.928. This scenario is most similar to the HWM operations with a safety factor of 3 in drum stacking. (HWM operations allow for unrestraint 55-gallon drums to be stacked 2-high.) In the regard, there should be a larger safety margin for HWM mixed-reflector drum operations.

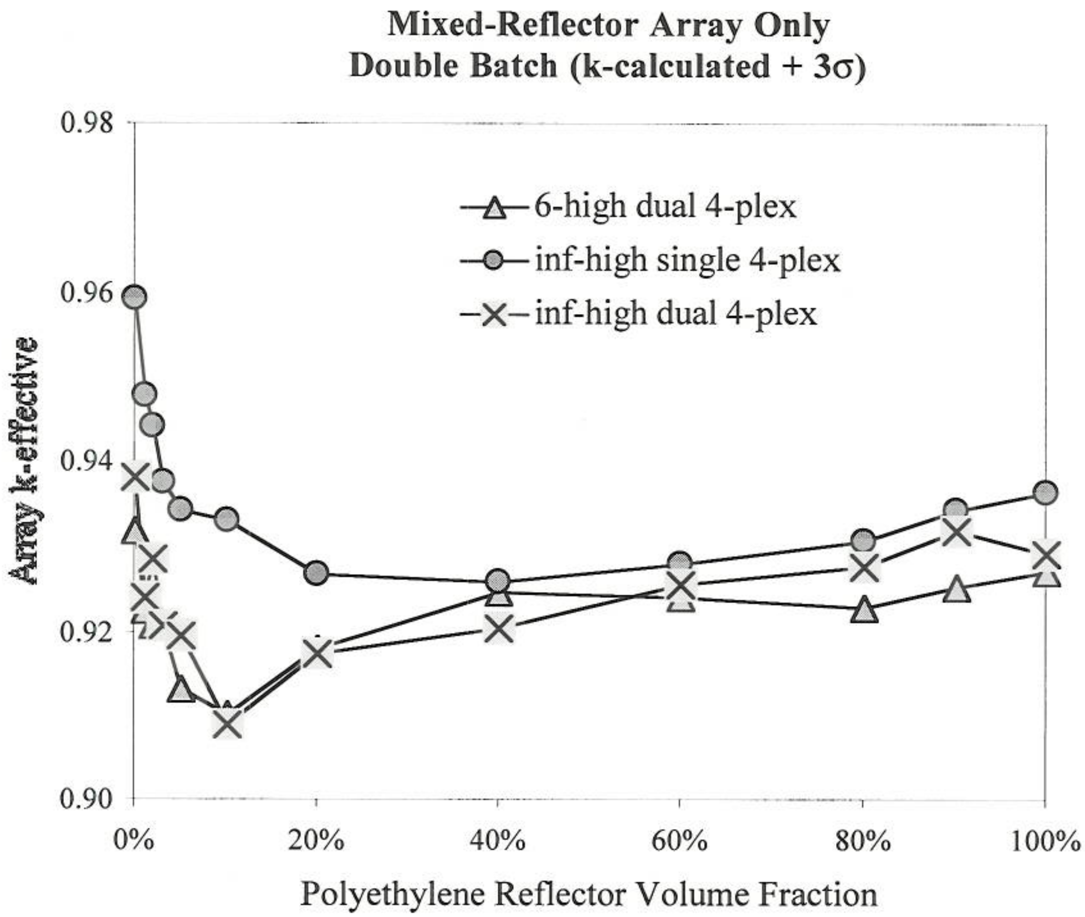


Figure 3. Array k_{eff} values as a function of PE reflector VF for a double-batch mixed-reflector core (130 grams Pu) moderated by PE, reflected first by Be, Nat-U, C-graphite, and then by PE for three different mixed-reflector drum configurations.

5.4.1.2 Fissile Double Batch in One-Reflector Containers

In this section, the doubly batched drums are of the one-reflector types, while the mixed-reflector drums remain singly batched. Since the one-reflector containers can be one of the three types, Be, Nat-U, or C/graphite, the interactions of single-batch mixed-reflector containers with these three type of one-reflector containers are separately analyzed in the following subsections. Fissile double batch in the one-reflector drums involves 240 grams of Pu. This amount of Pu is distributed into two balls, one with 150 grams and the other 90 grams. The ball with 150 grams of Pu depicts the core and the other ball depicts the fissile in the reflector. The scenario with the large ball with more than 150 grams of Pu can be proven to be incredible and therefore this 2-ball configurations can be served as the upper bound for all credible scenario. Section A.3 of Appendix A presents a schematics and brief discussion on the two-ball configurations. For more information, please refer to Appendix C of CSM 1087 [9], where the mathematical derivations have been documented in details.

Table 26 shows the fissile double-batch two-ball configuration parameters for three types of one-reflector drums, Be-only, Nat-U only, and carbon/graphite only. 50 grams of each types of reflectors are added to cover the effects of the trace reflectors. The parameters include the Pu volume fraction of the optimally PE moderated Pu core, the radii of the two Pu balls, the amounts of reflectors, and their corresponding shell thickness.

Table 26. Two-ball configuration parameters for double-batch 55-gallon one-reflector waste drums for different types of reflectors.

Drum Type	Be Reflector Only	Nat-U Reflector Only	C Reflector Only
Pu Volume Fraction	0.18%	0.17%	0.19%
150-gram Pu Ball Radius (cm)	8.44203	8.06441	8.29124
90-gram Pu Ball Radius (cm)	10.00913	10.20166	9.83036
Be Mass (gram)	350	50	50
Be Shell Thickness (cm)	0.08712	0.01110	0.01299
Nat-U Mass (gram)	50	100050	50
Nat-U Shell Thickness (cm)	0.00128	2.00893	0.00126
C/Graphite Mass (gram)	50	50	8050
C Shell Thickness (cm)	0.01088	0.00792	1.61708

The rest of the drums aside from the two-ball configurations are filled with the bulk polyethylene. The PE under this situation serves as a reflector. The array is modeled in units of dual 4-plexes. A drum in the dual 4-plexes is then modeled in the two-ball configurations. The rest of the drums consist of a 4-plex of single-batch mixed-reflector drums and three single batch one-reflector drums. The array is infinite in the X and Y directions. It is stacked 6-drum high (or 3-four-plex high) and reflected at the bottom by a 16" (40.64-cm)-thick concrete floor. For each of the calculations performed, 225 generations with 3000 particles/generation are used. Also for each of the calculations, the first 25 generations are skipped.

Table 27. Arrays with a single fissile double-batch one-reflector drums in dual 4-plexes(1 out of 8) configuration: the arrays k_{eff} values are as a function of Pu VF for two Pu cores (90 grams and 150 grams Pu) moderated by PE, reflected first by Be, Nat-U, C-graphite, and then by PE for three types of one-reflector drums.

PE Volume Fraction	Nat-U Only Input file: twoballvu			Be Only Input file: twobalvb			C/graphite Only Input file: twobalvc		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
0%	0.9529	0.0009	0.9556	0.9302	0.0009	0.9329	0.9297	0.0009	0.9324
1%	0.9406	0.0009	0.9433	0.9181	0.0011	0.9214	0.9197	0.0009	0.9224
2%	0.9290	0.0009	0.9317	0.9090	0.0011	0.9123	0.9104	0.0009	0.9131
3%	0.9194	0.0011	0.9227	0.8998	0.0011	0.9031	0.9030	0.0010	0.9060
5%	0.9096	0.0011	0.9129	0.8913	0.0011	0.8946	0.8919	0.0010	0.8949

10%	0.8966	0.0010	0.8996	0.8785	0.0009	0.8812	0.8820	0.0010	0.8850
20%	0.8970	0.0011	0.9003	0.8809	0.0009	0.8836	0.8808	0.0011	0.8841
40%	0.9080	0.0012	0.9116	0.8932	0.0011	0.8965	0.8885	0.0010	0.8915
60%	0.9175	0.0011	0.9208	0.8990	0.0011	0.9023	0.8958	0.0009	0.8985
80%	0.9229	0.0011	0.9262	0.8988	0.0010	0.9018	0.8982	0.0010	0.9012
90%	0.9262	0.0011	0.9295	0.8998	0.0010	0.9028	0.9018	0.0010	0.9048
100%	0.9286	0.0010	0.9316	0.8979	0.0010	0.9009	0.9018	0.0010	0.9048

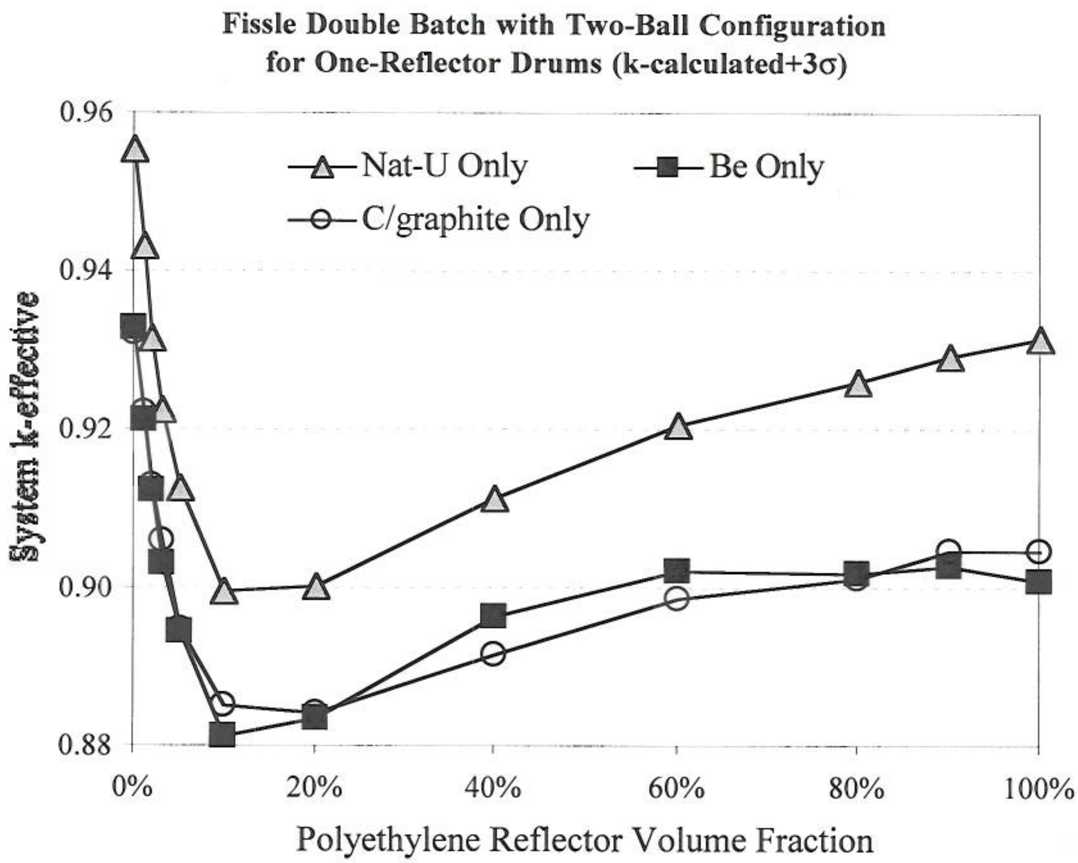


Figure 4. Array k_{eff} values as a function of PE reflector VF for two Pu cores (90 grams and 150 grams Pu) moderated by PE, reflected first by Be, Nat-U, C-graphite, and then by PE for three types of one-reflector drums.

The results in Table 27 and Figure 4 show that the k_{eff} maximum is not greater than 0.956, which is less than the subcritical limit of 0.972 for KENO V.a/44-group calculations. Therefore, all credible double-batch scenarios for any single mixed array container are criticality safe. The peaking of the keff values at a volume fraction of 0% for the k_{eff} values is attributed to: 1) the infinite X-Y array configuration used in the modeling, which result in the reduction of the neutron leakage, 2) the lack of reflector in the interspersed space outside the reflector shells, which results in the reduction of neutron absorption by reflectors. Therefore, the peaking of k_{eff} at a reflector (PE) volume fraction of 0% is by no means unexpected.

5.4.2 Moderator and Reflector Over Batch

5.4.2.1 Moderator Over Batch

The over batch of moderators will reduce the system k_{eff} for optimally moderated system because the core will be over-moderated. Therefore, in the over batch of moderators, the system k_{eff} remains to be bounded by the optimally moderated value. Even for the worst case that the over-batch moderators act like reflectors, the system k_{eff} would be hardly enhanced by the effect from moderator reflections. This results in systems deviating from the optimized condition and causes a corresponding reduction in system k_{eff} values. Also, it should be noted that good moderators in general are not the best reflectors. In Figure 3, it clearly shows that water, paraffin, polyethylene, and hence other hydrogenous compounds are not as effective compared to Nat-U and graphite on a full-reflection basis. Therefore, the moderator over batch is generally upper bounded by the optimized normal operation scenario (as discussed in Section 5.4.1). Even under the more severe situations that some of the moderators are incorporated in the system more as reflectors and less as moderators, these scenarios are upper bounded by the maximum of the reflector double-batch scenarios as discussed in the following subsection. Therefore, the moderator over batch scenario is criticality safe. Again, this is because the systems considered here are already optimally moderated and fully reflected. In summary, the addition of moderators in a moderator over-batch event can only over moderate the system and hardly has any effect on added neutron reflection.

5.4.2.2 Reflector Over Batch

Mixed-Reflector Drums with Reflector Double Batch

For this reflector over-batch scenario, the mixed-reflector drums are double batched with 700 grams of Be, 200.1 kilograms of Nat-U, and 220.1 kilograms of C (carbon/graphite). Two array configurations are analyzed: one deals with an infinite 3-D array and the other deals with an infinite XY 6-high array reflected by 16"(40.64-cm)-thick concrete floor.

Table 28. The system k_{eff} as a function of the PE reflector volume fraction inside the mixed-reflector drums in two array formations

Inter-Dispersed Moisture Content	Infinite 3-D Mixed-Reflector-Drum-Only Array; Input file: dbmref			Infinite XY 6-high Mixed-Reflector-Drum-Only Array; Input file: dbmref6		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
100%	0.8846	0.0018	0.8900	0.8844	0.0013	0.8883
90%	0.8859	0.0015	0.8904	0.8851	0.0014	0.8893
80%	0.8842	0.0014	0.8884	0.8843	0.0015	0.8888
60%	0.8843	0.0014	0.8885	0.8833	0.0015	0.8878
40%	0.8852	0.0015	0.8897	0.8851	0.0015	0.8896
20%	0.8875	0.0015	0.8920	0.8841	0.0015	0.8886
10%	0.8884	0.0017	0.8935	0.8900	0.0016	0.8948
5%	0.8940	0.0013	0.8979	0.8876	0.0014	0.8918
3%	0.8957	0.0018	0.9011	0.8894	0.0017	0.8945
2%	0.8940	0.0014	0.8982	0.8893	0.0014	0.8935
1%	0.8951	0.0015	0.8996	0.8956	0.0014	0.8998
0%	0.9023	0.0015	0.9068	0.8949	0.0012	0.8985

The reason why the thickness of the outside water or PE reflector is not increased beyond the above-mentioned value deals with the fact that the PE reflector is already at (near) full neutron reflection thickness. Any increase in the PE reflector thickness is expected to have no significant effect on the system k_{eff} values.

The worst scenario for the reflector double batch scenario results in a k_{eff} value of no greater than 0.907, which is below the subcritical limit of 0.971 for the XSDRNPM/44-group calculations. Therefore, it is demonstrated that the reflector double batch is criticality safe.

One-Reflector Drum Double Batch in Mixed Reflectors

In this scenario, arrays are made of mixed-reflector drums and one-reflector drums. Each mixed array drum has a Pu-reflector core made of 65 grams of Pu, 350 grams of Be, 100.05 kilograms of Nat-U, and 8.05 kilograms of C/graphite with PE filling up the rest of drum as described in Appendix A. The one-reflector drum has a Pu-reflector core made of 120 grams of Pu, 350 grams of Be, 100.05 kilograms of Nat-U, and 8.05 kilograms of C/graphite, with PE filling up the rest of drum. It should be noted that the one-reflector drums are not really modeled as having a reflector only. Rather, the one-reflector drums are modeled as three-reflector drums that inherently include and upper bound all of the one-reflector drum configurations. The mixed-reflector drums and the one-reflector drums are arranged in the 4-plex configurations with drums of one type. There is no mixing of drum types in the 4-plex configuration. The mixed-reflector 4-plex is then placed next to a one-reflector 4-plex to form a unit cell from which the mixed-drum arrays are constructed. It should be noted that the one-reflector drums are not really modeled as having a reflector only. Rather, the one-reflector drums are modeled as three-reflector drums that inherently include and upper bound all of the one-reflector drum configurations. That is, if the three-reflector configuration can be demonstrated to be criticality safe, all of the one-drum reflector configurations will be upper bound by the three-drum reflector case and be deduced as criticality safe. (This method works only for the normal operation scenario. For fissile double batch of the one-reflector drums in Table 21, the three-reflector configuration can not be demonstrated to be criticality safe.) This upper bounding method therefore can not be used and each of the three one-reflector configurations needs to be individually demonstrated that it is criticality safe.)

Table 29. The system k_{eff} as a function of the PE reflector volume fraction inside the mixed-reflector drums in two array formations

PE Reflector Volume Fraction	Infinite 3-D Mixed-Reflector/One-Reflector Drum Array; Input file: sbfis8			Infinite XY 6-high Mixed-Reflector/One Reflector-Drum Array; Input file: sbfis68		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
100%	0.8958	0.0019	0.9015	0.8947	0.0020	0.9007
90%	0.8912	0.0018	0.8966	0.8954	0.0020	0.9014
80%	0.8939	0.0020	0.8999	0.8942	0.0019	0.8999
60%	0.8885	0.0018	0.8939	0.8910	0.0016	0.8958
40%	0.8877	0.0020	0.8937	0.8856	0.0018	0.8910
20%	0.8903	0.0019	0.8960	0.8841	0.0021	0.8904
10%	0.8948	0.0021	0.9011	0.8939	0.0017	0.8990
5%	0.9064	0.0017	0.9115	0.9042	0.0016	0.9090
3%	0.9191	0.0017	0.9242	0.9115	0.0019	0.9172
2%	0.9296	0.0017	0.9347	0.9251	0.0015	0.9296
1%	0.9495	0.0017	0.9546	0.9381	0.0018	0.9435
0%	0.9662	0.0013	0.9701	0.9568	0.0015	0.9613

The optimized maximum k_{eff} value is no greater than 0.971 (0.9662±0.0013) for this mixed drum array for the infinite 3-D array. The number is less than 0.962 for 6-high arrays. Both values are below the subcritical limit of 0.972 for the KENO V.a/44-group calculations. In this regard, this scenario is criticality safe. In reality, the optimized value would be lower for HWM operations with finite array and a stacking limit of 2 drums (no stacking above 4 feet).

