

**Summary of Nuclear Criticality Safety  
Evaluation for Shielded Containers at the  
Waste Isolation Pilot Plant**

This document revision was prepared by Washington TRU Solutions under contract and subject to the warranty and other obligations of that contract.

Release to and Use by Third Parties. As it pertains to releases of this document to third parties, and the use of or reference to this document by such third parties in whole or in part, neither Washington TRU Solutions, nor its officers, directors, employees, agents, consultants or personal services contractors (i) make any warranty, expressed or implied, (ii) assume any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product or process disclosed herein or (iii) represent that use of the same will not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trademark, name, manufacture or otherwise, does not necessarily constitute or imply endorsement, recommendation, or favoring of the same by either Washington TRU Solutions, or its officers, directors, employees, agents, consultants or personal services contractors.

## **Summary of Nuclear Criticality Safety Evaluation for Shielded Containers at the Waste Isolation Pilot Plant**

Date Issued—August 2009

Prepared for the  
U.S. Department of Energy  
Waste Isolation Pilot Plant

Washington TRU Solutions  
managing the  
Waste Isolation Pilot Plant  
Carlsbad, NM  
under contract DE-AC29-01AL66444  
for the  
U.S. DEPARTMENT OF ENERGY

This page intentionally left blank.

Compiled by  
Senior NCS Engineer

Sandra Larson 8/21/09  
S. L. Larson Date

Approved by  
WIPP Nuclear Safety

Janos McCormick 8-24-09  
J. McCormick Date

This page intentionally left blank.

## Executive Summary

This report summarizes the nuclear criticality safety evaluation of remote-handled (RH) transuranic waste in shielded containers at the Waste Isolation Pilot Plant (WIPP) facility. The shielding in the container reduces the radiation dose rate such that the shielded container can be contact-handled (CH). The report is compiled from the nuclear criticality safety evaluation (NCSE) for all CH waste containers. (Larson 2009). The NCSE was written in compliance with the direction found in DOE Standard 3007, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities* (DOE 2007). It addresses the disposal configuration during active waste emplacement up to when the filled panel is removed from active ventilation with a panel closure or substantial and isolation barrier.

Transuranic waste is currently shipped to the WIPP from the U.S. Department of Energy generator sites. The CH waste containers currently approved for disposal at WIPP include 55-gallon drums, 85-gallon drums, 100-gallon drums; standard waste boxes (SWB); ten drum overpacks; and pipe configurations overpacked in 55-gallon drums. This summary focuses on a shielded container, which is a lead-lined 55-gallon drum, emplaced in the CH disposal array in three-packs. The shielded container is proposed as an alternative to disposal of remote-handled waste in canisters in the walls of the disposal rooms. TRU waste that emits significant radiation (mostly gammas) can be packaged within the lead shielded containers and the surface dose rate is reduced to CH levels for safe handling as a CH container. The shielded container will be shipped to WIPP in the Half-package Transporter (HalfPACT) transportation packages.

The criticality safety analysis considers the normal WIPP waste handling, storage, and disposal configurations of these waste containers based on bounding analysis which uses several conservative assumptions. A seven-pack array of shielded containers is analyzed in a more densely packed arrangement than the three-pack configuration for the shielded containers anticipated for use. Using the Monte Carlo computational method, two bounding geometric configurations are evaluated, an infinite array and a two-container model. An additional geometry modeled is a stack of two 55-gallon drum seven-pack assemblies surrounded by shielded containers on the sides and on the third tier. This analysis showed that intermixing of shielded and non-shielded containers does not pose a criticality safety concern.

The analysis uses waste container storage and disposal configurations that would result in worst case criticality scenarios. At this time, operational procedures for the storage or disposal of shielded containers will be consistent with Figure 2.4. Plans are to follow “typical” illustrations shown in this criticality analysis report.

The primary criticality control is the fissile mass and special reflector material mass limits established and presented in Section 8.0. Once the shielded container is approved for use, these mass limits will be incorporated into the *Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant* (WIPP WAC) and verified at generator sites through a waste certification process.

This report also summarizes the evaluation for credible upset scenarios during waste handling, disposal, and storage of the shielded container at WIPP. The evaluation concludes that normal and credible abnormal conditions are subcritical and no credible criticality accident scenarios exist for the shielded container during storage, handling, and disposal processes at the WIPP.

## Table of Contents

1.0	INTRODUCTION .....	1
2.0	DESCRIPTIONS .....	1
2.1	FACILITY AND PROCESS DESCRIPTION.....	1
2.2	DESCRIPTION OF SHIELDED CONTAINERS.....	7
3.0	REQUIREMENTS DOCUMENTATION .....	8
4.0	METHODOLOGY .....	8
4.1	EVALUATION METHOD.....	8
4.2	MONTE CARLO COMPUTATIONAL METHOD.....	9
5.0	PROCESS ANALYSIS .....	10
5.1	GEOMETRY.....	10
5.1.1	Waste Containing Less Than or Equal to 1 Weight Percent Special Reflectors .....	11
5.1.2	Waste Containing Greater Than 1 Weight Percent Special Reflectors .....	11
5.1.3	Machine Compacted Waste .....	12
5.1.4	Infinite Array Model Details.....	12
5.1.5	Two-container Model Details .....	14
5.2	MATERIAL COMPOSITIONS.....	14
5.2.1	Fissile Waste Mixture .....	15
5.2.2	Reflector Material in Waste Container .....	16
5.2.3	Container Materials of Construction.....	16
5.2.4	Reflector Material Outside the Waste Container .....	17
5.3	CONTAINER ARRAY RESULTS.....	18
5.3.1	Baseline Disposal Array Calculations .....	18
5.4	TWO-CONTAINER MODEL RESULTS.....	20
6.0	PARAMETERS .....	21
6.1	MASS .....	21
6.2	GEOMETRY.....	21
6.3	MODERATION .....	22
6.4	INTERACTION .....	22
6.5	NEUTRON ABSORPTION.....	22

6.6	REFLECTION.....	23
6.6.1	Internal Container Reflection.....	23
6.6.2	External Container Reflection.....	23
6.7	VOLUME.....	23
6.8	ENRICHMENT.....	23
6.9	CONCENTRATION.....	24
7.0	CONTINGENCY EVALUATION.....	24
7.1	LOSS OF CONFINEMENT OF FISSILE MATERIAL .....	24
7.2	EXCEEDING DISPOSAL ARRAY VERTICAL STACKING LIMIT .....	24
7.2.1	Exceeding Array Vertical Stacking Limit in the Underground Repository.....	24
7.2.2	Exceeding Interim Drum Storage Array Stacking Limit .....	26
7.3	UNDERGROUND ROOF FALL .....	26
7.4	EXCEEDING MASS LIMITS.....	27
7.4.1	Exceeding the Fissile Mass Limit for a Container.....	27
7.4.2	Exceeding the Beryllium Mass Limit for a Container .....	28
7.5	SPRINKLER ACTIVATION IN THE WASTE HANDLING BUILDING .....	28
7.6	EXCESS LIQUID IN WASTE CONTAINERS.....	30
7.7	FORKLIFT ACCIDENT CRUSHES CONTAINERS .....	30
7.8	CONTINGENCY ANALYSIS CONCLUSION.....	33
8.0	DESIGN FEATURES AND ADMINISTRATIVELY CONTROLLED LIMITS AND REQUIREMENTS .....	34
8.1	DESIGN FEATURES .....	34
8.2	ADMINISTRATIVE LIMITS AND REQUIREMENTS.....	34
9.0	CONCLUSIONS.....	35
10.0	REFERENCES .....	36

## List of Tables

Table 2-1, HalfPACT Limits for Shielded Containers .....	2
Table 2-2, Modeled Shielded Container vs. 55-gallon Drum Dimensions.....	7
Table 5-1, Fissile Mixture Parameters for Fully Compacted Waste Versus Hydrogen/Plutonium Ratio .....	15
Table 5-2, Fissile Mixture Parameters for Direct-loaded, Non-compacted Waste Versus Hydrogen/Plutonium Ratio .....	16
Table 5-3, Material Composition for ASTM A 569 Low Carbon Steel .....	17
Table 5-4, Material Composition for Lead .....	17
Table 5-5, Material Composition for Concrete.....	18
Table 5-6, Summary of Underground Array Calculation Results .....	19
Table 5-7, Summary of Two-Container Calculation Results.....	21
Table 7-1, Evaluation of Stacking Containers Four Tiers High in the Underground Repository .....	26
Table 7-2, Evaluation of Compaction Caused by Roof Fall in the Underground Repository .....	27
Table 7-3, Fissile Mass Overbatching Contingency Results .....	28
Table 7-4, Beryllium Overbatching Contingency Results.....	28
Table 7-5, Excess Liquid Contingency Results .....	30
Table 8-1, Summary of Limits Imposed on Shielded Containers.....	35

## List of Figures

Figure 2-1, Shielded Container Three-Pack and 55-gallon Drum Seven-Pack on a Facility Pallet.....	3
Figure 2-2, Layout of the WIPP Underground .....	4
Figure 2-3, Drum Assemblies on the Transporter and Emplaced in the Disposal Array .....	5
Figure 2-4, Typical Emplacement Pattern of Various Types of Containers in Underground Repository .....	6
Figure 2-5, Shielded Container .....	8
Figure 4-1, Flowchart for use of USL with Monte Carlo Calculations .....	10
Figure 5-1, Sample Array Model Layout of Shielded Containers .....	13
Figure 5-2, Typical Shielded Container Two-Container Model showing Payload with > 1 wt% Special Reflector Materials .....	14
Figure 5-3, Drum Array with Shielded Containers, Horizontal Section.....	20
Figure 7-1, Results with Interstitial Water between Containers.....	29
Figure 7-2, Top View of Model for the 41-ton Forklift Impact with an Array of 55-Gallon Drums Seven-Packs (Configuration 1) .....	32
Figure 7-3, System Reactivity Resulting from a 41-ton Forklift Impact with 55-Gallon Drums Seven-Packs .....	33