One-Reflector Drum Single Batch with Mixed Reflectors

Reflector over over-batch, which results in mixed reflectors, for the one-reflector drums in the mixed mixed-reflector and one-reflector drum configuration are demonstrated to be criticality safe in the normal operation scenarios. The scenario assumes that the one-reflector drums are reflected by 350 grams of Be, then by 100.05 kilograms of Nat-U, and finally by8.05 kilograms of C (carbon/graphite). This scenario is also upper bounded by the scenario involving one-reflector drum double batch with mixed reflectors.

All moderator and reflector over batch scenario are shown to be subcritical and is therefore criticality safe. Input decks for reflectors over batches are listed in Appendix B.

5.4.3 Loss of Interaction Controls

The loss of interaction controls for mixed-reflector drums with other HWM waste containers can be classified into two categories. The first category involves the interaction of mixed-reflector containers with fissile drum arrays (Section 5.4.3.1). The second category involves the interaction of mixed-reflector containers with Nat-U drum arrays (Section 5.4.3.2). The interactions between mixed-reflector arrays are criticality safe because infinite 2-D and 3-D arrays are proven subcritical in Section 5.3. The scenarios regarding the loss of interaction control considered here deal with the complete loss of the 76.2-cm (30") array separation, which will upper bound all credible loss-of-interaction-control scenarios.

5.4.3.1 Interaction with Fissile Arrays

Interaction with the fissile drum (or one-reflector) arrays needs not be considered. This analysis is performed based on the assumption that 55-gallon mixed-reflector and one-reflector drums are allowed to be mixed in the HWM array operations. This is because these drums are of the same size and therefore may be prone to be mixed up inadvertently in normal operations.

It should be noted that 55-gallon drums are not allowed to be mixed with 5-gallon and 30-gallon drums in uniform-size array, unless they can be declared to be the equivalent of the uniform-size array for smaller containers. This means a reduction in the drum fissile limit from the allowable 120 grams of Pu for 55-gallon drums to whatever the fissile mass limit of the smaller drum to which it is equivalent, 40 grams for 5-gallon drums and 80 grams for the 30 gallon drums. The 55-gallon drums may also be mixed with the 5-gallon and 30-gallon drums in a mixed array configuration. Under this situation, the mixed-array controls apply. Because of the mismatch in the drum size between the 55-gallon drums and the 5-/30-gallon drums, the reduced fissile mass limits in the smaller size drums, and the difference in the optimized conditions, it is expected that the neutronic coupling between the 55-gallon drums and the smaller size drums are not as strong as the interaction among the 55-gallon drums themselves. In this regard, the interaction of the mixed-reflector drums with the one-reflector drums of 5-gallon-size and 30-gallon-size is not considered here.

5.4.3.2 Interaction with Nat-U Drum Arrays

The interaction of mixed-reflector drums with the Nat-U drums are considered in this section. HWM Nat-U drum arrays have two drum types, 30-gallon or 55-gallon. The individual drum mass limits for the two Nat-U drum types are below listed in Table 30. Only one drum type is allowed in a single Nat-U drum array. No mixing of 30- and 55-gallon drums are allowed. All HWM Nat-U drums can have water, polyethylene, some oils (such as Superla and TrimSol), and materials with a hydrogen density of 0.133 g/cc with no limits.

Table 30. HWM mass limits for 30- and 55-gallon Nat-U drums and their equivalents [4,11].

Drum/ Container Type	Fissile Mass Limit	Nat-U Mass Limit	Optimized Nat-U Triangular Lattice (CSM1034 Table 12 [11])
30-gallon	trace amount only; up to 0.6 gram Pu-239 [4]	210 kilograms	8.27871 cm Pitch; 2.6 cm Nat-U Diameter; 0.129 g/cc Superla or PE or 15% dense Superla
55-gallon and equivalents	trace amount only; up to 1.0 gram Pu-239 [4]	650 kilograms	5.63865 cm Pitch; 2.4 cm Nat-U Diameter; 0.258 g/cc Superla or PE or 30% dense Superla

The interaction of a mixed array container or an entire mixed array with the Nat-U drum arrays is separately discussed for 55- and 30-gallon drums in Subsections 5.4.3.2.1 and 5.4.3.2.2, respectively.

In this analysis, all Nat-U drum arrays are assumed being stacked at infinite height. All Nat-U drums are completely filled without any empty space left inside. These filled drums have three different configurations. The first configuration deals with a drum filled with PE with solid Nat-U chunks on top of it. The second configuration deals a drum filled with solid Nat-U chunks in the bottom and PE on top of it. The third configuration has an optimized Nat-U lattice as derived in CSM-1034 [11].

5.4.3.2.1 Interaction with 55-gallon Nat-U Drum Arrays

Two interaction configurations are considered for this scenario. One deals the interaction of the mixed-reflector drums with the optimally polyethylene moderated latticed Nat-U drums and the other the interaction with the Nat-U drums with the Nat-U in solid chunks. Again, the interaction is modeled as interaction between the dual 4-plexes. One 4-plex is made of all Nat-U drums and the other 4-plex is made of all mixed reflector drums. Only infinite 3-D arrays are analyzed. The infinite 3-D array upper bounds all of the credible HWM Nat-U drum and mixed-reflector drum interaction scenarios.

Interaction with Optimally Moderated Latticed Nat-U Drums

The optimally moderated latticed Nat-U drums are optimized in the reactivity in the Nat-U. However, it is not expected to be optimally interacting with the fissile in the optimized-reflector drums. This is because the optimized regimes for the two types of drums are different and are not neutronically compatible. The array analyzed is infinite in all dimensions.

Table 32. k_{eff} values for the interaction between the mixed-reflector drums and optimized Nat-U lattice 55-gallon drums as a function of the PE reflector VF in the mixed-reflector drums.

Inter-Dispersed Moisture Content	Infinite 3-D Mixed-Reflector-Drum-Only Array; Input file: sbnatula		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
100%	0.8095	0.0017	0.8146
90%	0.8081	0.0016	0.8129
80%	0.8131	0.0018	0.8185
60%	0.8101	0.0016	0.8149

40%	0.8125	0.0018	0.8179
20%	0.8374	0.0013	0.8413
10%	0.8624	0.0016	0.8672
5%	0.8824	0.0014	0.8866
3%	0.8935	0.0012	0.8971
2%	0.8957	0.0014	0.8999
1%	0.9057	0.0012	0.9093
0%	0.9131	0.0013	0.9170

The results in Table 31 show that the k_{eff} maximum is not greater than 0.917, which is less than the subcritical limit of 0.972 for KENO V.a/44-group calculations. Therefore, all credible double-batch scenarios for any single mixed array container are criticality safe.

Interaction with Nat-U Drums with Nat-U Chunks

The Nat-U chunks in this type of Nat-U drums are optimized in neutron reflection.

Table 33. keff values for the interaction of the mixed-reflector drums and Nat-U chunks 55-gallon drums as a function of the PE reflector VF in the mixed-reflector drums.

Inter-Dispersed Moisture Content	Infinite 3-D Mixed-Reflector/Nat-U Chuck Arrays; Input file: sbnatuhm		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
100%	0.8058	0.0016	0.8106
90%	0.8069	0.0015	0.8114
80%	0.8085	0.0016	0.8133
60%	0.8084	0.0017	0.8135
40%	0.8129	0.0014	0.8171
20%	0.8194	0.0018	0.8248
10%	0.8255	0.0018	0.8309
5%	0.8336	0.0019	0.8393
3%	0.8443	0.0017	0.8494
2%	0.8515	0.0015	0.8560
1%	0.8627	0.0019	0.8684
0%	0.8723	0.0018	0.8777

The results in Table 33 indicate that the k_{eff} maximum is not greater than 0.878, which is less than the subcritical limit of 0.972 for KENO V.a/44-group calculations. Therefore, all credible interactions between the mixed-reflector and Nat-U chunk drums in HWM operations are subcritical and criticality safe.

The results in the two tables above indicate that any mixed-reflector drum interaction with the 55-gallon Nat-U drums array is always subcritical and criticality safe.

5.4.3.2.2 Interaction with 30-Gallon Nat-U Drum Arrays

Based on the fact that the 30-gallon drums have a lower allowable Nat-U density, 7 kilograms/gallon, as compared to the allowable 13 kilograms/gallon for the 55-gallon drums. Furthermore, 30-gallon drums are mismatch in size to the 55-gallon drums, this would result in more neutron leakage in a finite array as in realistic HWM operations. Therefore it is expected that the neutronic coupling is not as strong as interaction among the 55-gallon drums themselves. In this regard, the interaction of 30-gallon Nat-U drums with the 55-gallon mixed-reflector drums is expected to be up bounded by the interaction of 55-gallon Nat-U drums with the 55-gallon mixed-reflectors drums. Based on the above argument and the fact that the interaction of 55-gallon Nat-U drums with mixed-reflector drums of the same size is criticality safe (Section 5.4.3.2.2), it can be deduced that the interaction between the 30-gallon drums and the 55-gallon mixed-reflector drums are criticality safe as well. Therefore, no CS analysis was performed for this interaction scenario.

5.4.4 Flooding/Moisture/Fire Water

Water and moisture can effectively moderate the neutron to the thermal energy range and enhance the keff of a fissile containing system. This is no exception to the mixed-reflector container and array systems. However, the normal operation scenario for the mixed-reflector systems assumes the optimized moderation and reflection of the Pu-PE core with superior moderators and reflectors, such as PE, Be, Nat-U, and C/graphite. Therefore, the addition of water and moisture to the mixed-reflector systems are not expected to cause criticality safety concerns. Two scenarios will be considered. One scenario deals with the case that all of the drums remain intact and water proof. The water and moisture only fill the interspersed space outside the drums. The other scenario deals with the case that all of the drums are no longer water proof. The hydrogenous materials inside the drums are freely exchanging with the water or moisture outside. In this case, the water or moisture inside the drum is modeled as PE with the same percentage density. The PE moderator density, when not at full density, in the core is expected to be twice of the PE density elsewhere to factor in the potential concentrating mechanism for the core. Based on the discussion in Sections 5.4.4.1, 5.4.4.2 and 5.4.4.3, it is demonstrate that water and moisture from floods, rain, and fire fighting efforts do not jeopardize the criticality safety operations involving the mixed-reflector drums or arrays.

It should be noted that flooding is unlikely to happen for HWM facilities because LLNL is located above the 500-year flood basin. Furthermore, HWM container storage facilities are located in the east and south sides of LLNL and are on relatively high ground because LLNL is on relatively flat foothills that have low relief and gradually slope downward northwest and north, ranging in elevation from 206 m (676 ft) in the southeast corner to 174 m (571 ft) in the northwest corner. The gently falling slope across this diagonal is a fairly consistent 1.5% evenly across. Major flooding is not possible since LLNL is evenly sloped [19]. The floodwater will be drained by gravitation toward the low land in the northwest corner and beyond. Flooding in the HWM storage areas is therefore not a credible scenario.

5.4.4.1 Interspersed Water and Moisture

This scenario deals with the case that all of the drums remain intact and water proof. The water and moisture only fill the interspersed space outside the drums. The most reactive normal operation configurations, which correspond to a PE reflector volume fraction of 0%, are chosen as the base case. Two configurations of interaction are considered: one with the mixed-reflector drums only. The other with the mixed one-reflector and mixed-reflector drums. Also for each interaction configurations, two arrays are analyzed: one deals with an infinite 3-D array and the other deals with an infinite XY array with the drums stacked 6-high and reflected by a 40.64-cm (16")-thick concrete floor.

Arrays with Mixed-Reflector Drums Only

Table 34. k_{eff} values as a function of the interspersed moisture for infinite 3-D and infinite XY 6-high arrays made of mixed-reflector drums only.

Interspersed Moisture Content	Infinite 3-D Mixed-Reflector-Drum-Only Array; Input file: sb65pw			Infinite XY 6-high Mixed-Reflector-Drum-Only Array; Input file: sb65pw6		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
100%	0.8005	0.0020	0.8065	0.8002	0.0017	0.8053
90%	0.8030	0.0017	0.8081	0.7999	0.0014	0.8041
80%	0.8066	0.0017	0.8117	0.8065	0.0017	0.8116
60%	0.8131	0.0015	0.8176	0.8074	0.0015	0.8119
40%	0.8185	0.0017	0.8236	0.8194	0.0016	0.8242
20%	0.8382	0.0016	0.8430	0.8352	0.0016	0.8400
10%	0.8557	0.0016	0.8605	0.8487	0.0017	0.8538
5%	0.8696	0.0015	0.8741	0.8564	0.0014	0.8606
3%	0.8700	0.0016	0.8748	0.8606	0.0016	0.8654
2%	0.8760	0.0014	0.8802	0.8658	0.0016	0.8706
1%	0.8846	0.0018	0.8900	0.8685	0.0015	0.8730
0%	0.8864	0.0014	0.8906	0.8682	0.0015	0.8727

The results in Table 34 indicate that the k_{eff} maximum is not greater than 0.891, which is less than the subcritical limit of 0.972 for KENO V.a/44-group calculations. Therefore, all credible double-batch scenarios for any single mixed array container are criticality safe.

Arrays with Mixed Mixed-Reflector and One-Reflector Drums

The results in Table 35 demonstrate that the k_{eff} maximum is no greater than 0.971, which is less than the subcritical limit of 0.972 for KENO V.a/44-group calculations. Inherently in the subcritical limit is a safety margin of 0.02. Although it can be argued that 0.971 and 0.972 are statistically identical. The use of the 0.02 safety margin in the subcritical limit would ensure the safety of such ssytems. It should also be noted that for 6-high stacking, the k_{eff} maximum is nogreater than 0.960, which is clearly less than the subcritical limit of 0.972. For HWM operations, the 55-gallon containers are stacked 2-high. 6-high stacking has a safety factor of 3 inherently built in for the HWM operations. Please note that the one-reflector drums are actually modeled as three-reflector drums, which upper bound all one-reflector drums. It may be odd that infinite 2-D arrays are more reactive than infinite 3-D arrays, 0.971 versus 0.960. The superior neutron reflection and moderation by the full-reflection concrete floor underneath the 2-D arrays may be the cause for this.

Therefore, all credible flooding and moisture scenarios for any single mixed-reflector arrays are criticality safe based on the results in Tables 34 and 35.

Table 35. k_{eff} values as a function of the interspersed moisture for infinite 3-D and infinite XY 6-high arrays with mixed one-reflector and mixed reflector drums.

Inter-Dispersed Moisture Content	Infinite 3-D Mixed-Reflector/One-Reflector Drum Array; Input file: flmixed			Infinite XY 6-high Mixed-Reflector/One-Reflector Drum Array; Input file: flmixed6		
	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$	$k_{eff,calc}$	σ	$k_{eff} + 3\sigma$
100%	0.8492	0.0015	0.8537	0.8548	0.0019	0.8605
90%	0.8552	0.0016	0.8600	0.8473	0.0016	0.8521
80%	0.8546	0.0019	0.8603	0.8548	0.0018	0.8602
60%	0.8626	0.0017	0.8677	0.8604	0.0016	0.8652
40%	0.8733	0.0017	0.8784	0.8718	0.0018	0.8772
20%	0.8958	0.0021	0.9021	0.8877	0.0015	0.8922
10%	0.9175	0.0015	0.9220	0.9147	0.0018	0.9201
5%	0.9361	0.0015	0.9406	0.9278	0.0019	0.9335
3%	0.9436	0.0016	0.9484	0.9422	0.0014	0.9464
2%	0.9527	0.0014	0.9569	0.9433	0.0016	0.9481
1%	0.9623	0.0015	0.9668	0.9508	0.0018	0.9562
0%	0.9668	0.0014	0.9710	0.9547	0.0015	0.9592

5.4.4.2 Water and Moisture Leaking into the Drums

This scenario deals with the case that all of the drums are no longer water proof. The hydrogenous materials inside the drums are freely exchanging with the water or moisture outside. However, it has been shown that the most reactive configuration is the one with no water in the interspersed space and with no PE reflector inside the drum. In this regard, any leaking of water into the drums will only result the system reactivity suppression, which is caused by the neutron absorption by the water, from the optimized normal operation condition. Therefore, this scenario is upper bounded by the maximum of the scenarios presented in subsection 5.4.4.1, which is no greater than 0.960 for 6-high stacking. This s below the subcritical limit of 0.972 for the KENO V.a/44-Group calculations. In this regard, water damage scenario is criticality safe for HWM mixed-reflector array operations.

5.4.4.3 Additional Notes on Fire Damage and Flooding

The physical consequences for fires may go beyond flooding. For instance, the waste containers may lose their integrity from fire damage. However, optimized geometry, moderation, and reflection are safety margins built in the related CS controls. The loss of integrity in all containers may unavoidably breach the spacing controls, but the spill configuration would not be neutronically more optimized than the one assumed in the upper bound calculations. Therefore, the flooding scenario upper bounds the fire damage scenarios.

The HWM waste acceptance criteria limit all drum received by HWM to have less than 120 grams of fissile. This is assured by a sampling verification program. Furthermore, under full flooding situations, the mixed-reflector container and array operations remain criticality-safe. Therefore, water can be used as a mean for fire suppression. Hence, the operations involving mixed-reflector container arrays are assigned Criticality Hazard Type 1 [16].

5.4.5 Spilling

Spilling of a mixed array container or an entire mixed array will remain nuclear subcritical, because the scenarios is upper bounded by the maximum k_{eff} for the normal operation conditions (Section 5.3). The normal operation scenarios assume optimized moderation and full reflection. Such configurations will be hard to achieve in a spill event. For the spilling of two entire mixed array or one mixed array and one 120-gram fissile drum, the system would still remain subcritical, because this scenario is upper bounded by the interaction of two mixed arrays, which again is under optimized moderation and reflection condition. The spilling of three or more arrays would be unlikely of any criticality concern for the following reasons:

- All TRU drums/containers are sealed when in storage.
- All fissile waste drums need to be placed in Type B containers, which can sustain a 4-foot drop. Therefore, spill caused by dropping is unlikely to happen.
- Spill is mostly likely to be caused by human errors. The most likely scenario would be the spilling of a single unsealed drum. The most likely fissile content would be no more than 65 grams of Pu in such a event. Even with the optimized reflector configurations, the maximal k_{eff} is expected to no more than 0.82 (Section 5.1.4).
- Near optimized nuclear condition also needs present for nuclear criticality to occur when the spilled event involves adequate amount of fissile, which can be from either multiple drum spilling or severe over-batch of the single spilled container.

Based on the above argument, criticality from the spilling of three or more fissile containing containers/arrays would be incredible. Based on the discussions in the above, it can be safely deducted that a small spill will not be a criticality concern, while a major spill will be incredible to happen. The current HWM practices, that the spill cleanup first before the operation resumption, will prevent the accumulation of excessive amounts of fissile in the sump or anywhere else through a sequence of incremental spilling. Therefore, the likely scenario for spilling will not jeopardize the criticality-safe operation in HWM facilities.

5.4.6 Seismic Considerations

Because LLNL is near major geological faults, the potential effect of earthquakes on the mixed-reflector drum array operations need to be considered. Earthquake can potentially rearrange and mix up the waste containers in a mixed array and containers from the nearby arrays. However, from the array interaction part of this analysis (Section 5.4.3), it is demonstrated that mixed-reflector drum array interactions with other type of drums are criticality safe. Also, earthquake will not cause major spills of waste unless many containers are simultaneously damaged in such a event. Since all 55-gallon fissile containers (Type A) would remain intact with a 4-foot (121.92-cm) drop, no drum damage is expected if they are allowed to be stacked 2-high. Therefore, earthquake damage is not expected to occur for the mixed-reflector waste containers. With waste drums remain intact, other earthquake damages , such as water pipe breaking (covered in Section 5.4.4), will not jeopardize the criticality safe operations of the HWM facility. Small-scale spilling of unsealed drums may also occur, but such occurrences are expected to be criticality safe also (Section 5.4.5). Furthermore, it should also be noted that the motions from the earthquakes will have the inherent criticality-safe effects on the waste drums:

- Maximal normal operation scenario is the optimized configuration, any deviation from it can only have the system k_{eff} reduced.
- Earthquake motions will shake up and hence homogenize the waste content inside the drums. This would also reduce the overall system k_{eff} for mixed-reflector drum array.

In this regard, criticality-safe operations of the mixed array will remain intact throughout the evolution of any credible seismic activities.

6.0 CRITICALITY BARRIERS AND CONTINGENCY ASSESSMENTS

This section discusses the criticality safety barriers available for the mixed-reflector drum operations. The criticality barriers are mixed-reflector drum array system or operation parameters that can potentially prevent the occurrence of a critical accident [20] on the loss of any contingency. For instance, when the fissile mass limit is severely violated (i.e., double batch and beyond), the system may not go critical if either the moderation and reflection conditions are not optimized simultaneously. Therefore, the actual (non-optimized) moderation and reflection conditions at the time of over mass can be considered as barriers to the occurrence of criticality. The potential criticality barriers for the mixed array operations are as listed in Table 46 below:

Table 36. The available criticality barriers and contingency for the mixed array operations [21].

Barrier Parameters	Barrier	System k_{eff} Analysis Assumptions and Normal Condition Controls	
		Optimized	Normal Condition
Neutronic coupling (e.g., spacing)	yes, controlled	No separation between arrays	30" (76.2 cm) isolation separation between any two arrays
Material Form	-	-	-
Poison	-	-	-
Density	yes, not controlled	Optimized plutonium density in the core (optimized moderation)	-
Reflection (albedo)	yes, controlled	Reflectors optimally stratified; up to 700g Be, 200.1kg Nat-U, and 220.1 kg C/graphite. Also, full PE reflection	up to 350g Be, 100.05kg Nat-U, and 110.05kg C/graphite. Full PE reflection also
Shape (geometry)	yes, not controlled	Optimized core and reflector configurations are considered	-
Volume	yes, not controlled	Near optimized fully reflected systems fits in a 55-gallon drum	-
Chemical/ mixture concentration	yes, not controlled	Optimized fissile distribution with moderator	-
Enrichment	yes, not controlled	Full enrichment (Pure Pu-239) assumed	-
Moderation	yes, controlled	Optimized moderation with PE	-
Mass	yes, controlled	Double batch (130 grams/mixed-reflector drum)	65 grams Pu/mixed-reflector drum

6.1 Criticality Safety Barriers

Table 37. List of available criticality safety barriers for mixed-size and mixed-type array operations

Barrier Parameters	Barriers Formally Claimed (BFC; yes=1; no=0)	Remarks
Neutronic Coupling (Spacing)	1	30" (76.2 cm) Interaction Separation
Poison	0	Not Used
Density	1	Optimized Density
Reflection (Albedo)	1	Optimized with 350-gram Be, 100.05-kilogram Nat-U and 110.05-kilogram C/graphite
Shape (Geometry)	1	Optimized Geometry
Volume	1	Optimized Volume
Material Form	0	
Concentration	1	Optimized Fissile Concentration
Enrichment	1	Full Enrichment
Moderation	1	Optimized Moderation
Mass	1	Mass Limits: 65 grams per drum

Sum: BFC=9

A summary of the available criticality barriers for mixed array operations is as listed in Table 37:

6.2 Operation Scenario Contingency Assessment

The criticality barriers and the number of contingency lost for all credible mixed-reflector array normal and off-normal operation scenarios are as summarized in Table 36. Table 38 is prepared based on the information in Tables 23, 36, and 37.

Table 38. List of Failures and the Associated Contingency Lost for Normal and Off-Normal Mixed-Size and Mixed-Type Array Operation Scenarios

Case	Description of Normal or Off-Normal Conditions	Barrier Lost	Barriers Remain Intact	CS Controls Remain Intact
1	normal operation conditions	0	Spacing, Density, Shape, Volume, Moderation, Reflection, Mass, Concentration, Enrichment	Mass Reflection Spacing
2	fissile over-batch	1	Spacing, Density, Shape, Volume, Moderation, Reflection, Concentration, Enrichment	Reflection Spacing
3	reflector over-batch	1	Spacing, Density, Shape, Volume, Mass, Moderation, Enrichment, Concentration	Mass Spacing
3a	moderator over-batch	0	Spacing, Density, Shape, Volume, Moderation, Reflection, Mass, Concentration, Enrichment	Mass Reflection Spacing
4	Interaction with fissile drum arrays	1	Density, Shape, Volume, Moderation, Reflection, Mass, Concentration, Enrichment	Mass Reflection
4a	Interaction with Nat-U drum arrays	1	Density, Shape, Volume, Moderation, Reflection, Mass, Concentration, Enrichment	Mass Reflection
4b	Interaction with another mixed arrays	1	Density, Shape, Volume, Moderation, Reflection, Mass, Concentration, Enrichment	Mass Reflection
5	flooding/Raining	0	Spacing, Density, Shape, Volume, Moderation, Reflection, Mass, Concentration, Enrichment	Mass Reflection Spacing
5a	fire (suppression) water/fire damage	1	Density, Shape, Volume, Moderation, Reflection, Mass, Concentration, Enrichment	Mass Reflection
6	spill	1	Density, Shape, Volume, Moderation, Reflection, Mass, Concentration, Enrichment	Mass Reflection
7	seismic consideration	1	Density, Shape, Volume, Moderation, Reflection, Mass, Concentration, Enrichment	Mass Reflection

7.0 CONCLUSION

Based on the criticality safety limits and controls outlined in Section 3.0, the operations involving the use of mixed-reflector drums satisfy the double-contingency principle as required by DOE Order 420.1 [22] and are therefore criticality safe. The mixed-reflector mass limit is 120 grams for each 55-gallon drum or its equivalent. A reflector waiver of 50 grams is allowed for Be, Nat-U, or C/graphite combined. The waived reflectors may be excluded from the reflector mass calculations when determining if a drum is compliant. The mixed-reflector drums are allowed to mix with the typical

55-gallon one-reflector drums with a Pu mass limit of 120 grams. The fissile mass limit for the mixed–reflector container is 65 grams of Pu equivalent each. The corresponding reflector mass limits are 300 grams of Be, and/or 100 kilograms of Nat-U, and/or 110 kilograms of C/graphite for each container. All other unaffected control parameters for the one-reflector containers remain in effect for the mixed-reflector drums. For instance, Superior moderators, such as TrimSol, Superla white mineral oil No. 9, paraffin, and polyethylene, are allowed in unlimited quantities. Hydrogenous materials with a hydrogen density greater than 0.133 gram/cc are not allowed. Also, an isolation separation of no less than 76.2 cm (30") is required between a mixed array and any other array. Waste containers in the action of being transported are exempted from this 76.2-cm (30") separation requirement.

All deviations from the CS controls and mass limits listed in Section 3.0 will require individual criticality safety analyses on a case-by-case basis for each of them to confirm their criticality safety prior to their deployment and implementation.

8.0 REFERENCES

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13. P. Chou, CSAM 99-192, Rev. 1, 1999.
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15. D. Crawford's August 25, 1999 e-mail to S. Huang and P. Chou.
16. Health and Safety (H&S) Manual, Chapter 31, Criticality Safety, Lawrence Livermore National Laboratory, June 1999 (or Chapter 31, Criticality Safety, of Section 8, Volume II, of the Environment, Health and Safety (EH&S) Manual, LLNL.)

17. American National Standard, ANSI/ANS-8.1, 'Nuclear Criticality Safety in Operations with Fissionable Materials Reactors," American Nuclear Society, 1998.
18. H.C. Paxton and N.L. Pruvost, "Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U," LA-10860-MS, Los Alamos National Laboratory, July 1987.
19. LLNL Comprehensive Site Plan, posted at the internet address: http:// www.llnl.gov.comp_plan/ geogr.html; more information are also available in LLNL EIS/EIR, Volume 1, Section 2.1 An Overview of LLNL, 1992.
20. S.G. Vessard and C.M. Steele, 'Quantifying the Severity of Criticality Limit Violations,' Am. Nucl. Trans., **77**, pp. 219-220 (1997).
21. S. Huang, 'Response to a Criticality Safety Infraction,' Criticality Safety Group Procedure CSG-P-013, 1998.
22. DOE Order 420.1, 'Facility Safety,' Change 2, October 1996. (Former equivalent: DOE Order 5480.24, 'Nuclear Criticality Safety', August 1992).

Appendix A

Configurations Used in KENO V.a Calculations: Four-Plex Drum, Array, and Two-Ball Configurations

In the Appendix, the container and array models used in the KENO V.a calculations of this work are summarily described.

A.1 Four-Plex (4-plex) Drum Stacking Configurations

An optimized four-plex drum configuration has been used in the KENO V.a modeling. This drum configuration allows the maximum interactions between the fissile in drums.

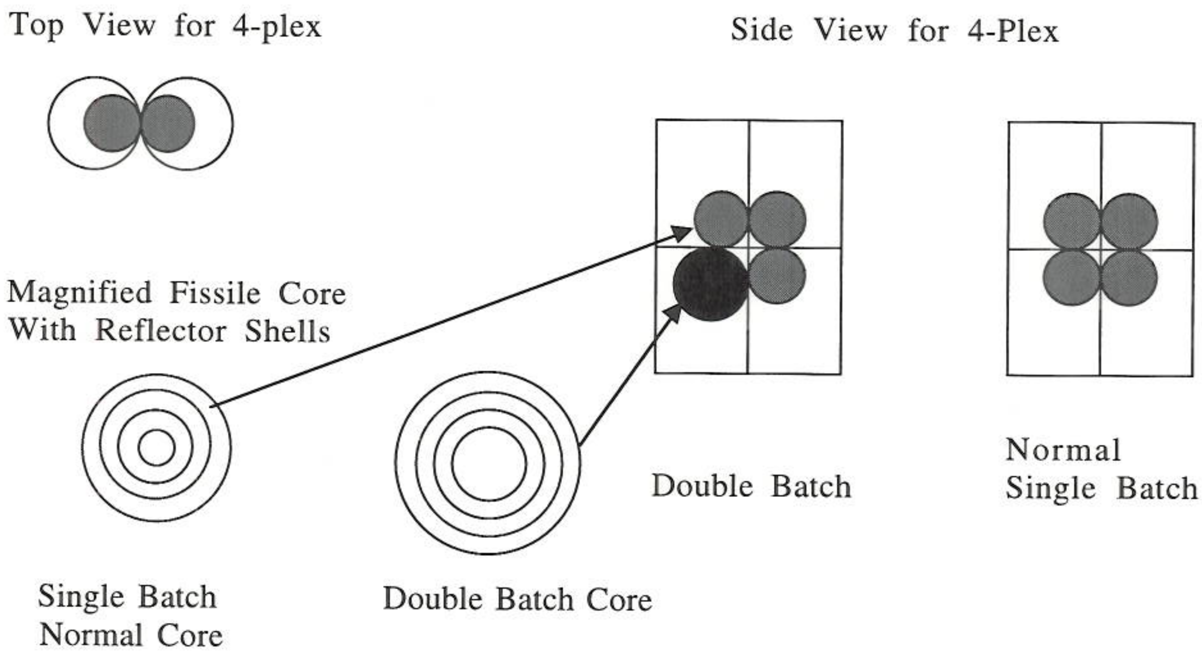


Figure A.1 Schematics for Singly- and Doubly-Batched Reflected Cores and 4-plexes.

Regardless of normal single batch or double batch, the configuration consist of a moderated fissile mixture surrounded and reflected by three reflector shells made of beryllium, Nat-U, and carbon (graphite), in the sequence of inside out. Such reflector configurations are the most. The reason for it deals with the ability of the reflector to reflect neutrons. More prolific neutron reflectors need to be placed as closer to the core as possible to maximize the chance (or the solid angles as well) of reflected neutrons being returned to the core. Out of the three reflectors, Be is the most prolific neutron reflector primarily caused by its ability to multiply neutrons from the (n,2n) reactions. Nat-U is a good neutron reflector because of its high density (neutron reflection) and its U-235 content (neutron multiplication). Graphite or carbon, out of the three types of reflectors, is the least prolific in neutron reflection. It has a very small neutron interaction cross section. This results in neutrons being reflected deep in the graphite and have very small solid angles of returning to the core, even though it has very small neutron absorption cross section. Therefore, the most optimized reflector configuration is to have the reflectors ordered in the sequence of Be, Nat-U, and graphite (carbon) from inside out so that the neutron reflection is maximized.

The drums are arranged in a 4-plex configuration with four drums as a unit. Two drums are placed next to each other with the other two drums placed on tops of them. In general, the cores inside these four drums are arranged in such a way that the interactions between them are maximized. The cores in the bottom drums are placed next to each other with the tops of the two cores touching the drum tops. In the same token, the cores in the top drums are again placed next to each other. However, this time the two top cores are touching the drum bottoms.

A.2 Array Unit (Dual 4-plex) Configurations

For normal-batch or single-batch configurations, all of the cores are singly batched. For double-batch configurations, one of the four cores in the 4-plex is doubly batched while the rest of the cores are singly batched. Since the occurrence of double batch would be relatively uncommon, the next-to-each-other interaction between two doubly batched drums would be rare. Therefore, in this work, the double-batch configuration used in this analysis is drums in a 2x2x2 formation (or in a dual 4-plex arrangement) with a doubly-batched 4-plex placed next to a singly-batched 4-plex. 1 out of every eight containers is doubly batched in such configurations. The array unit configurations illustrated in Figure 2 are periodically used in the formation of 2-D or 3-D infinite arrays. These infinite arrays are used as the upper bound for the HWM waste drum storage operations. For single-batch array configurations, the dual 4-plex arrangement will be made of two singly-batched 4-plexes.

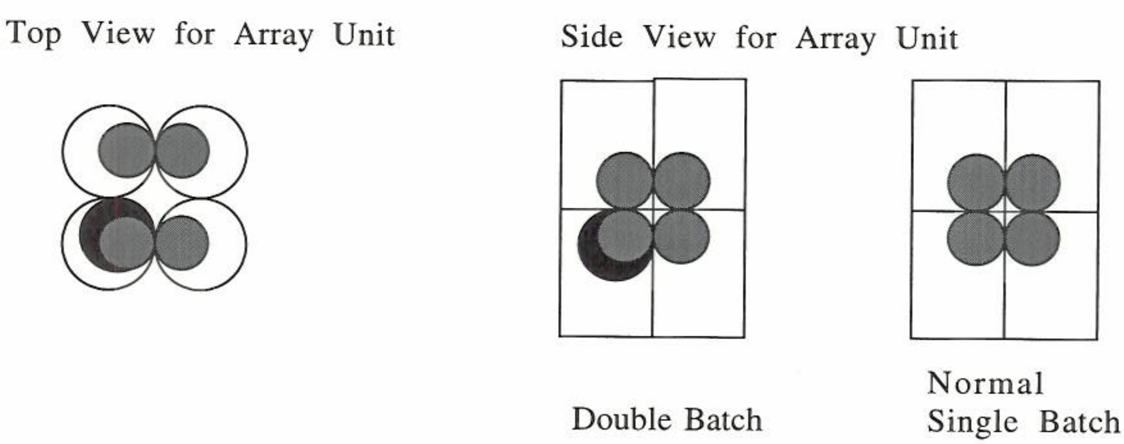


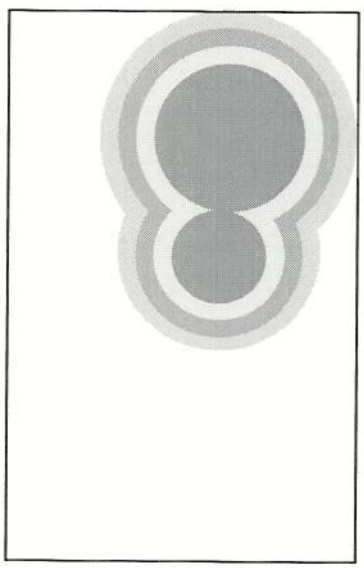
Figure A.2 Schematics for Singly- and Doubly-Batched Array Units (Dual 4-plexes)

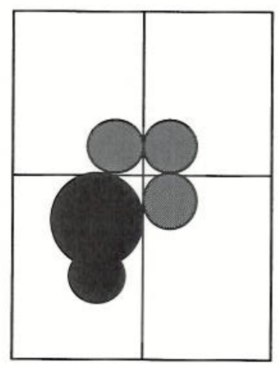
The dual 4-plex configurations maximize the interaction between the adjacent drums in array formations. The reflected cores in them meet the normal HWM mass limits or better for abnormal scenarios. Therefore, such operations are expected to be the upper bound scenario for all credible array operation scenarios at HWM.