## List of Acronyms

ASTM	American Society for Testing and Materials
Be	beryllium
BeO	beryllium oxide
CH	contact-handled
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ENDF-VI	Evaluated Neutron Data File VI
FGE	fissile gram equivalent based on <sup>239</sup> Pu
g/cm <sup>3</sup>	grams per cubic centimeter
H/D	height-to-diameter
H/Pu	hydrogen/plutonium ratio
HalfPACT	half-package transporter
MCNP5	Monte Carlo N-Particle transport code, version 5
MgO	magnesium oxide
mrem/hr	millirem per hour
NCSE	nuclear criticality safety evaluation
NaCl	sodium chloride
NDA	non-destructive analysis
Pu	plutonium

RH	remote-handled
SAR	Safety Analysis Report
SWB	standard waste box
TDOP	ten-drum overpack
TRAMPAC	TRUPACT-II Authorized Methods for Payload Control
TRU	transuranic
USL	upper subcritical limit
WHB	Waste Handling Building
WIPP	Waste Isolation Pilot Plant
WIPP WAC	<i>Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant</i>
wt%	weight percent
WTS	Washington TRU Solutions LLC
WWIS	WIPP Waste Information System

## 1.0 Introduction

This summary provides the criticality safety analysis of shielded containers at the WIPP as excerpted from the nuclear criticality safety evaluation (NCSE) for contact-handled (CH) transuranic (TRU) waste container handling, storage, and disposal process at the Waste Isolation Pilot Plant (WIPP). It addresses the disposal configuration during active waste emplacement up to when the filled panel is removed from active ventilation with a panel closure or substantial and isolation barrier. The full NCSE, WIPP-016 (Larson 2009), contains the complete analysis and further details of the calculations referenced herein.

Many CH waste containers are currently approved for disposal at WIPP but this summary focuses on the shielded container, which is a lead-lined 55-gallon drum. The shielded container is proposed as an alternative to disposal of remote-handled (RH) waste in canisters in the walls of the disposal rooms. The shielded container will contain RH waste but the shielding reduces the dose rate such that the container can be contact-handled. The possible increased neutron source from the RH waste does not impact the multiplication factor (i.e.,  $k_{\text{eff}}$ ). The shielded container is shipped to the WIPP from the U.S. Department of Energy (DOE) generator sites in the Half-package Transporter (HalfPACT) transportation package. The criticality analysis of 55-gallon drums is also discussed in this summary because in some cases, a shielded container calculation was not performed because it is bounded by the 55-gallon drum calculation.

The criticality safety analysis considers both normal and worst-case WIPP waste handling, storage, and disposal configurations of shielded containers. The primary criticality control is the fissile mass and special moderator material mass limits established and presented in Section 8.0. Once the shielded container is approved for use, these mass limits for shielded containers will be incorporated into the *Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant* (WIPP WAC) and verified at generator sites through a waste certification process, as is done with currently approved containers.

This report also summarizes the evaluation for credible upset scenarios during waste handling, disposal, and storage of shielded containers at WIPP. The evaluation concludes that no credible criticality accident scenarios exist for the TRU waste storage, handling, and disposal process in shielded containers at the WIPP.

## 2.0 Descriptions

### 2.1 Facility and Process Description

The WIPP is located in southeastern New Mexico, 26 miles east of Carlsbad. This site is owned by the DOE and operated by the Washington TRU Solutions LLC (WTS). The purpose of the WIPP facility is to serve as a final repository for TRU waste generated at other DOE sites and to demonstrate the feasibility of safe disposal of radioactive wastes in deep underground salt formations. The majority of waste to be disposed of at the WIPP is TRU waste with plutonium as the primary TRU isotope.

Two categories of waste, CH and RH, are approved for disposal at the WIPP. Contact-handled waste containers have surface radiation levels not exceeding 200 millirem/hr (mrem/hr) and are handled directly by human operators. Remote-handled waste containers have surface radiation levels up to 1,000 rem/hr. This report only summarizes the criticality safety analysis of the shielded container, which contains RH waste but the container shielding reduces the dose rate such that the container can be contact-handled. The waste approved for disposal at the WIPP must meet the requirements of the *Waste Isolation Pilot Plant Hazardous Waste Facility Permit* (NMED 2007) and the requirements of the criticality safety evaluation, WIPP-016.