A.3 Two-Ball Double Batch Configurations

The two-ball configurations are discussed in this section. The derivations of the two-ball configuration are discussed in detail in Appendix C of CSM 1087. The two-ball configurations represent the upper bound scenarios for the double batch of the fissile (240 grams of fissile, instead of the regularly allowed 120 grams of fissile) in the one-reflector (generally) 55-gallon drums. Scenarios more severe than these 2-ball configurations have been determined to be incredible under normal HWM operations. The two-ball configurations consist of two Pu balls (one with 150 grams of fissile and the other with 90 grams of fissile). The two balls depict the credible distribution of the fissile in a waste drum. The 150-gram Pu ball represents the credible scenario for the fissile in the core. The 90-gram Pu ball represents the maximum scenario for the fissile in the reflector, i.e., the fissile in the reflector are concentrated, instead of being dispersed throughout the reflector. Also, one of the assumptions for the two-ball configurations is that the fissile pieces have to be fine (no more than 10 cm in diameter). For large fissile pieces, they are easy to scavenge and should not result in the waste stream. Therefore, the two-ball configurations are very conservative in the modeling of the fissile distribution in the waste drums.

Two-Ball Double Batch Configuration (single drum and 4-plex)





Two-Ball Configuration in a 4-Plex

Two-Ball Configuration in a Single Drum

The two-ball configuration is made of 2 Pu/moderator cores in contact with each. The two balls are then surrounded by a beryllium shell, the by a Nat-U shell, and finally by a carbon/graphite shell. Although the three shells are of different thickness, each of the three shells is uniform in thickness throughout.

APPENDIX B

Input Decks for Criticality Safety Analysis on the Mixed Reflectors for HWM Waste Containers

B.1 Optimization Search for Core Pu Volume Fraction (Section 5.1.4 Tables 13-21)

Only the sample input decks are included. Because the simplicity of the spherical geometry for this problem, 1-D ENDF/B-V 44-group XSDRNPM has been used for calculations in this section.

B.1.1 Table 13: Optimization Search for Core Pu Volume Fraction for Normal Mixed-Reflector Containers (Input Files: db65x and db65xw)

db65x

```
=csas1x    parm=(size=2000000)
db65x: 65gPu 0.11%VF 350gBe 100.05kgNat-U 110.05kgC
44groupndf5 multiregion
plutoniumalp 1 0.0011 293 end
poly(h2o)    1 0.9989 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical end
1 8.92545 2 9.11057 3 12.62021 4 24.39662 5 30.0 end zone
end data
end
```

db65xw

```
=csas1x    parm=(size=2000000)
db65xw: 65gPu 0.11%VF 350gBe 100.05kgNat-U 110.05kgC
44groupndf5 multiregion
plutoniumalp 1 0.0011 293 end
poly(h2o)    1 0.9989 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical end
1 8.92545 2 9.11057 3 12.62021 4 24.39662 5 54.87662 end zone
end data
end
```

B.1.2 Table 14: Optimization Search for Core Pu Volume Fraction for Mixed-Reflector Containers with Fissile Double Batch (Input Files: db130x and db130xw)

db130x

```
=csas1x    parm=(size=2000000)
db130x: 130gPu 0.15%VF 350gBe 100.05kgNat-U 110.05kgC
44groupndf5 multiregion
plutoniumalp 1 0.0015 293 end
poly(h2o)    1 0.9985 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical end
1 10.14084 2 10.28518 3 13.27961 4 24.58105 5 30.0 end zone
end data
end
```

db130xw

```
=csas1x    parm=(size=2000000)
db130xw: 130gPu 0.14%VF 350gBe 100.05kgNat-U 110.05kgC 1'PE
44groupndf5 multiregion
plutoniumalp 1 0.0014 293 end
poly(h2o)    1 0.9986 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical end
1 10.37676 2 10.51474 3 13.41894 4 24.62207 5 55.10207 end zone
end data
end
```

B.1.3 Table 15: Optimization Search for Core Pu Volume Fraction for Mixed-Reflector Containers with Reflector Double Batch (Input Files: db65rx and db65rxw)

Please note that the first case has no PE reflection at all and its outer radius for carbon/graphite is larger than 30 cm. As a matter of fact, all of systems considered here have an outer radius of more than 30 cm.

db65rx

```
=csas1x    parm=(size=2000000)
db65rx: 65gPu 0.11%VF 700gBe 200.1kgNat-U 220.1kgC
44groupndf5 multiregion
plutoniumalp 1 0.0011 293 end
poly(h2o)    1 0.9989 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical end
1 8.92545 2 9.28846 3 14.90158 4 30.48488 end zone
end data
end
```

db65rxw

```
=csas1x    parm=(size=2000000)
db65rxw: 65gPu 0.11%VF 700gBe 200.1kgNat-U 220.1kgC 1'thickPE
44groupndf5 multiregion
plutoniumalp 1 0.0011 293 end
poly(h2o)    1 0.9989 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical end
1 8.92545 2 9.28846 3 14.90158 4 30.48488 5 60.96488 end zone
end data
end
```

B.1.4 Table 16: Optimization Search for Core Pu Volume Fraction for One-Reflector (Regular Fissile) Containers with Single-Batch Mixed Reflectors (Reflector Over Batch/Input File: max120a)

max120a

```
=csas1x    parm=(size=2000000)
max120a: 120g Pu 0.14%VF 350g be 100.05kg Nat-U 8.05kg C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0014 293 end
poly(h2o)    1 0.9986 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.10356 2 10.24894 3 13.25791 4 14.80566 5 45.28566 end zone
end data
end
```

B.1.5 Table 17: Optimization Search for Core Pu Volume Fraction for One-Reflector (Regular Fissile) Containers with Double-Batch Mixed Reflectors (Input File: mx120rdb)

mx120rdb

```
=csas1x    parm=(size=2000000)
mx120rdb: 120g Pu 0.14%VF 700g be 200.1kg Nat-U 16.1kg C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0014 293 end
poly(h2o)    1 0.9986 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.10356 2 10.39031 3 15.36773 4 17.60846 5 48.08846 end zone
end data
```

```
end
```

B.1.6 Table 18: Optimization Search for Core Pu Volume Fraction for Be One-Reflector (Regular Fissile) Containers with Fissile Double-Batch (Input File: max240be)

max240be

```
=csas1x    parm=(size=2000000)
max240be: 240g Pu 0.18%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0018 293 end
poly(h2o)    1 0.9982 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 11.70675 2 11.81559 3 11.81708 4 11.83064 5 42.31064 end zone
end data
end
```

B.1.7 Table 19: Optimization Search for Core Pu Volume Fraction for Nat-U One-Reflector (Regular Fissile) Containers with Fissile Double-Batch (Input File: max240u)

max240u

```
=csas1x    parm=(size=2000000)
max240u: 240g Pu 0.17%VF 50g be 100.05kg Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0017 293 end
poly(h2o)    1 0.9983 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 11.93193 2 11.94702 3 14.35654 4 14.36573 5 44.84573 end zone
end data
end
```

B.1.8 Table 20: Optimization Search for Core Pu Volume Fraction for C (Carbon/Graphite) One-Reflector (Regular Fissile) Containers with Fissile Double-Batch (Input File: max240c)

max240c

```
=csas1x    parm=(size=2000000)
max240c: 240g Pu 0.19%VF 50g be 50g Nat-U 8.05kg C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0019 293 end
poly(h2o)    1 0.9981 293 end
beryllium    2 1.0 293 end
```

```
uranium        3 1.0 293 end
graphite       4 den=2.10 1.0 293 end
poly(h2o)      5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 11.49765 2 11.51390 3 11.51548 4 13.46661 5 43.94661 end zone
end data
end
```

B.1.9 Table 21: Optimization Search for Core Pu Volume Fraction for Mixed -Reflector (Regular Fissile) Containers with Fissile Double-Batch (Input File: max240aw)

max240aw

```
=csas1x    parm=(size=2000000)
max240aw: 240g Pu 0.18%VF 350g be 100.05kg Nat-U 8.05kg C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0018 293 end
poly(h2o)    1 0.9982 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 11.70675 2 11.81559 3 14.26595 4 15.63020 5 46.11020 end zone
end data
end
```

B.2 Input Decks for Normal Batch

B.2.1 Table 23: Normal Batch in The Mixed-Reflector-Drum-Only Arrays (Input Files: sb65p and sb65p6)

sb65p

```
=csas25    parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' reflector mixing sb-65g
plutoniumalp 11 0.0011 293 end
poly(h2o)     11 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel  6  1.0 293 end
orconcrete   7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
end comp
sb65p: single batch mixed-reflector drums only; poly filling 0%VF
```

```
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere  11 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole    91     3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole    91    -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole    91     3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole    91    -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=100 nux=1 nuy=3 nuz=2 fill f71 end fill
end array
read bounds all=periodic end bounds
end data
end
```

sb65p6

```
=csas25    parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' reflector mixing sb-65g
plutoniumalp 11 0.0011 293 end
poly(h2o)    11 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
```

```
carbonsteel 6  1.0 293 end
orconcrete  7  1.0 293 end
h2o         8  0.0001 293 end
poly(h2o)   9  den=0.92 1.0 293 end
end comp
sb65p6: inf XY 6-high array SB mixed-reflector drums poly filling 0%VF
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere  11 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole    91   -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole    91   -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f71 end fill
end array
read bounds xyf=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 4 card, '`poly(h2o) 4  den=0.92 0.0001 293 end`', is to be modified accordingly.

B.2.2 Table 24: Fissile Double Batch in The Mixed Mixed- and One-Reflector-Drum Arrays (Input Files: sbfiss and sbfiss6)

sbfiss

```
=csas25    parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' fissile drum reflector (mixed-reflector) upper bound 0.14%VF
plutoniumalp 1 0.0014 293 end
poly(h2o)    1 den=0.92 0.9986 293 end
' reflector mixing sb-65g
plutoniumalp 10 0.0011 293 end
poly(h2o)    10 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel 6  1.0 293 end
orconcrete   7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
uranium     11  1.0 293 end
end comp
sbfiss: fis drum reflector (mixed-reflector) with SB mixed-refl drum 0.01% VF PE
      Reflector
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere  10 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole     91    3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole     91   -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole     91    3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole     91   -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
```

```
cuboid   8 1 4p28.630 83.005 -0.355
' fissile drum reflector db 120g 0.14%VF 350gBe 100.01kgU 8.05kgC
unit 191
sphere   1 1 10.10356
sphere   3 1 10.24894
sphere   2 1 13.25791
sphere   5 1 14.80566
unit 11
cylinder 4 1 28.267 82.65 0.0
hole   191    13.46133 0.0 67.84433
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 12
cylinder 4 1 28.267 82.65 0.0
hole   191   -13.46133 0.0 67.84433
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 13
cylinder 4 1 28.267 82.65 0.0
hole   191    13.46133 0.0 14.80567
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 14
cylinder 4 1 28.267 82.65 0.0
hole   191   -13.46133 0.0 14.80567
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 21
cylinder 500 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 31
cylinder 13 1 28.267 82.65 69.05
cylinder 14 1 28.267 82.65  0.0
cylinder  9 1 28.495 82.878 -0.228
cylinder  6 1 28.630 83.005 -0.355
cuboid    8 1 4p28.630 83.005 -0.355
unit 32
cylinder 13 1 28.267 13.60  0.0
cylinder 14 1 28.267 82.65  0.0
cylinder  9 1 28.495 82.878 -0.228
cylinder  6 1 28.630 83.005 -0.355
cuboid    8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
unit 72
array 72 0.0 0.0 0.0
unit 73
array 73 0.0 0.0 0.0
unit 84
array 84 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
```

```
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11 12 13 14 end fill
ara=84 nux=2 nuy=1 nuz=2 fill 71 2r72 71 end fill
ara=100 nux=1 nuy=2 nuz=3 fill f84 end fill
end array
read bounds all=periodic end bounds
end data
end
```

sbfiss6

```
=csas25    parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' fissile drum reflector (mixed-reflector) upper bound 0.14%VF
plutoniumalp 1 0.0014 293 end
poly(h2o)     1 den=0.92 0.9986 293 end
' reflector mixing sb-65g
plutoniumalp 10 0.0011 293 end
poly(h2o)     10 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel 6  1.0 293 end
orconcrete  7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
uranium     11  1.0 293 end
end comp
sbfiss6: fis drum reflector (mixed-reflector) with SB mixed-refl drum 0.01% VF PE
      Reflector
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere  10 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole    91   -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 24.39663
```

```
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole    91    -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' fissile drum reflector db 120g 0.14%VF 350gBe 100.01kgU 8.05kgC
unit 191
sphere   1 1 10.10356
sphere   3 1 10.24894
sphere   2 1 13.25791
sphere   5 1 14.80566
unit 11
cylinder 4 1 28.267 82.65 0.0
hole   191    13.46122 0.0 67.84433
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 12
cylinder 4 1 28.267 82.65 0.0
hole   191   -13.46122 0.0 67.84433
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 13
cylinder 4 1 28.267 82.65 0.0
hole   191    13.46122 0.0 14.80567
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 14
cylinder 4 1 28.267 82.65 0.0
hole   191   -13.46122 0.0 14.80567
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 21
cylinder 500 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 31
cylinder 13 1 28.267 82.65 69.05
cylinder 14 1 28.267 82.65  0.0
cylinder  9 1 28.495 82.878 -0.228
cylinder  6 1 28.630 83.005 -0.355
cuboid    8 1 4p28.630 83.005 -0.355
unit 32
cylinder 13 1 28.267 13.60  0.0
cylinder 14 1 28.267 82.65  0.0
cylinder  9 1 28.495 82.878 -0.228
cylinder  6 1 28.630 83.005 -0.355
cuboid    8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
```

```
unit 72
array 72 0.0 0.0 0.0
unit 73
array 73 0.0 0.0 0.0
unit 84
array 84 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11 12 13 14 end fill
ara=84 nux=2 nuy=1 nuz=2 fill 71 2r72 71 end fill
ara=100 nux=1 nuy=2 nuz=3 fill f84 end fill
end array
read bounds xyf=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 4 card, '`poly(h2o) 4  den=0.92 0.0001 293 end`', is to be modified accordingly.

B.3 Input Decks for Fissile Double Batch

B.3.1 Table 25: Fissile Double Batch in The Mixed-Reflector-Drum-Only Arrays (Input Files: db130db4, db130db8, and db130db46)

db130db4

```
=csas25     parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
plutoniumalp 1 0.0019 293 end
poly(h2o)     1 den=0.92 0.9981 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 1.0 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel 6  1.0 293 end
orconcrete  7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
plutoniumalp 10 0.0019 293 end
poly(h2o)     10 den=0.92 0.9981 293 end
' reflector mixing sb-65g
plutoniumalp 11 0.0011 293 end
poly(h2o)     11 den=0.92 0.9989 293 end
' reflector mixing db-130g
plutoniumalp 12 0.0015 293 end
poly(h2o)     12 den=0.92 0.9985 293 end
' reflector mixing db-700gBe 200.1kgU 220.1kgC
plutoniumalp 13 0.0011 293 end
poly(h2o)     13 den=0.92 0.9989 293 end
end comp
db130db4: fissile DB in mixed-reflector drums (1 drums in 4) poly filler 100% TD
```

```
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere  11 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole     91    3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole     91   -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole     91    3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole     91   -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' reflector mixing db-130g db130x 0.15%VF
unit 92
sphere  12 1 10.14084
sphere   3 1 10.28518
sphere   2 1 13.27961
sphere   5 1 24.58105
unit 11
cylinder 4 1 28.267 82.65 0.0
hole     92   3.68594 0.0 58.06894
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 12
cylinder 4 1 28.267 82.65 0.0
hole     92  -3.68594 0.0 58.06894
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 13
cylinder 4 1 28.267 82.65 0.0
hole     92   3.68594 0.0 24.58106
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 14
cylinder 4 1 28.267 82.65 0.0
```

```
hole     92  -3.68594 0.0 24.58106
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' reflector mixing sb-65g db65rx 0.11%VF twice refl amounts
unit 93
sphere  13 1  8.92545
sphere   3 1  9.28846
sphere   2 1 14.90158
unit 21
cylinder 5 1 28.267 82.65 36.69457
hole     93  -13.36541 0.0 67.74841
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 22
cylinder 5 1 28.267 82.65 36.69457
hole     93  -13.36541 0.0 67.74841
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 23
cylinder 5 1 28.267 45.95543 0.0
hole     93   13.36541 0.0 14.90159
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 24
cylinder 5 1 28.267 45.95543 0.0
hole     93  -13.36541 0.0 14.90159
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
unit 72
array 72 0.0 0.0 0.0
unit 73
array 73 0.0 0.0 0.0
unit 84
array 84 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11  2  3  4 end fill
ara=73 nux=2 nuy=1 nuz=2 fill 21  2  3  4 end fill
ara=84 nux=1 nuy=2 nuz=1 fill 71 72 end fill
ara=100 nux=1 nuy=3 nuz=2 fill f72 end fill
end array
read bounds all=periodic end bounds
read plot
```

```
xul=0.0 yul=28.267 zul=400.0 xlr=400.0 ylr=28.267 zlr=0.0
uax=1.0 wdn=-1.0 nax=500 ttl=/slice at y=28.267/ end
xul=0.0 yul=400.0 zul=67.5 xlr=400.0 ylr=0.0 zlr=67.5
uax=1.0 vdn=-1.0 nax=500 ttl=/slice at z=67.5/ end
end plot
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 4 card, '`poly(h2o) 4 den=0.92 0.0001 293 end`', is to be modified accordingly.

sb130db8 To generate decks from **sb130db4** for this case, where there is 1 double batch drum out of every 8 drums (dual 4-plex configuration), the ARRAY 100 card, '`ara=100 nux=1 nuy=3 nuz=2 fill f72 end fill`', needs to be modified by substituting 'f84' for 'f72'.

sb130db46 To generate decks from **sb130db4** for this case, where the array is infinite in the X and Y directions and is 6-high in the Z direction with 16"(40.64 cm) concrete floor reflection. The following cards