Shielded containers that reduce the dose rate from the contained RH waste to CH values have been proposed as an alternative to disposal of RH waste in canisters. The shielded containers will be configured as an assembly of three containers, or three-pack, and transported in the HalfPACT. The fissile contents during transportation, including the overall package limit, are restricted by the *HalfPACT Safety Analysis Report* (DOE-CBFO 2009a) as given in Table 2-1.

**Table 2-1, HalfPACT Limits for Shielded Containers**

Contents	Fissile limit per Container ( <sup>239</sup> Pu FGE)	Fissile limit per Package (i.e., 3 shielded containers) ( <sup>239</sup> Pu FGE)
Not machine compacted waste with ≤ 1 wt% Be/BeO	200	325
Not machine compacted waste with > 1 wt% Be/BeO	Unauthorized	Unauthorized
Machine compacted waste with ≤ 1 wt% Be/BeO	200	245

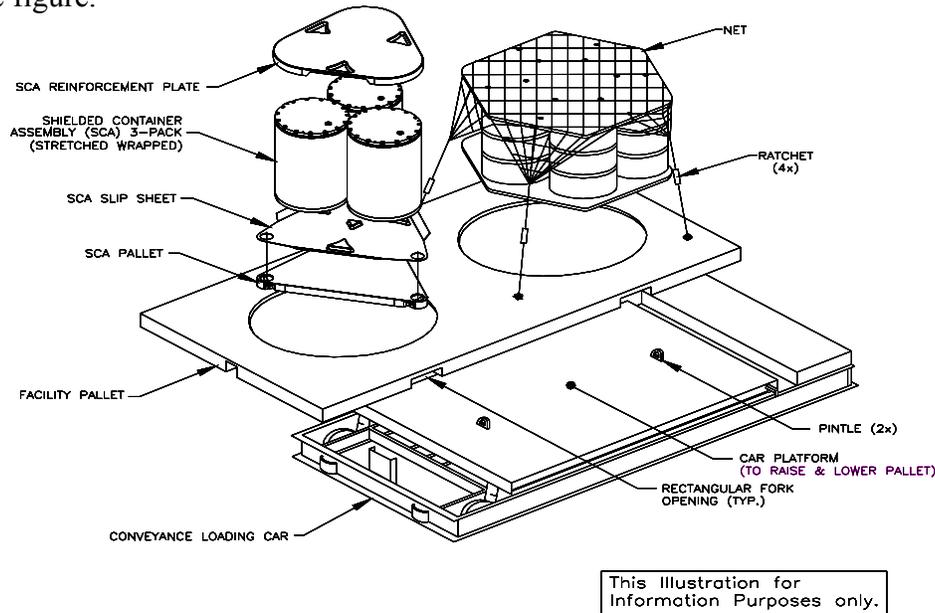
Transporters carrying TRU waste arrive at the WIPP and are parked on the south side of the Waste Handling Building (WHB). After the CH TRU shipping package is inspected for contamination, the loaded shipping package is moved into the WHB. The WHB has two TRUDOCKs and four overhead cranes for opening and unloading the HalfPACT shipping packages. Each TRUDOCK is designed to handle up to two HalfPACTs. The CH bay provides space for transferring loaded facility pallets to the waste hoist via forklifts, a shielded holding area, a waste handling equipment battery recharge area, and temporary storage areas for waste containers.

Once at the TRUDOCKs, the shipping packages are opened and surveyed for radiation and contamination levels. Then the waste containers are removed and placed on a facility pallet. Figure 2-1 shows a three-pack of shielded containers and a seven-pack of 55-gallon drums loaded onto a facility pallet for transport in the underground. This figure also illustrates the use of slipsheets. The 0.15-inch-thick polyethylene slipsheet is used to provide a mechanism for sliding the waste container(s) off the pallet and into a disposal location. The reinforcement plate shown in Figure 2-1 is a second polyethylene sheet. A pallet could hold up to four drum

assemblies but the shielded container assemblies are not very stable stacked so only two assemblies stacked one high are placed on the pallet. The pallet is either transferred to the conveyance loading car, which is moved into the hoist cage for transfer to the underground repository for permanent disposal, or is temporarily stored in the WHB in a designated area for future transfer to the repository.

The WIPP underground disposal repository consists of eight panels and two panel equivalents mined from the Salado formation, a 2,000-foot-thick series of salt beds [approximately 95% sodium chloride (NaCl)]. Figure 2-2 shows a plan view of the WIPP underground disposal repository. The disposal level lies 2,150 feet below the surface, a little below the middle of the Salado formation. A typical underground panel contains seven rooms, each of which is 300 feet long, 33 feet wide and 13 feet high. The access drifts connect the rooms in a panel and provide an additional length of 33 feet on each side of the room for drum storage. The emplacement of containers is illustrated in Figure 2-3. A magnesium oxide (MgO) backfill is used in the WIPP to reduce actinide solubility in the unlikely event the facility is flooded and consumes carbon dioxide that would be produced by microbial consumption of cellulose, plastic, and rubber in the emplaced CH waste. A “supersack” of MgO is placed on top of the waste container stack.