```
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11  2  3  4 end fill
ara=73 nux=2 nuy=1 nuz=2 fill 21  2  3  4 end fill
ara=84 nux=1 nuy=2 nuz=1 fill 71 72 end fill
ara=100 nux=1 nuy=3 nuz=2 fill f72 end fill
end array
read bounds all=periodic end bounds
```

need to be replaced by (bolds and remarks)

```
global unit 100
array 100 0.0 0.0 0.0
replicate 7 1 5*0.0 40.96 1     ' --> the apostrophe in the front is removed
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11  2  3  4 end fill
ara=73 nux=2 nuy=1 nuz=2 fill 21  2  3  4 end fill
ara=84 nux=1 nuy=2 nuz=1 fill 71 72 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f72 end fill
end array
read bounds xyf=periodic end bounds
```

B.3.2 Table 27: Fissile Double Batch in The Mixed Mixed- and One-Reflector-Drum Arrays (Input Files: twoballvu, twobalvb, and twobalvc)

The input decks included here are for fissile double batch in one-reflector (or regular fissile) drums with 240 grams of Pu instead of 120 grams. Based on the HWM operation experience, a credible bounding scenario for fissile double batching is that two Pu cores are formed; one is the true core, which contains 5/8 of the total Pu amount and the other is the reflector core, which contains 3/8 of the total amount of Pu and represents the Pu in reflectors. A reflector core is formed to upper bound the interaction between the core and reflector Pu. For more details on the derivation for this two-core double batch system, see the main text and Appendix C in CSM 1087 for details.

twoballvu

```
=csas25     parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' 120g sb drum reflector overbatch
plutoniumalp 1 0.0014 293 end
poly(h2o)     1 den=0.92 0.9986 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel 6  1.0 293 end
orconcrete  7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
' 240g db reflector mixing
plutoniumalp 10 0.0018 293 end
poly(h2o)     10 den=0.92 0.9982 293 end
' reflector mixing sb-65g
plutoniumalp 11 0.0011 293 end
poly(h2o)     11 den=0.92 0.9989 293 end
' reflector mixing db-130g
plutoniumalp 12 0.0015 293 end
poly(h2o)     12 den=0.92 0.9985 293 end
' reflector mixing db-700gBe 200.1kgU 220.1kgC
plutoniumalp 13 0.0011 293 end
poly(h2o)     13 den=0.92 0.9989 293 end
' 120g sb Nat-U reflector
plutoniumalp 14 0.0016 293 end
poly(h2o)     14 den=0.92 0.9984 293 end
' 120g sb C reflector
plutoniumalp 15 0.0014 293 end
poly(h2o)     15 den=0.92 0.9986 293 end
' 120g sb be reflector
plutoniumalp 16 0.0016 293 end
poly(h2o)     16 den=0.92 0.9984 293 end
' 240g db be reflector
plutoniumalp 17 0.0018 293 end
poly(h2o)     17 den=0.92 0.9982 293 end
' 240g db Nat-U reflector
plutoniumalp 18 0.0017 293 end
poly(h2o)     18 den=0.92 0.9983 293 end
' 240g db c-graphite reflector
plutoniumalp 19 0.0019 293 end
poly(h2o)     19 den=0.92 0.9981 293 end
end comp
TwoBallvu: 240g DB Nat-U Refl and mixed-reflector drums in inf XY 6-High Arrays
```

```
read param npg=3000 gen=225 nsk=25 end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere  11 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole    91   -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole    91   -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' reflector mixing db-130g db130x 0.15%VF
unit 92
sphere  12 1 10.14084
sphere   3 1 10.28518
sphere   2 1 13.27961
sphere   5 1 24.58105
unit 11
cylinder 4 1 28.267 82.65 0.0
hole    92   3.68594 0.0 58.06894
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 12
cylinder 4 1 28.267 82.65 0.0
hole    92  -3.68594 0.0 58.06894
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 13
cylinder 4 1 28.267 82.65 0.0
hole    92   3.68594 0.0 24.58106
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 14
cylinder 4 1 28.267 82.65 0.0
```

```
hole     92  -3.68594 0.0 24.58106
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' reflector mixing sb-65g db65rx 0.11%VF twice refl amounts
unit 93
sphere  13 1  8.92545
sphere   3 1  9.28846
sphere   2 1 14.90158
unit 21
cylinder 5 1 28.267 82.65 36.69457
hole     93  -13.36541 0.0 67.74841
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 22
cylinder 5 1 28.267 82.65 36.69457
hole     93  -13.36541 0.0 67.74841
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 23
cylinder 5 1 28.267 45.95543 0.0
hole     93   13.36541 0.0 14.90159
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 24
cylinder 5 1 28.267 45.95543 0.0
hole     93  -13.36541 0.0 14.90159
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' reflector mixing sb-120g 0.14%VF
unit 191
sphere   1 1 10.10356
sphere   3 1 10.24894
sphere   2 1 13.25791
sphere   5 1 14.80566
unit 31
cylinder 4 1 28.267 82.65 0.0
hole    191   13.46133 0.0 67.84433
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 32
cylinder 4 1 28.267 82.65 0.0
hole    191  -13.46133 0.0 67.84433
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 33
cylinder 4 1 28.267 82.65 0.0
hole    191   13.46133 0.0 14.80567
```

```
cylinder 4 1 28.267 82.65 0.0
hole   193   15.32361 0.0 12.94339
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 234
cylinder 4 1 28.267 82.65 0.0
hole   193  -15.32361 0.0 12.94339
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' reflector C sb-120g 0.14%VF
unit 194
sphere  15 1 10.10356
sphere   3 1 10.12459
sphere   2 1 10.12662
sphere   5 1 12.50104
unit 331
cylinder 4 1 28.267 82.65 0.0
hole   194   15.76595 0.0 70.14895
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 332
cylinder 4 1 28.267 82.65 0.0
hole   194  -15.76595 0.0 70.14895
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 333
cylinder 4 1 28.267 82.65 0.0
hole   194   15.76595 0.0 12.50105
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 334
cylinder 4 1 28.267 82.65 0.0
hole   194  -15.76595 0.0 12.50105
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' 240g db reflector mixed 0.18%VF
unit 1921
sphere     10 1  8.44203
hemisphe-z 3 1  8.52922 chord 8.44203
hemisphe-z 2 1 10.57968 chord 8.44203
hemisphe-z 5 1 11.77695 chord 8.44203
unit 1922
sphere     10 1 10.00913
hemisphe+z 3 1 10.09632 chord 10.00913
hemisphe+z 2 1 12.14678 chord 10.00913
hemisphe+z 5 1 13.34405 chord 10.00913
unit 1923
sphere     10 1  8.44203
hemisphe+z 3 1  8.52922 chord 8.44203
hemisphe+z 2 1 10.57968 chord 8.44203
hemisphe+z 5 1 11.77695 chord 8.44203
unit 1924
```

```
sphere     10 1 10.00913
hemisphe-z 3 1 10.09632 chord 10.00913
hemisphe-z 2 1 12.14678 chord 10.00913
hemisphe-z 5 1 13.34405 chord 10.00913
unit 41
cylinder 4 1 28.267 82.65 0.0
hole   1922  14.92294 0.0 69.30594
hole   1921  14.92294 0.0 50.85477
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 42
cylinder 4 1 28.267 82.65 0.0
hole   1922 -14.92294 0.0 69.30594
hole   1921 -14.92294 0.0 50.85477
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 43
cylinder 4 1 28.267 82.65 0.0
hole   1924  14.92294 0.0 13.34406
hole   1923  14.92294 0.0 31.79523
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 44
cylinder 4 1 28.267 82.65 0.0
hole   1924 -14.92294 0.0 13.34406
hole   1923 -14.92294 0.0 31.79523
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' 240g db reflector be 0.18%VF
unit 1821
sphere     10 1  8.44203
hemisphe-z 3 1  8.52922 chord 8.44203
hemisphe-z 2 1  8.53042 chord 8.44203
hemisphe-z 5 1  8.54131 chord 8.44203
unit 1822
sphere     10 1 10.00913
hemisphe+z 3 1 10.09632 chord 10.00913
hemisphe+z 2 1 10.09753 chord 10.00913
hemisphe+z 5 1 10.10841 chord 10.00913
unit 141
cylinder 4 1 28.267 82.65 0.0
hole   1822  18.15858 0.0 72.54158
hole   1821  18.15858 0.0 54.09040
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' 240g db reflector nat-u 0.17%VF
unit 1721
sphere     10 1  8.60441
hemisphe-z 3 1  8.61551 chord 8.60441
hemisphe-z 2 1 10.62444 chord 8.60441
hemisphe-z 5 1 10.63236 chord 8.60441
unit 1722
sphere     10 1 10.20166
```

```
hemisphe+z 3 1 10.21276 chord 10.20166
hemisphe+z 2 1 12.22169 chord 10.20166
hemisphe+z 5 1 12.22961 chord 10.20166
unit 241
cylinder 4 1 28.267 82.65 0.0
hole   1722  16.03738 0.0 70.42038
hole   1721  16.03738 0.0 51.61429
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' 240g db reflector c 0.19%VF
unit 1621
sphere    10 1  8.29124
hemisphe-z 3 1  8.30423 chord 8.29124
hemisphe-z 2 1  8.30549 chord 8.29124
hemisphe-z 5 1  9.92257 chord 8.29124
unit 1622
sphere    10 1  9.83036
hemisphe+z 3 1  9.84335 chord 9.83036
hemisphe+z 2 1  9.84461 chord 9.83036
hemisphe+z 5 1 11.46169 chord 9.83036
unit 341
cylinder 4 1 28.267 82.65 0.0
hole   1622  16.80530 0.0 71.18830
hole   1621  16.80530 0.0 53.06668
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
unit 72
array 72 0.0 0.0 0.0
unit 73
array 73 0.0 0.0 0.0
unit 74
array 74 0.0 0.0 0.0
unit 75
array 75 0.0 0.0 0.0
unit 84
array 84 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11 12 13 14 end fill
ara=73 nux=2 nuy=1 nuz=2 fill 21 22 23 24 end fill
ara=74 nux=2 nuy=1 nuz=2 fill 31 32 33 34 end fill
ara=75 nux=2 nuy=1 nuz=2 fill 241 32 33 34 end fill
ara=84 nux=1 nuy=2 nuz=1 fill 71 75 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f84 end fill
end array
read bounds xyf=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 4 card, '`poly(h2o) 4 den=0.92 0.0001 293 end`', is to be modified accordingly.

twobalvb To generate decks from **twoballvu** for this case, where the two-ball core is primary reflected by Be in a ual 4-plex configuration, the ARRAY 75 card, '`ara=75 nux=2 nuy=1 nuz=2 fill 241 32 33 34 end fill`', needs to be modified by substituting '241' for '141'.

twobalvc To generate decks from **twoballvu** for this case, where the two-ball core is primary reflected by Be in a ual 4-plex configuration, the ARRAY 75 card, '`ara=75 nux=2 nuy=1 nuz=2 fill 241 32 33 34 end fill`', needs to be modified by substituting '241' for '341'.

B.4 Input Decks for Reflector Double Batch

B.4.1 Table 28: Reflector Double Batch in The Mixed-Reflector-Drum-Only Arrays (Input Files: dbmref and dbmref6)

dbmref

```
=csas25     parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' reflector mixing db-700gBe 200.1kgU 220.1kgC
plutoniumalp 13 0.0011 293 end
poly(h2o)     13 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel 6  1.0 293 end
orconcrete   7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
end comp
dbmref: all mixed-refl. drums db in reflectors 0.01% VF PE Refl.
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65rx 0.11%VF twice refl amounts
unit 93
sphere  13 1   8.92545
sphere   3 1   9.28846
sphere   2 1  14.90158
unit 21
cylinder 5 1 28.267 82.65 36.69457
hole     93   -13.36541 0.0 67.74841
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 22
cylinder 5 1 28.267 82.65 36.69457
hole     93   -13.36541 0.0 67.74841
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
```

```
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 23
cylinder 5 1 28.267 45.95543 0.0
hole    93   13.36541 0.0 14.90159
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 24
cylinder 5 1 28.267 45.95543 0.0
hole    93  -13.36541 0.0 14.90159
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 73
array 73 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=73 nux=2 nuy=1 nuz=2 fill 21 22 23 24 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f73 end fill
end array
read bounds all=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 4 card, '`poly(h2o) 4  den=0.92 0.0001 293 end`', is to be modified accordingly.

dbremf6 To generate decks from **dbmref** for this case, where the array is infinite in the X and Y directions and is 6-high in the Z direction with 16"(40.64 cm) concrete floor reflection. The following cards

```
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11  2  3  4 end fill
ara=73 nux=2 nuy=1 nuz=2 fill 21  2  3  4 end fill
ara=84 nux=1 nuy=2 nuz=1 fill 71 72 end fill
ara=100 nux=1 nuy=3 nuz=2 fill f72 end fill
end array
read bounds all=periodic end bounds
```

need to be replaced by

```
global unit 100
array 100 0.0 0.0 0.0
replicate 7 1 5*0.0 40.96 1     ' --> the apostrophe in the front is removed
```

```
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11  2  3  4 end fill
ara=73 nux=2 nuy=1 nuz=2 fill 21  2  3  4 end fill
ara=84 nux=1 nuy=2 nuz=1 fill 71 72 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f72 end fill
end array
read bounds xyf=periodic end bounds
```

B.4.2 Table 29: Reflector Double Batch in The Mixed- and One-Reflector Drum Arrays (Input Files: sbfis8 and sbfis86)

sbfis8

```
=csas25    parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' fissile drum reflector DB upper bound 0.14%VF
plutoniumalp 1 0.0014 293 end
poly(h2o)     1 den=0.92 0.9986 293 end
' reflector mixing sb-65g
plutoniumalp 10 0.0011 293 end
poly(h2o)     10 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel 6  1.0 293 end
orconcrete  7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
uranium     11  1.0 293 end
end comp
sbfis8: fis drum reflector DB with SB mixed-refl drum 0.01% VF PE Reflector
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere  10 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole    91     3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole    91    -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
```

```
hole     91     3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole     91    -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' fissile drum reflector mixed db 120g 0.14%VF 700gBe 200.1kgU 16.1kgC
unit 191
sphere   1 1 10.10356
sphere   3 1 10.39031
sphere   2 1 15.36773
sphere   5 1 17.60846
' fissile drum reflector mixed sb 120g 0.14%VF 350gBe 100.05kgU 8.05kgC
unit 192
sphere   1 1 10.10356
sphere   3 1 10.24894
sphere   2 1 13.25791
sphere   5 1 14.80566
unit 11
cylinder 4 1 28.267 82.65 0.0
hole   191    10.65853 0.0 65.04153
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 12
cylinder 4 1 28.267 82.65 0.0
hole   192  -13.46133 0.0 67.84433
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 13
cylinder 4 1 28.267 82.65 0.0
hole   192  -13.46133 0.0 14.80567
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 14
cylinder 4 1 28.267 82.65 0.0
hole   192  -13.46133 0.0 14.80567
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 21
cylinder 500 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 31
cylinder 13 1 28.267 82.65 69.05
cylinder 14 1 28.267 82.65  0.0
cylinder  9 1 28.495 82.878 -0.228
cylinder  6 1 28.630 83.005 -0.355
cuboid    8 1 4p28.630 83.005 -0.355
unit 32
```

```
cylinder 13 1 28.267 13.60  0.0
cylinder 14 1 28.267 82.65  0.0
cylinder  9 1 28.495 82.878 -0.228
cylinder  6 1 28.630 83.005 -0.355
cuboid    8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
unit 72
array 72 0.0 0.0 0.0
unit 73
array 73 0.0 0.0 0.0
unit 84
array 84 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11 12 13 14 end fill
ara=84 nux=2 nuy=1 nuz=2 fill 71 2r72 71 end fill
ara=100 nux=1 nuy=2 nuz=3 fill f84 end fill
end array
read bounds all=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 4 card, '`poly(h2o) 4 den=0.92 0.0001 293 end`', is to be modified accordingly.

sbfis86 To generate decks from **sbfis8** for this case, where the array is infinite in the X and Y directions and is 6-high in the Z direction with 16"(40.64 cm) concrete floor reflection. The following cards

```
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11  2  3  4 end fill
ara=84 nux=2 nuy=1 nuz=2 fill 71 2r72 71 end fill
ara=100 nux=1 nuy=2 nuz=3 fill f84 end fill
end array
read bounds all=periodic end bounds
```

need to be replaced by

```
global unit 100
array 100 0.0 0.0 0.0
replicate 7 1 5*0.0 40.96 1  <---- apostrophe in the front deleted
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11  2  3  4 end fill
```

```
ara=84 nux=2 nuy=1 nuz=2 fill 71 2r72 71 end fill
ara=100 nux=1 nuy=2 nuz=3 fill f84 end fill
end array
read bounds xyf=periodic end bounds
```

B.5 Loss of Interaction Controls

B.5.1 Mixed-Reflector Drums with Optimally Moderated Latticed Nat-U Drums (Input File: sbnatula)

sbnatula

```
=csas2x    parm=(size=2000000)
reflector mixing
44groupndf5 latticecell
' reflector mixing sb-65g
plutoniumalp 1 0.0011 293 end
poly(h2o)     1 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel 6  1.0 293 end
orconcrete  7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
uranium     11  1.0 293 end
arbmsuperla 0.86 2 0 1 0 1000 30 6012 15 12 0.15 293 end
uranium     13  1.0 293 end
poly(h2o)   14  den=0.92 1.0 293 end
end comp
triangpitch 8.27871 2.6 11 12 end
sbnatula: Lattice ht Nat-U drum and mixed-refl drum 0.1% VF PE refl
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere   1 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole     91     3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole     91    -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
```

```
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole    91   -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 21
cylinder 500 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
unit 73
array 73 0.0 0.0 0.0
unit 84
array 84 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=73 nux=2 nuy=1 nuz=2 fill f21 end fill
ara=84 nux=2 nuy=1 nuz=2 fill 71 2r73 71 end fill
ara=100 nux=1 nuy=2 nuz=3 fill f84 end fill
end array
read bounds all=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 4 card, '`poly(h2o) 4  den=0.92 0.0001 293 end`', is to be modified accordingly.

B.5.2 Table 33: Mixed-Reflector Drums with Nat-U Drums with Nat-U in Chunks (Input File: sbnatuhm)

sbnatuhm

```
=csas25    parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' reflector mixing sb-65g
plutoniumalp 1 0.0011 293 end
poly(h2o)     1 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
```

```
graphite     5  den=2.10 1.0 293 end
carbonsteel 6  1.0 293 end
orconcrete  7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)   9  den=0.92 1.0 293 end
uranium    13  1.0 293 end
poly(h2o)  14  den=0.92 0.0001 293 end
end comp
sbnatuhm: solid Nat-U chunks drums with mixed-refl drums 0.01%VF PE Refl.
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere   1 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole    91     3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole    91    -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole    91     3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole    91    -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 31
cylinder 13 1 28.267 82.65 69.05
cylinder 14 1 28.267 82.65  0.0
cylinder  9 1 28.495 82.878 -0.228
cylinder  6 1 28.630 83.005 -0.355
cuboid    8 1 4p28.630 83.005 -0.355
unit 32
cylinder 13 1 28.267 13.60  0.0
cylinder 14 1 28.267 82.65  0.0
cylinder  9 1 28.495 82.878 -0.228
cylinder  6 1 28.630 83.005 -0.355
cuboid    8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
unit 74
array 74 0.0 0.0 0.0
unit 84
```

```
array 84 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=74 nux=2 nuy=1 nuz=2 fill 2r31 f32 end fill
ara=84 nux=2 nuy=1 nuz=2 fill 71 2r74 71 end fill
ara=100 nux=1 nuy=2 nuz=3 fill f84 end fill
end array
read bounds all=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 4 card, '`poly(h2o) 4  den=0.92 0.0001 293 end`', is to be modified accordingly.

B.4 Input Decks for Reflector Double Batch

B.4.1 Table 28: Reflector Double Batch in The Mixed-Reflector-Drum-Only Arrays (Input Files: dbmref and dbmref6)

dbmref

```
=csas25    parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' reflector mixing db-700gBe 200.1kgU 220.1kgC
plutoniumalp 13 0.0011 293 end
poly(h2o)     13 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel  6  1.0 293 end
orconcrete   7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
end comp
dbmref: all mixed-refl. drums db in reflectors 0.01% VF PE Refl.
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65rx 0.11%VF twice refl amounts
unit 93
sphere  13 1  8.92545
sphere   3 1  9.28846
sphere   2 1 14.90158
unit 21
cylinder 5 1 28.267 82.65 36.69457
hole    93  -13.36541 0.0 67.74841
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
```

```
cuboid   8 1 4p28.630 83.005 -0.355
unit 22
cylinder 5 1 28.267 82.65 36.69457
hole    93  -13.36541 0.0 67.74841
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 23
cylinder 5 1 28.267 45.95543 0.0
hole    93   13.36541 0.0 14.90159
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 24
cylinder 5 1 28.267 45.95543 0.0
hole    93  -13.36541 0.0 14.90159
cylinder 4 1 28.267 82.65 0.0
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 73
array 73 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=73 nux=2 nuy=1 nuz=2 fill 21 22 23 24 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f73 end fill
end array
read bounds all=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 4 card, '`poly(h2o) 4  den=0.92 0.0001 293 end`', is to be modified accordingly.

dbremf6 To generate decks from **dbmref** for this case, where the array is infinite in the X and Y directions and is 6-high in the Z direction with 16"(40.64 cm) concrete floor reflection. The following cards

```
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11  2  3  4 end fill
ara=73 nux=2 nuy=1 nuz=2 fill 21  2  3  4 end fill
ara=84 nux=1 nuy=2 nuz=1 fill 71 72 end fill
ara=100 nux=1 nuy=3 nuz=2 fill f72 end fill
end array
read bounds all=periodic end bounds
```

need to be replaced by

```
global unit 100
array 100 0.0 0.0 0.0
replicate 7 1 5*0.0 40.96 1     ' --> the apostrophe in the front is removed
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=72 nux=2 nuy=1 nuz=2 fill 11  2  3  4 end fill
ara=73 nux=2 nuy=1 nuz=2 fill 21  2  3  4 end fill
ara=84 nux=1 nuy=2 nuz=1 fill 71 72 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f72 end fill
end array
read bounds xyf=periodic end bounds
```

B.6 Input Decks for Flooding and Moisture

B.6.1 Table 34: Flooding and Moisture in the Mixed-Reflector-Drum-Only Arrays (Input Files: sb65pw and sb65pw6)

sb65pw

```
=csas25    parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' reflector mixing sb-65g
plutoniumalp 11 0.0011 293 end
poly(h2o)     11 den=0.92 0.9989 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel  6  1.0 293 end
orconcrete   7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
end comp
reflector mixing: single batch poly filling 0%VF water 0%
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere  11 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole     91     3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole     91    -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
```

```
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole    91   -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=100 nux=1 nuy=3 nuz=2 fill f71 end fill
end array
read bounds all=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 9 card, '`h2o 8 0.0001 293 end`', is to be modified accordingly.

sb65pw6 To generate decks from **sb65pw** for this case, where the array is infinite in the X and Y directions and is 6-high in the Z direction with 16"(40.64 cm) concrete floor reflection. The following cards

```
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=100 nux=1 nuy=3 nuz=2 fill f71 end fill
end array
read bounds all=periodic end bounds
```

need to be replaced by

```
global unit 100
array 100 0.0 0.0 0.0
replicate 7 1 5*0.0 40.96 1     ' --→ the apostrophe in the front is removed
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f71 end fill
end array
```

```
read bounds xyf=periodic end bounds
```

B.6.2 Table 35: Flooding and Moisture in the Mixed Mixed-Reflector and One-Reflector Drum Arrays (Input Files: flmixed and flmixed)

flmixed

```
=csas25    parm=(size=2000000)
reflector mixing
44groupndf5 infhommedium
' 120g sb drum reflector overbatch
plutoniumalp 1 0.0013 293 end
poly(h2o)    1 den=0.92 0.9987 293 end
uranium      2  1.0 293 end
beryllium    3  1.0 293 end
poly(h2o)    4  den=0.92 0.0001 293 end
graphite     5  den=2.10 1.0 293 end
carbonsteel 6  1.0 293 end
orconcrete  7  1.0 293 end
h2o          8  0.0001 293 end
poly(h2o)    9  den=0.92 1.0 293 end
' reflector mixing sb-65g
plutoniumalp 11 0.0011 293 end
poly(h2o)    11 den=0.92 0.9989 293 end
end comp
flmixed: mixed-refl and one-refl drums 0%VF PE Refl. 0% Moisture
read param npg=1000 gen=215 nsk=15 nub=yes fdn=yes end param
read geom
' reflector mixing sb-65g db65x 0.11%VF
unit 91
sphere  11 1  8.92545
sphere   3 1  9.11057
sphere   2 1 12.62021
sphere   5 1 24.39662
unit 1
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 2
cylinder 4 1 28.267 82.65 0.0
hole    91   -3.87037 0.0 58.25337
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 3
cylinder 4 1 28.267 82.65 0.0
hole    91    3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 4
cylinder 4 1 28.267 82.65 0.0
hole    91   -3.87037 0.0 24.39663
cylinder 9 1 28.495 82.878 -0.228
```

```
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
' reflector mixing sb-120g 0.13%VF
unit 191
sphere   1 1 10.35625
sphere   3 1 10.49476
sphere   2 1 13.40669
sphere   5 1 14.92534
unit 31
cylinder 4 1 28.267 82.65 0.0
hole   191   13.34165 0.0 67.72465
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 32
cylinder 4 1 28.267 82.65 0.0
hole   191  -13.34165 0.0 67.72465
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 33
cylinder 4 1 28.267 82.65 0.0
hole   191   13.34165 0.0 14.92535
cylinder 9 1 28.495 82.878 -0.230
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 34
cylinder 4 1 28.267 82.65 0.0
hole   191  -13.34165 0.0 14.92535
cylinder 9 1 28.495 82.878 -0.228
cylinder 6 1 28.630 83.005 -0.355
cuboid   8 1 4p28.630 83.005 -0.355
unit 71
array 71 0.0 0.0 0.0
unit 74
array 74 0.0 0.0 0.0
unit 84
array 84 0.0 0.0 0.0
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=74 nux=2 nuy=1 nuz=2 fill 31 32 33 34 end fill
ara=84 nux=1 nuy=2 nuz=2 fill 71 2r74 71 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f84 end fill
end array
read bounds all=periodic end bounds
end data
end
```

To generate decks for PE reflector with different volume fractions, the Material 9 card, '`h2o 8  0.0001 293 end`', is to be modified accordingly.

flmixed6 To generate decks from **flmixed** for this case, where the array is infinite in the X and Y directions and is 6-high in the Z direction with 16"(40.64 cm) concrete floor reflection. The following cards

```
global unit 100
array 100 0.0 0.0 0.0
'replicate 7 1 5*0.0 40.96 1
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=74 nux=2 nuy=1 nuz=2 fill 31 32 33 34 end fill
ara=84 nux=1 nuy=2 nuz=2 fill 71 2r74 71 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f84 end fill
end array
read bounds all=periodic end bounds
```

need to be replaced by

```
global unit 100
array 100 0.0 0.0 0.0
replicate 7 1 5*0.0 40.96 1     ' --> the apostrophe in the front is removed
end geom
read array
ara=71 nux=2 nuy=1 nuz=2 fill  1  2  3  4 end fill
ara=74 nux=2 nuy=1 nuz=2 fill 31 32 33 34 end fill
ara=84 nux=1 nuy=2 nuz=2 fill 71 2r74 71 end fill
ara=100 nux=1 nuy=3 nuz=3 fill f84 end fill
end array
read bounds xyf=periodic end bounds
```

Appendix C

50-Gram Reflector Waiver for HWM Applications on 5-, 30-, and 55-Gallon Waste Drums

1.0 INTRODUCTION

1.1 Objective

The objective of this analysis is to develop and establish the technical basis on the criticality safety controls for the 50-gram reflector waivers for waste containers at Hazardous Waste Management (HWM) facilities.

1.2 Background

For general uniform array storage at HWM, the containers need to be of 5-, 30-, or 55-gallon drum equivalents. In addition to be in compliance with the fissile mass limits, qualified HWM waste containers are also required to meet the reflector mass limits. The currently prevailing reflectors controls for HWM waste containers are:

9.0 300 grams of beryllium, or
10.0 100 kilograms of natural and/or depleted uranium (Nat-/Dep-U), or
11.0 8 kilograms of carbon and/or graphite.

The reflector controls depict that in any qualified HWM waste container, only one of the three types of reflectors is allowed. It can be up to 300 grams of beryllium, or up to 100 kilograms of Nat-/Dep-U, or up to 8 kilograms of carbon/graphite. Mixing of the three types of reflectors is not allowed for containers in the container controls.

However, it is always possible that trace amounts of the other reflectors, in addition to the major reflector, are also present in HWM waste streams. This work introduces a 50-gram waiver for the reflector to account for trace amounts of the other reflectors in presence of a major reflector. This will formalize the allowance of trace amounts of reflectors for HWM container operations, ease the burden of HWM personnel in the compliance with the reflector controls, and most of all, streamline further the HWM operations

2.0 FACILITY AND OPERATIONS DESCRIPTION

2.1 Facility Description

This CS control on the reflector waivers is applicable to all HWM operations. The applicable HWM facilities include Area 514, Area 612, Building 625, Building 693, Building 169 Consolidated Waste Accumulation Area (CWAA), Building 280, and the Decontamination Waste Treatment Facility (DWTF).

2.2 Operations Description

The reflector controls are an integrated part of the CS controls for the HWM waste containers. Each of the HWM containers needs to meet the drum control requirements, which include the reflector controls, before being placed in arrays.

If a container meets the drum control requirements, it may be placed in a uniform array.

If the containers does not meet the drum control requirements but does meet the mixed array control requirement, it may be placed in a mixed array.

If a container neither meet the drum control requirement nor meet the mixed array control requirement, it may still be allowable at HWM if the Criticality Safety Group (CSG) can determine that criticality safety is not jeopardized at HWM with the presence of such a container. It should be noted that without the CSG determination, the container should not be allowed in HWM facilities.

For each individual HWM waste container, one and only one of the three types of reflectors, Be, Nat-/Dep-U, or C/graphite is allowed. This reflector waiver is to waive trace amounts of reflectors before the reflector control rules are applied.

3.0 CRITICALITY SAFETY CONTROL

The reflector waiver is to be used with the current reflector control rules in CSM 920 Rev. 2, CSM 921 Rev.1 and CSM 941. It is to be integrated into the general site-wide CS controls (CSAM99-061). This reflector waiver shall be applied before the reflector controls. It allows that up to 50 grams of reflector materials be excluded from the reflector controls.

4.0 CRITICALITY SAFETY ASSESSMENT METHODOLOGY

4.1 Introduction

The amount of the reflector waiver is 50 grams total. It is very small compared to the presently allowable amount of 300 grams for beryllium, or 100 kilograms for Nat-U, or 8 kilograms for carbon or graphite. Therefore, it is demonstrated in this report that the application of the 50-gram reflector waiver to any single HWM container will not cause a system reactivity increase beyond than the uncertainty associated with the nuclear calculation method that may arise from uncertainty in nuclear data and so on. To exclude the statistical uncertainty associated with Monte Carlo calculations, the 1-D transport code, XSDRNPM of SCALE 4.4, is used. The calculations are performed using Godiva, a dual processor SUN Ultra 60 UNIX workstation. Detail verification and validation of XSDRNPM on the Godiva platform are documented in Section 4 of the main text and will not be repeated in this Appendix.

4.2 Uncertainty in XSDRNPM Results

In Section 4.4.2, XSDRNPM Validation, of the main text, it is listed that the average k_{eff} value, k_{av}, is 1.007166 with a standard deviation of 0.005948 for the XSDRNPM validation results. The biases as a function of the confidence levels are as list in Table 1.

Table 1. 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	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 D.1 shows that the biases range from 0.00094 to 0.01131 for confidence levels of 90% to 99.5%. It should be noted that the 99% confidence level is selected. This corresponds to a XSDRNPM bias of 0.00899, or about 0.009. Using a safety margin of 0.02, the subcritical limit is 0.971 for all XSDRNPM calculations performed in this analysis.

4.3 Material and Container Information

The materials used in this analysis and their properties are as listed in Table 8. It should be noted that the SCALE4.4 properties are used as the defaults for most of the materials in this table.

Table 2. Basic Material Property Information

Material	**Density (g/cc)**	**Remarks** (Unless Otherwise Specified, below listed are SCALE4.4 defaults)
Beryllium	1.85	
Carbon/Graphite	2.1	Typical density ranges from 2.0 to 2.25 g/cc (from NIOSH Pocket Guide to Chemical Hazards)
Plutonium	19.84	α-Phase Pu
Polyethylene (PE)	0.923	CH_2 polymer at theoretical density
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.

The 55-gram reflector waiver is applicable to waste containers of 5-gallon, 30-gallon, and 55-gallon capacities.

Table 3. Waste Container Fissile Mass Limit and Drum Dimension Information

Container Capacity (liters/gallon)	Fissile (Pu) Mass Limit (g)	Inner Height (cm/in)	Outer Height (cm/in)	Inner Diameter (cm/in)	Outer Diameter (cm/in)
21.89/5	40	34.13125/13.4375	34.16402/13.45	28.575/11.25	28.6078/11.263
123.2/30	80	73.025/28.75	73.134/28.793	46.355/18.25	46.464/18.293

207.5/55	120	82.65/32.54	83.36/32.819*	56.534/22.2275	57.26/22.543*

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

The fissile mass limits for 5-gallon, 30-gallon, and 55-gallon containers are 40, 80, and 120 grams of Pu equivalent (see CSAM 98-195 Rev.1 for definition), respectively.

5.0 ANALYSIS

5.1 Operation Boundaries for HWM Containers

The operation boundaries for HWM waste containers are discussed in this subsection. Typical HWM container operations involves the use of 5-gallon, 30-gallon, and 55-gallon waste containers. The three types of containers have dimensions as listed in Table 3. Equivalent containers may be used as well. The criticality safety controls imposed for containers of various sizes are as listed in Tables 4 and 5:

Table 4. The criticality safety controls and limits for fissile drums

Container Type	Fissile (Pu) Mass Limits	Reflector/Moderator Mass Limits
55-gallon	120 grams	No hydrogenous materials with hydrogen density greater than 0.133 g/cc are allowed. Hydrogenous material with hydrogen density no greater than 0.133 g/cc, such as water, polyethylene, and paraffin, are allowed with no limits in quantities. Only one of the three types of the reflectors is allowed up to the amount as specified below: (d) 300 grams of Be, or (e) 100 kilograms of Nat-U, or (f) 8 kilograms of C or graphite
30-gallon	80 grams	
5-gallon	40 grams	

The waste containers are subject to the array controls as well. The array controls vary with the sizes of the containers. The uniform array controls only allow containers of the same size or equivalent size to be placed in the same array.