Figure 2-4 shows a typical waste emplacement pattern with various waste containers. This pattern is designed so that seven-packs of 55-gallon drums, four-packs of 85-gallon drums, and three-packs of 100-gallon drums all occupy the same “footprint.” A closely-packed hexagonal lattice is achieved for a seven-pack. Three-packs of shielded containers are smaller than this footprint and two three-packs may be placed side by side. More likely though, a single three-pack will be placed on the top of other waste assemblies as the third tier. Both configurations are shown in the figure.



This illustration for Information Purposes only.

**Figure 2-1, Shielded Container Three-Pack and 55-gallon Drum Seven-Pack on a Facility Pallet**

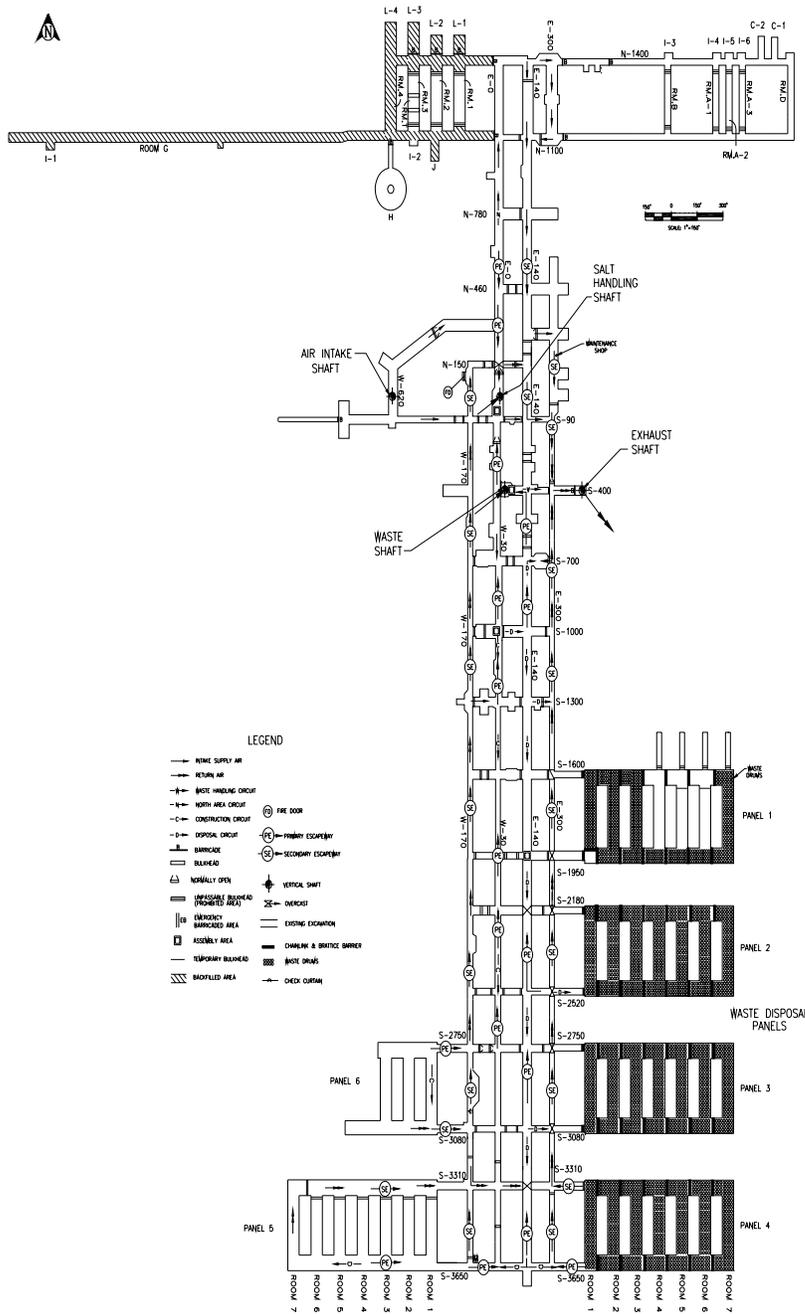
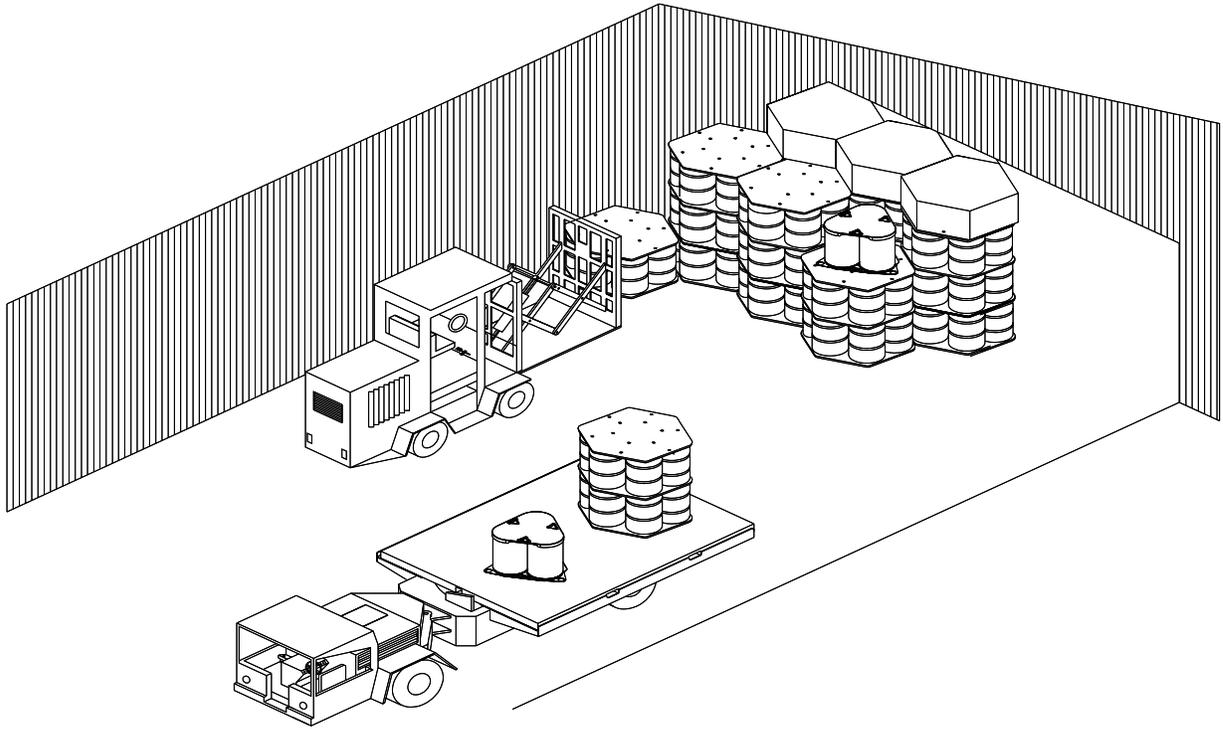


Figure 2-2, Layout of the WIPP Underground



**Figure 2-3, Drum Assemblies on the Transporter and Emplaced in the Disposal Array**

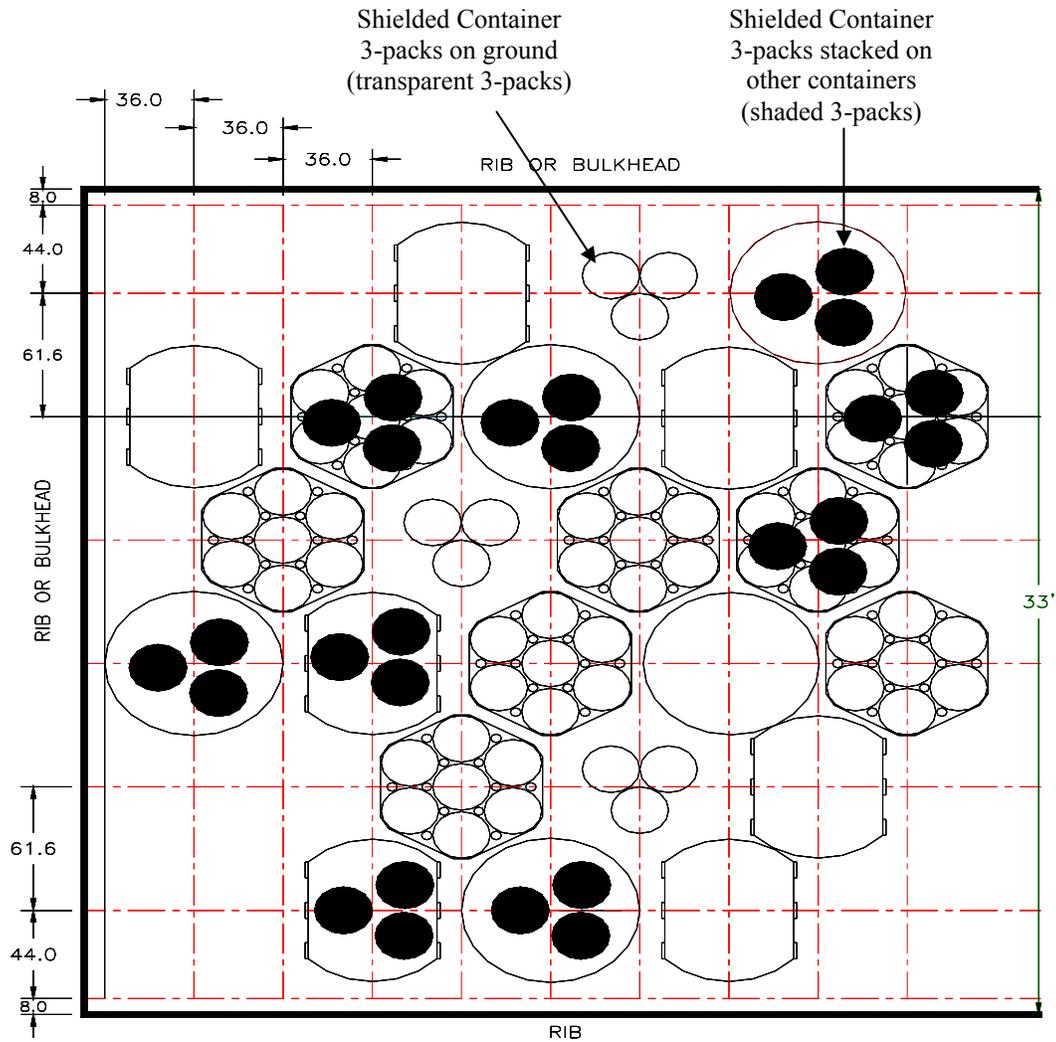


Figure 2-4, Typical Emplacement Pattern of Various Types of Containers in Underground Repository

## 2.2 Description of Shielded Containers

A lead-lined 55-gallon drum, referred to as the shielded container, is proposed for some future RH waste shipments. The shielded container is comparable in size to a 55-gallon drum and the two containers are compared below.

The 55-gallon drums have an inner diameter of 22.5 inches, an interior height of 33.25 inches, a diameter across the rolling hoops of 24 inches, and an exterior height of 35 inches. The drums are constructed with an 18-gauge (0.0478-inch nominal) wall. Table 2-2 summarizes the geometric characteristics of the 55-gallon drum compared to the shielded container.

The shielded container has approximately the same exterior dimensions as a 55-gallon drum and is designed to hold a 30-gallon drum. The cylindrical sidewall of the shielded container has nominal 1-inch-thick lead shielding sandwiched within a double-walled steel shell, as shown in Figure 2-5. The external wall is 11 gauge steel and the internal wall is 7 gauge steel. The lid and the bottom of the container are made of carbon steel and are approximately 3 inches thick. The container has been tested to DOT Type 7A specifications, which will ensure that the container is safe for transport and handling, and will contain the waste under the most severe accident conditions. The shielded container dimensions modeled in the analysis, as summarized in Table 2-2, are taken from Drawing 165-F-026, *Shielded Container Assembly* (WTS 2008). The tolerances were applied in a manner that maximizes the lead shielding thickness, which also maximizes reactivity because lead is an excellent neutron reflector.

**Table 2-2, Modeled Shielded Container vs. 55-gallon Drum Dimensions**

Dimension	55-gallon Drums		Shielded Container	
	Modeled Value (in.)	Modeled Value (cm)	Modeled Value (in.)	Modeled Value (cm)
Inner Height	33.25	84.455	29.688	75.4063
Inner Diameter	22.5	57.15	20.603	52.3316
Inner Steel Wall Thickness	N/A	N/A	0.171	0.4343
Lead Wall Thickness	N/A	N/A	1.044	2.6518
Outer Steel Wall Thickness	0.0478	0.12141	0.112	0.2845
Outer Diameter	22.5956	57.3928	23.086	58.6384
Lid/Bottom Thickness	0.0478	0.12141	3.030	7.6962