Table 5. The criticality safety controls and limits for fissile drum arrays

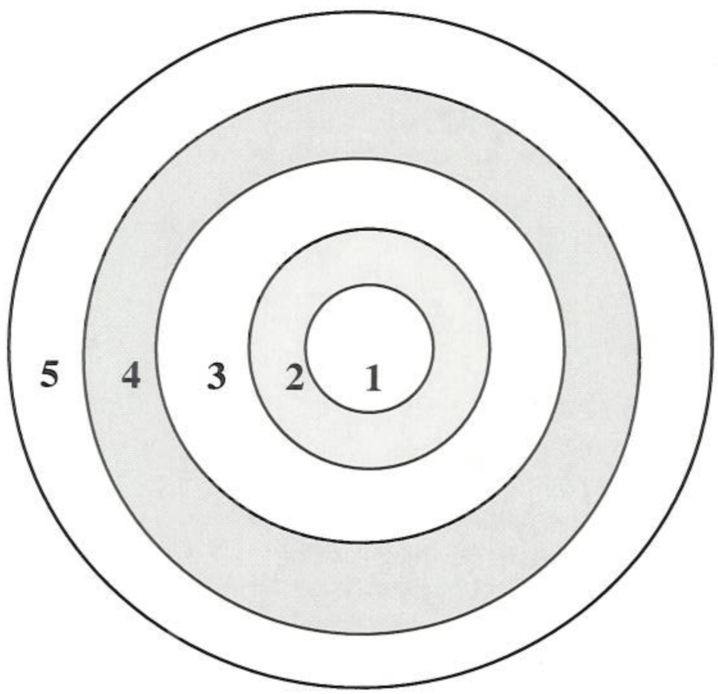
Fissile Array Type	Array Length*	Array Width*	Drum Stacking Limits
Uniform 55-gallon	No Limit	2-wide or up to 4-feet-high for the bottom of the second tier drums	2-high
Uniform 30-gallon	No Limit	2-wide	2-high
Uniform 5-gallon	No Limit	4-wide	4-high

* The array length, in reality, is limited by the size of the facilities; the array width is derived based on the size of the pallets above which waste drums are stacked.

5.2 Configuration Considered

The spherical geometry is chosen because of its low surface to volume ratio, which allows less neutron leakage and better neutron economy, as compared to any other geometry. The spherical core is completely surrounded by layers of reflector shells, beryllium, Nat-U, graphite/carbon, and polyethylene, in the order from inside out. The optimized configuration for core and reflectors is as shown in Figure 1. As a rule of thumb, the more effective reflectors are placed closer to the core. The effectiveness of the reflectors for the configuration of this problem is in the order of beryllium, Nat-U, carbon/graphite, and polyethylene.

Optimized Configuration



1 denotes the plutonium (α phase)-paraffin/polyethylene core
2 denotes the beryllium reflector shell
3 denotes the natural/depleted uranium reflector shell
4 denotes the carbon (graphite) reflector shell
5 denotes an outermost polyethylene reflector shell

Figure 1. The optimized core and reflector configuration used for this analysis. The arrangements for the stratified reflectors are shown in the order as modeled in all calculations.

5.3 Calculations

The fissile drum configurations for the three types of containers are schematically represented as in Figure 1. The 5-gallon drum configuration is represented by a 40-gram Pu PE moderated fissile core surrounded by the reflector layers. Likewise, the 30-gallon and 55-gallon drum configurations are represented by an 80-gram Pu PE moderated core and a 120-gram Pu PE moderated core, respectively, surrounded by the reflector layers. The purpose here is to demonstrate that for the single container configuration the application of the 50-gram reflector waiver will not cause an increase in reactivity of more than the uncertainty in the results, which is shown to be 0.005948.

5.3.1 5-Gallon Drums

With Waiver

Table 6. 5-Gallon Drum with Reflector Waivers; 40 grams Pu; 300-gram Be reflection; 50 grams of trace reflectors each for Be, Nat-U, and carbon/graphite; 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	U Mass (g)	U Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} Value
0.07%	40	8.82627	350	9.01544	50	9.01801	50	9.04125	0.517420
0.08%	40	8.44203	350	8.64820	50	8.65099	50	8.67623	0.526357
0.09%	40	8.11701	350	8.33936	50	8.34237	50	8.36950	0.532325
0.10%	40	7.83688	350	8.07472	50	8.07793	50	8.10686	0.536138
0.11%	40	7.59182	350	7.84453	50	7.84792	50	7.87856	0.538334
0.12%	40	7.37479	350	7.64182	50	7.64539	50	7.67767	0.539327
0.13%	40	7.18062	350	7.46148	50	7.46523	50	7.49908	0.539395
0.14%	40	7.00542	350	7.29966	50	7.30358	50	7.33893	0.538752
0.15%	40	6.84615	350	7.15337	50	7.15745	50	7.19424	0.537558
0.16%	40	6.70044	350	7.02027	50	7.02450	50	7.06269	0.535943
0.17%	40	6.56640	350	6.89848	50	6.90287	50	6.94241	0.533998

Table 7. 5-Gallon Drum with Reflector Waivers; 40 grams Pu; 100-kilogram Nat-U reflection; 50 grams of trace reflectors each for Be, Nat-U, and carbon/graphite; 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	U Mass (g)	U Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} Value
0.07%	40	8.82627	50	8.85379	100050	12.48876	50	12.50090	0.662586
0.08%	40	8.44203	50	8.47210	100050	12.30230	50	12.31481	0.665713

0.09%	40	8.11701	50	8.14952	100050	12.15327	50	12.16609	0.666480
0.10%	40	7.83688	50	7.87175	100050	12.03136	50	12.04444	0.665609
0.11%	40	7.59182	50	7.62895	100050	11.92975	50	11.94305	0.663574
0.12%	40	7.37479	50	7.41412	100050	11.84373	50	11.85722	0.660721
0.13%	40	7.18062	50	7.22210	100050	11.76995	50	11.78361	0.657295
0.14%	40	7.00542	50	7.04897	100050	11.70597	50	11.71978	0.653473
0.15%	40	6.84615	50	6.89173	100050	11.64995	50	11.66389	0.649376
0.16%	40	6.70044	50	6.74801	100050	11.60048	50	11.61454	0.645107
0.17%	40	6.56640	50	6.61590	100050	11.55648	50	11.57065	0.640729

Table 8. 5-Gallon Drum with Reflector Waivers; 40 grams Pu; 8000-gram carbon/graphite reflection; 50 grams of trace reflectors each for Be, Nat-U, and carbon/graphite; 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	U Mass (g)	U Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} Value
0.07%	40	8.82627	50	8.85379	50	8.85646	8050	11.71994	0.534863
0.08%	40	8.44203	50	8.47210	50	8.47501	8050	11.50753	0.543878
0.09%	40	8.11701	50	8.14952	50	8.15266	8050	11.33674	0.549575
0.10%	40	7.83688	50	7.87175	50	7.87512	8050	11.19630	0.552855
0.11%	40	7.59182	50	7.62895	50	7.63254	8050	11.07872	0.554313
0.12%	40	7.37479	50	7.41412	50	7.41792	8050	10.97879	0.554412
0.13%	40	7.18062	50	7.22210	50	7.22610	8050	10.89280	0.553468
0.14%	40	7.00542	50	7.04897	50	7.05317	8050	10.81799	0.551725
0.15%	40	6.84615	50	6.89173	50	6.89613	8050	10.75231	0.549366
0.16%	40	6.70044	50	6.74801	50	6.75259	8050	10.69417	0.546534
0.17%	40	6.56640	50	6.61590	50	6.62067	8050	10.64235	0.543339

Without Waiver

Table 9. 5-Gallon Drum with No Reflector Waivers; 40 grams Pu; 300-gram Be reflection and then 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	k_{eff} Value Without Waiver	k_{eff} Value With Waiver	k_{eff} Value Difference
0.07%	40	8.82627	300	8.98891	0.516317	0.517420	0.001103
0.08%	40	8.44203	300	8.61935	0.525226	0.526357	0.001131
0.09%	40	8.11701	300	8.30832	0.531176	0.532325	0.001149
0.10%	40	7.83688	300	8.04160	0.534984	0.536138	0.001154

0.11%	40	7.59182	300	7.80942	0.537184	0.538334	0.001150
0.12%	40	7.37479	300	7.60481	0.538186	0.539327	0.001141
0.13%	40	7.18062	300	7.42265	0.538270	0.539395	0.001125
0.14%	40	7.00542	300	7.25907	0.537647	0.538752	0.001105
0.15%	40	6.84615	300	7.11109	0.536478	0.537558	0.001080
0.16%	40	6.70044	300	6.97635	0.534891	0.535943	0.001052
0.17%	40	6.56640	300	6.85299	0.532973	0.533998	0.001025

Table 10. 5-Gallon Drum with No Reflector Waivers; 40 grams Pu; 100-kilogram Nat-U reflection and 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	U Mass (g)	U Radius (cm)	k_{eff} Value Without Waiver	k_{eff} Value With Waiver	k_{eff} Value Difference
0.07%	40	8.82627	100000	12.47362	0.662492	0.662586	0.000094
0.08%	40	8.44203	100000	12.28669	0.665576	0.665713	0.000137
0.09%	40	8.11701	100000	12.13728	0.666299	0.666480	0.000181
0.10%	40	7.83688	100000	12.01504	0.665379	0.665609	0.000230
0.11%	40	7.59182	100000	11.91314	0.663307	0.663574	0.000267
0.12%	40	7.37479	100000	11.82688	0.660414	0.660721	0.000307
0.13%	40	7.18062	100000	11.75289	0.656948	0.657295	0.000347
0.14%	40	7.00542	100000	11.68872	0.653089	0.653473	0.000384
0.15%	40	6.84615	100000	11.63254	0.648955	0.649376	0.000421
0.16%	40	6.70044	100000	11.58292	0.644651	0.645107	0.000456
0.17%	40	6.56640	100000	11.53879	0.640239	0.640729	0.000490

Table 11. 5-Gallon Drum with No Reflector Waivers; 40 grams Pu; 8000-gram carbon/graphite reflection and 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} Value Without Waiver	k_{eff} Value With Waiver	k_{eff} Value Difference
0.07%	40	8.82627	8000	11.68888	0.534061	0.534863	0.000802
0.08%	40	8.44203	8000	11.47532	0.543062	0.543878	0.000816
0.09%	40	8.11701	8000	11.30354	0.548745	0.549575	0.000830
0.10%	40	7.83688	8000	11.16226	0.552011	0.552855	0.000844
0.11%	40	7.59182	8000	11.04395	0.553453	0.554313	0.000860
0.12%	40	7.37479	8000	10.94338	0.553536	0.554412	0.000876
0.13%	40	7.18062	8000	10.85682	0.552574	0.553468	0.000894
0.14%	40	7.00542	8000	10.78151	0.550811	0.551725	0.000914
0.15%	40	6.84615	8000	10.71538	0.548431	0.549366	0.000935
0.16%	40	6.70044	8000	10.65684	0.545573	0.546534	0.000961

0.17%	40	6.56640	8000	10.60465	0.542358	0.543339	0.000981

Discussions on the 5-Gallon Drum Results

The results show that the k_{eff} value differences are the largest for the Be reflected cases. This is anticipated because 150 grams (50 grams for each type of reflectors) of reflectors total have been added. The relative increase in the reflector is 50% in the mass. On the other hand, the k_{eff} value differences are the least for the Nat-U reflected cases. This is because the relative increase in the reflector mass from the application of the reflector waivers is not very significant because the large amount of the Nat-U reflector involved (100 kilograms).

However, the limiting case is the one dealing with the Nat-U reflector cases because of the largest k_{eff} values. The reason for the Nat-U reflector case to have large keff values is very apparent. Out of the three type of reflectors, beryllium, Nat-U, and carbon/graphite, only Nat-U are allowed in significant amount (100 kilograms), which would yield a reflector shell thickness around the core on the order of the neutron mean free path. The beryllium reflector (300 grams) will only form a thin shell around the core that significant reflection would not occur. Carbon/graphite, on the other hand, will form a reflector shell (8 kilograms) comparable in thickness to that of the Nat-U reflector. However, the neutron mean free path in carbon/graphite is very large, which yield less neutron reflection compared to Nat-U. For the optimized case (Nat-U reflection) with a Pu volume fraction of 0.09%, the k_{eff} value difference is 0.000181, which is significantly smaller than the uncertainty of 0.005948 in the calculation method. It should be noted that this difference should be smaller if exactly 50 grams of reflectors are only waived. In this analysis, 50 grams of each type of reflectors are waived for a total waiver amount of 150 grams.

5.3.2 30-Gallon Drums

With Waiver

Table 12. 30-Gallon Drum with Reflector Waivers; 80 grams Pu; 300-gram Be reflection; 50 grams of trace reflectors each for Be, Nat-U, and carbon/graphite; 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	U Mass (g)	U Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} max80be
0.09%	80	10.22679	350	10.36876	50	10.37070	50	10.38828	0.667263
0.10%	80	9.87385	350	10.02592	50	10.02800	50	10.04681	0.674413
0.11%	80	9.56509	350	9.72689	50	9.72910	50	9.74908	0.679299
0.12%	80	9.29165	350	9.46286	50	9.46519	50	9.48629	0.682445
0.13%	80	9.04702	350	9.22734	50	9.22979	50	9.25198	0.684208
0.14%	80	8.82627	350	9.01544	50	9.01801	50	9.04125	0.684940
0.15%	80	8.62561	350	8.82339	50	8.82607	50	8.85033	0.684842
0.16%	80	8.44203	350	8.64820	50	8.65099	50	8.67623	0.684083

0.17%	80	8.27314	350	8.48750	50	8.49040	50	8.51660	0.682801
0.18%	80	8.11701	350	8.33936	50	8.34237	50	8.36950	0.681101
0.19%	80	7.97203	350	8.20221	50	8.20531	50	8.23336	0.679071
0.20%	80	7.83688	350	8.07472	50	8.07793	50	8.10686	0.676771

Table 13. 30-Gallon Drum with Reflector Waivers; 80 grams Pu; 100-kilogram Nat-U reflection; 50 grams of trace reflectors each for Be, Nat-U, and carbon/graphite; 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	U Mass (g)	U Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} max80u
0.09%	80	10.22679	50	10.24731	100050	13.25694	50	13.26771	0.766194
0.10%	80	9.87385	50	9.89587	100050	13.05089	50	13.06200	0.770497
0.11%	80	9.56509	50	9.58854	100050	12.87732	50	12.88874	0.772729
0.12%	80	9.29165	50	9.31650	100050	12.72903	50	12.74071	0.773406
0.13%	80	9.04702	50	9.07322	100050	12.60079	50	12.61272	0.772893
0.14%	80	8.82627	50	8.85379	100050	12.48876	50	12.50090	0.771471
0.15%	80	8.62561	50	8.65442	100050	12.39002	50	12.40235	0.769358
0.16%	80	8.44203	50	8.47210	100050	12.30230	50	12.31481	0.766702
0.17%	80	8.27314	50	8.30444	100050	12.22386	50	12.23653	0.763638
0.18%	80	8.11701	50	8.14952	100050	12.15327	50	12.16609	0.760253
0.19%	80	7.97203	50	8.00573	100050	12.08942	50	12.10237	0.756634
0.20%	80	7.83688	50	7.87175	100050	12.03136	50	12.04444	0.752835

Table 14. 30-Gallon Drum with Reflector Waivers; 80 grams Pu; 8000-gram carbon/graphite reflection; 50 grams of trace reflectors each for Be, Nat-U, and carbon/graphite; 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	U Mass (g)	U Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} max80c
0.09%	80	10.22679	50	10.24731	50	10.24930	8050	12.58199	0.689732
0.10%	80	9.87385	50	9.89587	50	9.89800	8050	12.35262	0.697921
0.11%	80	9.56509	50	9.58854	50	9.59081	8050	12.15841	0.703586
0.12%	80	9.29165	50	9.31650	50	9.31890	8050	11.99169	0.707278
0.13%	80	9.04702	50	9.07322	50	9.07576	8050	11.84691	0.709418
0.14%	80	8.82627	50	8.85379	50	8.85646	8050	11.71994	0.710350
0.15%	80	8.62561	50	8.65442	50	8.65720	8050	11.60762	0.710311

0.16%	80	8.44203	50	8.47210	50	8.47501	8050	11.50753	0.709488
0.17%	80	8.27314	50	8.30444	50	8.30747	8050	11.41775	0.808036
0.18%	80	8.11701	50	8.14952	50	8.15266	8050	11.33674	0.706076
0.19%	80	7.97203	50	8.00573	50	8.00898	8050	11.26326	0.703706
0.20%	80	7.83688	50	7.87175	50	7.87512	8050	11.19630	0.700999

Without Waiver

Table 15. 30-Gallon Drum with No Reflector Waivers; 80 grams Pu; 300-gram Be reflection and 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	k_{eff} Value Without Waiver	k_{eff} Value With Waiver	k_{eff} Value Difference
0.09%	80	10.22679	300	10.34871	0.666484	0.667263	0.000779
0.10%	80	9.87385	300	10.00448	0.673598	0.674413	0.000815
0.11%	80	9.56509	300	9.70411	0.678455	0.679299	0.000844
0.12%	80	9.29165	300	9.43878	0.681578	0.682445	0.000867
0.13%	80	9.04702	300	9.20201	0.683320	0.684208	0.000888
0.14%	80	8.82627	300	8.98891	0.684035	0.684940	0.000905
0.15%	80	8.62561	300	8.79568	0.683924	0.684842	0.000918
0.16%	80	8.44203	300	8.61935	0.683154	0.684083	0.000929
0.17%	80	8.27314	300	8.45754	0.681863	0.682801	0.000938
0.18%	80	8.11701	300	8.30832	0.680157	0.681101	0.000944
0.19%	80	7.97203	300	8.17012	0.678122	0.679071	0.000949
0.20%	80	7.83688	350	8.04160	0.675821	0.676771	0.000950

Table 16. 30-Gallon Drum with No Reflector Waivers; 80 grams Pu; 100-kilogram Nat-U reflection and 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	U Mass (g)	U Radius (cm)	k_{eff} Value Without Waiver	k_{eff} Value With Waiver	k_{eff} Value Difference
0.09%	80	10.22679	100000	13.24350	0.765930	0.766194	0.000264
0.10%	80	9.87385	100000	13.03702	0.770194	0.770497	0.000303
0.11%	80	9.56509	100000	12.86308	0.772387	0.772729	0.000342
0.12%	80	9.29165	100000	12.71445	0.773027	0.773406	0.000379
0.13%	80	9.04702	100000	12.58592	0.772479	0.772893	0.000414
0.14%	80	8.82627	100000	12.47362	0.771022	0.771471	0.000449
0.15%	80	8.62561	100000	12.37463	0.768876	0.769358	0.000482
0.16%	80	8.44203	100000	12.28669	0.766187	0.766702	0.000515

0.17%	80	8.27314	100000	12.20805	0.763092	0.763638	0.000546
0.18%	80	8.11701	100000	12.13728	0.759677	0.760253	0.000576
0.19%	80	7.97203	100000	12.07325	0.756029	0.756634	0.000605
0.20%	80	7.83688	100000	12.01504	0.752197	0.752835	0.000638

Table 17. 30-Gallon Drum with No Reflector Waivers; 80 grams Pu; 8000-gram carbon/graphite reflection and 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} Value Without Waiver	k_{eff} Value With Waiver	k_{eff} Value Difference
0.09%	80	10.22679	8000	12.55506	0.689274	0.689732	0.000458
0.10%	80	9.87385	8000	12.32468	0.697463	0.697921	0.000458
0.11%	80	9.56509	8000	12.12956	0.703129	0.703586	0.000457
0.12%	80	9.29165	8000	11.96203	0.706822	0.707278	0.000456
0.13%	80	9.04702	8000	11.81652	0.708963	0.709418	0.000455
0.14%	80	8.82627	8000	11.68888	0.709896	0.710350	0.000454
0.15%	80	8.62561	8000	11.57596	0.709856	0.710311	0.000455
0.16%	80	8.44203	8000	11.47532	0.709032	0.709488	0.000456
0.17%	80	8.27314	8000	11.38502	0.707579	0.708036	0.000457
0.18%	80	8.11701	8000	11.30354	0.705616	0.706076	0.000460
0.19%	80	7.97203	8000	11.22962	0.703242	0.703706	0.000464
0.20%	80	7.83688	8000	11.16226	0.700531	0.700999	0.000468

Discussions on the 30-Gallon Drum Results

The results for the 30-gallon drum also show that the k_{eff} value differences are the largest for the Be reflected cases. This is anticipated because 150 grams (50 grams for each type of reflectors) of reflectors total have been added. The relative increase in the reflector is 50% in the mass. On the other hand, the k_{eff} value differences are less for the Nat-U and carbon/graphite reflected cases. This is because the relative increase in the reflector mass from the application of the reflector waivers is not very significant because the large amount of the Nat-U and carbon/graphite reflector involved (100 kilograms and 8 kilograms, respectively).

However, the limiting case is the one dealing with the Nat-U reflector because it has the largest k_{eff} values. For the optimized case (Nat-U reflection) with a Pu volume fraction of 0.12%, the k_{eff} value difference is 0.000379, which is significantly smaller than the uncertainty of 0.005948 in the calculation method. It should be noted that this difference should be smaller if exactly 50 grams of reflectors are only waived. In this analysis, 50 grams of each type of reflectors are waived for a total waiver amount of 150 grams.

5.3.3 55-Gallon Drums

With Waiver

Table 18. 55-Gallon Drum with Reflector Waivers; 120 grams Pu; 300-gram Be reflection; 50 grams of trace reflectors each for Be, Nat-U, and carbon/graphite; 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	U Mass (g)	U Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} Value
0.10%	120	11.30274	350	11.41938	50	11.42098	50	11.43549	0.755739
0.11%	120	10.94930	350	11.07346	50	11.07516	50	11.09059	0.762609
0.12%	120	10.63629	350	10.76773	50	10.76953	50	10.78585	0.767420
0.13%	120	10.35625	350	10.49476	50	10.49666	50	10.51383	0.770571
0.14%	120	10.10356	350	10.24894	50	10.25093	50	10.26893	0.772434
0.15%	120	9.87385	350	10.02592	50	10.02800	50	10.04681	0.773259
0.16%	120	9.66371	350	9.82230	50	9.82447	50	9.84406	0.773288
0.17%	120	9.47038	350	9.63535	50	9.63760	50	9.65796	0.772660
0.18%	120	9.29165	350	9.46286	50	9.46519	50	9.48629	0.771499
0.19%	120	9.12569	350	9.30301	50	9.30542	50	9.32725	0.769911
0.20%	120	8.97099	350	9.15429	50	9.15678	50	9.17932	0.768577

Table 19. 55-Gallon Drum with Reflector Waivers; 120 grams Pu; 100-kilogram Nat-U reflection; 50 grams of trace reflectors each for Be, Nat-U, and carbon/graphite; 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	U Mass (g)	U Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} Value
0.10%	120	11.30274	50	11.31955	100050	13.93201	50	13.94176	0.833339
0.11%	120	10.94930	50	10.96721	100050	13.70283	50	13.71291	0.838489
0.12%	120	10.63629	50	10.65526	100050	13.50582	50	13.51620	0.841658
0.13%	120	10.35625	50	10.37627	100050	13.33451	50	13.34516	0.843329
0.14%	120	10.10356	50	10.12459	100050	13.18409	50	13.19498	0.843714
0.15%	120	9.87385	50	9.89587	100050	13.05089	50	13.06200	0.843190
0.16%	120	9.66371	50	9.68668	100050	12.93206	50	12.94338	0.841922
0.17%	120	9.47038	50	9.49430	100050	12.82538	50	12.83688	0.840053
0.18%	120	9.29165	50	9.31650	100050	12.72903	50	12.74071	0.837714
0.19%	120	9.12569	50	9.15145	100050	12.64157	50	12.65342	0.835006
0.20%	120	8.97099	50	8.99764	100050	12.56181	50	12.57381	0.831992

Table 20. 55-Gallon Drum with Reflector Waivers; 120 grams Pu; 8000-gram carbon/graphite reflection; 50 grams of trace reflectors each for Be, Nat-U, and carbon/graphite; 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	U Mass (g)	U Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} Value
0.10%	120	11.30274	50	11.31955	50	11.32118	8050	13.32545	0.778662
0.11%	120	10.94930	50	10.96721	50	10.96894	8050	13.07433	0.786914
0.12%	120	10.63629	50	10.65526	50	10.65710	8050	12.85744	0.792867
0.13%	120	10.35625	50	10.37627	50	10.37821	8050	12.66802	0.797018
0.14%	120	10.10356	50	10.12459	50	10.12662	8050	12.50104	0.799682
0.15%	120	9.87385	50	9.89587	50	9.89800	8050	12.35262	0.801206
0.16%	120	9.66371	50	9.68668	50	9.68891	8050	12.21976	0.801779
0.17%	120	9.47038	50	9.49430	50	9.49662	8050	12.10009	0.801579
0.18%	120	9.29165	50	9.31650	50	9.31890	8050	11.99169	0.800744
0.19%	120	9.12569	50	9.15145	50	9.15394	8050	11.89301	0.799386
0.20%	120	8.97099	50	8.99764	50	9.00022	8050	11.80278	0.797576

Without Waiver

Table 21. 55-Gallon Drum with No Reflector Waivers; 120 grams Pu; 300-gram Be reflection and 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	Be Mass (g)	Be Radius (cm)	k_{eff} Value Without Waiver	k_{eff} Value With Waiver	k_{eff} Value Difference
0.10%	120	11.30274	300	11.40286	0.755121	0.755739	0.000618
0.11%	120	10.94930	300	11.05589	0.761957	0.762609	0.000652
0.12%	120	10.63629	300	10.74915	0.766739	0.767420	0.000681
0.13%	120	10.35625	300	10.47520	0.769863	0.770571	0.000708
0.14%	120	10.10356	300	10.22842	0.771700	0.772434	0.000734
0.15%	120	9.87385	300	10.00448	0.772501	0.773259	0.000758
0.16%	120	9.66371	300	9.79996	0.772510	0.773288	0.000778
0.17%	120	9.47038	300	9.61213	0.771864	0.772660	0.000796
0.18%	120	9.29165	300	9.43878	0.770687	0.771499	0.000812
0.19%	120	9.12569	300	9.27809	0.769085	0.769911	0.000826
0.20%	120	8.97099	300	9.12855	0.767595	0.768577	0.000982

Table 22. 55-Gallon Drum with No Reflector Waivers; 120 grams Pu; 100-kilogram Nat-U reflection and 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu	Core	U Mass	U Radius	k_{eff} Value	k_{eff} Value	k_{eff} Value

	Mass (g)	Radius (cm)	(g)	(cm)	Without Waiver	With Waiver	Difference
0.10%	120	11.30274	100000	13.91984	0.833035	0.833339	0.000304
0.11%	120	10.94930	100000	13.69025	0.838149	0.838489	0.000340
0.12%	120	10.63629	100000	13.49287	0.841285	0.841658	0.000373
0.13%	120	10.35625	100000	13.32122	0.842879	0.843285	0.000406
0.14%	120	10.10356	100000	13.17050	0.843276	0.843714	0.000438
0.15%	120	9.87385	100000	13.03702	0.842722	0.843190	0.000468
0.16%	120	9.66371	100000	12.91794	0.841424	0.841922	0.000498
0.17%	120	9.47038	100000	12.81101	0.839526	0.840053	0.000527
0.18%	120	9.29165	100000	12.71445	0.837160	0.837714	0.000554
0.19%	120	9.12569	100000	12.62679	0.834424	0.835006	0.000582
0.20%	120	8.97099	100000	12.54684	0.831384	0.831992	0.000608

Table 23. 55-Gallon Drum with No Reflector Waivers; 120 grams Pu; 8000-gram carbon/graphite reflection and 1-foot polyethylene (PE) reflection outside.

Pu VF	Pu Mass (g)	Core Radius (cm)	C Mass (g)	C Radius (cm)	k_{eff} Value Without Waiver	k_{eff} Value With Waiver	k_{eff} Value Difference
0.10%	120	11.30274	8000	13.30145	0.778323	0.778662	0.000339
0.11%	120	10.94930	8000	13.04939	0.786575	0.786914	0.000339
0.12%	120	10.63629	8000	12.83165	0.792531	0.792867	0.000336
0.13%	120	10.35625	8000	12.64146	0.796684	0.797018	0.000334
0.14%	120	10.10356	8000	12.47376	0.799352	0.799682	0.000330
0.15%	120	9.87385	8000	12.32468	0.800879	0.801206	0.000327
0.16%	120	9.66371	8000	12.19121	0.801457	0.801779	0.000322
0.17%	120	9.47038	8000	12.07096	0.801259	0.801579	0.000320
0.18%	120	9.29165	8000	11.96203	0.800427	0.800744	0.000317
0.19%	120	9.12569	8000	11.86286	0.799072	0.799386	0.000314
0.20%	120	8.97099	8000	11.77216	0.797284	0.797596	0.000312

Discussions on the 55-Gallon Drum Results

The results for the 55-gallon drum still show that the k_{eff} value differences are the largest for the Be reflected cases. This is anticipated because 150 grams (50 grams for each type of reflectors) of reflectors total have been added. The relative increase in the reflector is 50% in the mass. On the other hand, the k_{eff} value differences are less for the Nat-U and carbon/graphite reflected cases. This is because the relative increase in the reflector mass from the application of the reflector waivers is not very significant because the large amount of the Nat-U and carbon/graphite reflector involved (100 kilograms and 8 kilograms, respectively).

However, the limiting case is the one dealing with the Nat-U reflector because of the larger k_{eff} values. For the optimized case (Nat-U reflection) with a Pu volume fraction of 0.14%, the k_{eff} value difference is 0.000438, which is significantly smaller than the uncertainty of 0.005948 in the calculation method. It should be noted that this difference should be smaller if exactly 50 grams of reflectors are only waived. In this analysis, 50 grams of each type of reflectors are waived for a total waiver amount of 150 grams.

6.0 Conclusions

For realistic HWM array applications, the 50-gram reflector waiver will be randomly applied. This is because in realistic applications in arrays some of the containers may not need the use of the reflector waiver because they are compliant to the single reflector requirements. Only few containers would need the use of the reflector waivers, when trace amounts of the non-major reflectors do exist. Furthermore, most of the reflectors will not amount to the full quantities permitted by the reflector mass limits. Because of this anticipated fluctuation in the distribution of the amount of reflector in these waste containers in arrays, it can be concluded that the application of 50-gram waivers in some of the drums will not cause significant increases in system reactivity beyond the uncertainty of 0.005948, which is inherently included in the results of the XSDRNPM calculations. With a safety margin of 0.02, the effect of the 50-gram reflector waiver should be adequately addressed with enough safety margins.

It should also be noted that in the single drum simulations, 150 grams of reflectors have been assumed, e.g., 50 grams for each of the three types of the reflectors, beryllium, Nat-U, and carbon/graphite. There is a factor of 3 in safety margins compared to the actual reflector waiver of 50 grams total. Therefore, the actual increase in reactivity from the use of the reflector waiver would be smaller and be upper bounded by the calculation results.

Based on the above argument, it can be derived that the 50-gram reflector waiver would be criticality safe for HWM waste container operations.

7.0 Input Files

The input files used for this analysis by the drum types and the reflector types are as listed in Table 24.

Table 24. List of Input Files

Container Type	Reflector Type	Input File Name with Reflector Waiver	Input File Name without Reflector Waiver
5-gallon	Beryllium	max40be	max40beo
	Nat-U	max40u	max40uo
	Carbon/Graphite	max40c	max40co
30-gallon	Beryllium	max80be	max80beo
	Nat-U	max80u	max80uo
	Carbon/Graphite	max80c	max80co

55-gallon	Beryllium	max120be	max120bo
	Nat-U	max120u	max120uo
	Carbon/Graphite	max120c	max120co

7.1 Sample Input Files

The sample input decks included here are for 55-gallon drums with 120 grams of Pu and 300 grams of Be reflection. When reflector waivers are applied, 50 grams of each of the three types of reflectors, Be, Nat-U, and carbon/graphite, are added.

Input Decks with Reflector Waivers

```
File Name: max120be
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.10%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0010 293 end
poly(h2o)    1 0.9990 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 11.30274 2 11.41938 3 11.42098 4 11.43549 5 41.91549 end zone
end data
end
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.11%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0011 293 end
poly(h2o)    1 0.9989 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.94930 2 11.07346 3 11.07516 4 11.09059 5 41.57059 end zone
end data
end
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.12%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0012 293 end
poly(h2o)    1 0.9988 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.63629 2 10.76773 3 10.76953 4 10.78585 5 41.26585 end zone
```

```
end data
end
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.13%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0013 293 end
poly(h2o)    1 0.9987 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.35625 2 10.49476 3 10.49666 4 10.51383 5 40.99383 end zone
end data
end
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.14%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0014 293 end
poly(h2o)    1 0.9986 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.10356 2 10.24894 3 10.25093 4 10.26893 5 40.74893 end zone
end data
end
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.15%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0015 293 end
poly(h2o)    1 0.9985 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.87385 2 10.02592 3 10.02800 4 10.04681 5 40.52681 end zone
end data
end
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.16%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0016 293 end
poly(h2o)    1 0.9984 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.66371 2 9.82230 3 9.82447 4 9.84406 5 40.32406 end zone
end data
end
```

```
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.17%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0017 293 end
poly(h2o)    1 0.9983 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.47038 2 9.63535 3 9.63760 4 9.65796 5 40.13796 end zone
end data
end
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.18%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0018 293 end
poly(h2o)    1 0.9982 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.29165 2 9.46286 3 9.46519 4 9.48629 5 39.96629 end zone
end data
end
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.19%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0019 293 end
poly(h2o)    1 0.9981 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.12569 2 9.30301 3 9.30542 4 9.32725 5 39.80725 end zone
end data
end
=csas1x    parm=(size=2000000)
max120be: 120g Pu 0.20%VF 350g be 50g Nat-U 50g C be-U-c
44groupndf5 multiregion
plutoniumalp 1 0.0020 293 end
poly(h2o)    1 0.9980 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 8.97099 2 9.15429 3 9.15678 4 9.17932 5 30.65932 end zone
end data
end
```

Input Decks without Reflector Waivers

```
File Name: max120bo
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.10%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0010 293 end
poly(h2o)    1 0.9990 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 11.30274 2 11.40286 5 41.88286 end zone
end data
end
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.11%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0011 293 end
poly(h2o)    1 0.9989 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.94930 2 11.05589 5 41.53589 end zone
end data
end
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.12%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0012 293 end
poly(h2o)    1 0.9988 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.63629 2 10.74915 5 41.22915 end zone
end data
end
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.13%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0013 293 end
poly(h2o)    1 0.9987 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.35625 2 10.47520 5 40.95520 end zone
```

```
end data
end
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.14%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0014 293 end
poly(h2o)    1 0.9986 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 10.10356 2 10.22842 5 40.70842 end zone
end data
end
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.15%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0015 293 end
poly(h2o)    1 0.9985 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.87385 2 10.00448 5 40.48448 end zone
end data
end
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.16%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0016 293 end
poly(h2o)    1 0.9984 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.66371 2 9.79996 5 40.27996 end zone
end data
end
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.17%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0017 293 end
poly(h2o)    1 0.9983 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.47038 2 9.61213 5 40.09213 end zone
end data
end
```

```
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.18%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0018 293 end
poly(h2o)    1 0.9982 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.29165 2 9.43878 5 39.91878 end zone
end data
end
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.19%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0019 293 end
poly(h2o)    1 0.9981 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 9.12569 2 9.27809 5 39.75809 end zone
end data
end
=csas1x    parm=(size=2000000)
max120bo: 120g Pu 0.20%VF 300g be
44groupndf5 multiregion
plutoniumalp 1 0.0020 293 end
poly(h2o)    1 0.9980 293 end
beryllium    2 1.0 293 end
uranium      3 1.0 293 end
graphite     4 den=2.10 1.0 293 end
poly(h2o)    5 1.0 293 end
end comp
spherical reflected reflected 0.0 end
1 8.97099 2 9.12855 5 30.60855 end zone
end data
end
```