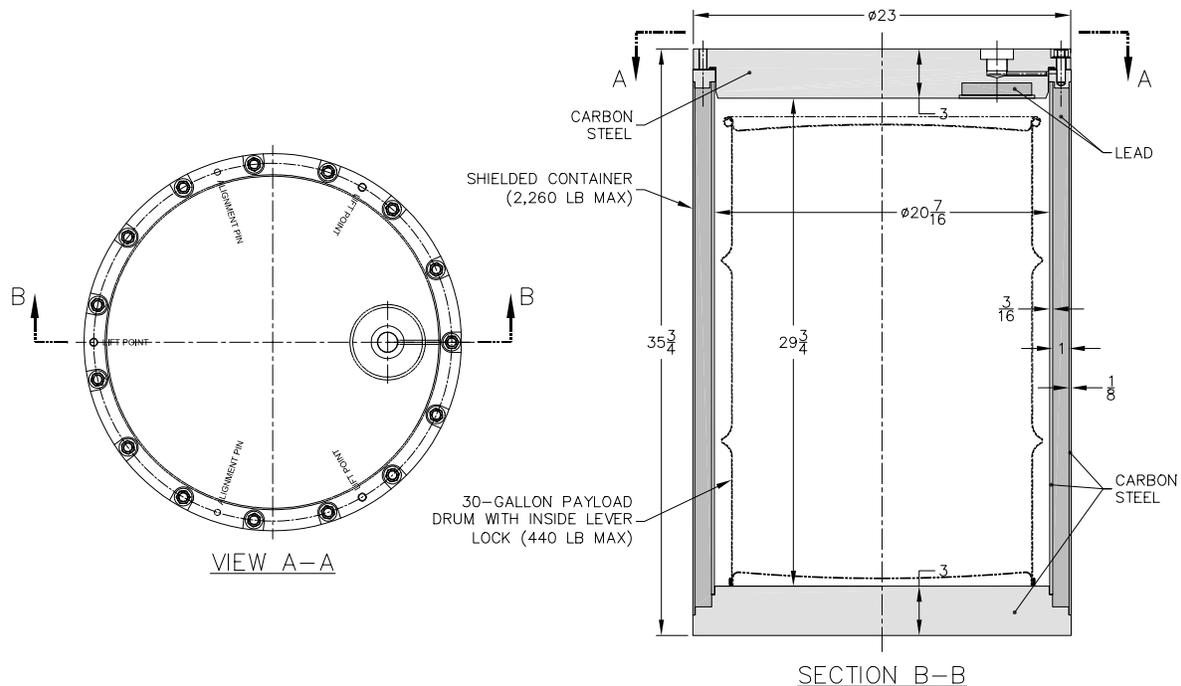


Figure 2-5, Shielded Container

### 3.0 Requirements Documentation

The WIPP facility is subject to the requirements of DOE Order 420.1B, *Facility Safety*, Chapter III, “Nuclear Criticality Safety” (DOE 2005). The NCSE that this summary report is based on is written to meet the content requirements of the *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities* (DOE 2007).

### 4.0 Methodology

#### 4.1 Evaluation Method

The methodology used in this NCSE assumes control of both  $^{239}\text{Pu}$  and special reflector materials, namely beryllium, in each waste container. Mass limits for plutonium and beryllium are the primary criticality safety control for storage, handling, and disposal of waste at the WIPP facility. After defining and evaluating the container geometries, loading configurations, and payloads in Sections 5.1 and 5.2, the overall bounding configurations for handling, storage, and disposal are identified and narrowed to two bounding configurations. The two bounding configurations are evaluated using MCNP5 (*MCNP — A General Monte Carlo N-Particle Transport Code, Version 5* [LANL 2005]) to determine the appropriate fissile mass limits as discussed in Section 5.0. The calculations summarized here are discussed in more detail in WIPP-016 (Larson 2009). Section 6.0 contains the parameter evaluation, where the controlled parameters are identified as well as the contingent conditions to be evaluated in the event control of the parameter is lost. Section 7.0 evaluates various contingent conditions related to waste operations at WIPP.

## 4.2 Monte Carlo Computational Method

Monte Carlo calculations are performed to evaluate the reactivity state of various container type / package contents combinations and configurations. Calculations in this evaluation are performed using MCNP5 (LANL 2005) on a personal computer. The MCNP5 computer code is run under the allowed Microsoft® platforms and validated in accordance with established guidelines. Only the precompiled version of MCNP5 supplied by the vendor (Los Alamos National Laboratory) and the Evaluated Neutron Data File VI (ENDF-VI) library as supplied with the code are used.

When computer codes are used, DOE orders and standards require that the neutron multiplication factor, or  $k_{\text{eff}}$ , calculated by the code including the associated uncertainty,  $\sigma$ , is less than an acceptance criterion termed the Upper Subcritical Limit (USL) in order to state that the modeled system will remain subcritical. This process is summarized in Figure 4-1. The USL is determined by the process of validation where criticality experiments with a known  $k_{\text{eff}}$  value are modeled with the code and the calculated  $k_{\text{eff}}$  values are statistically evaluated. Also included in the determination of the USL is the “administrative margin” which is a somewhat arbitrary reduction in the USL terms that take into account the over quality of the computational methods. This subject term reflects the judgment of the criticality expert with respect to how much conservatism and what level of knowledge were used in the criticality models. Once validated, the computer code is used to calculate  $k_{\text{eff}}$  values of field configurations such as the underground repository. The MCNP5 output also gives an uncertainty in the  $k_{\text{eff}}$  value that is multiplied by two and added to  $k_{\text{eff}}$  and the resulting  $k_{\text{eff}} + 2\sigma$  value is compared to the USL value.

The MCNP5 validation reports and USL determination are detailed in the NCSE (Larson 2009). The critical benchmarks modeled contain materials used in the shielded container analysis including plutonium, water, polyethylene, beryllium, steel, lead and concrete. Salt and MgO are not well represented in critical experiments but the administrative margin was increased to account for this lack of representation. The resulting USL is 0.96.

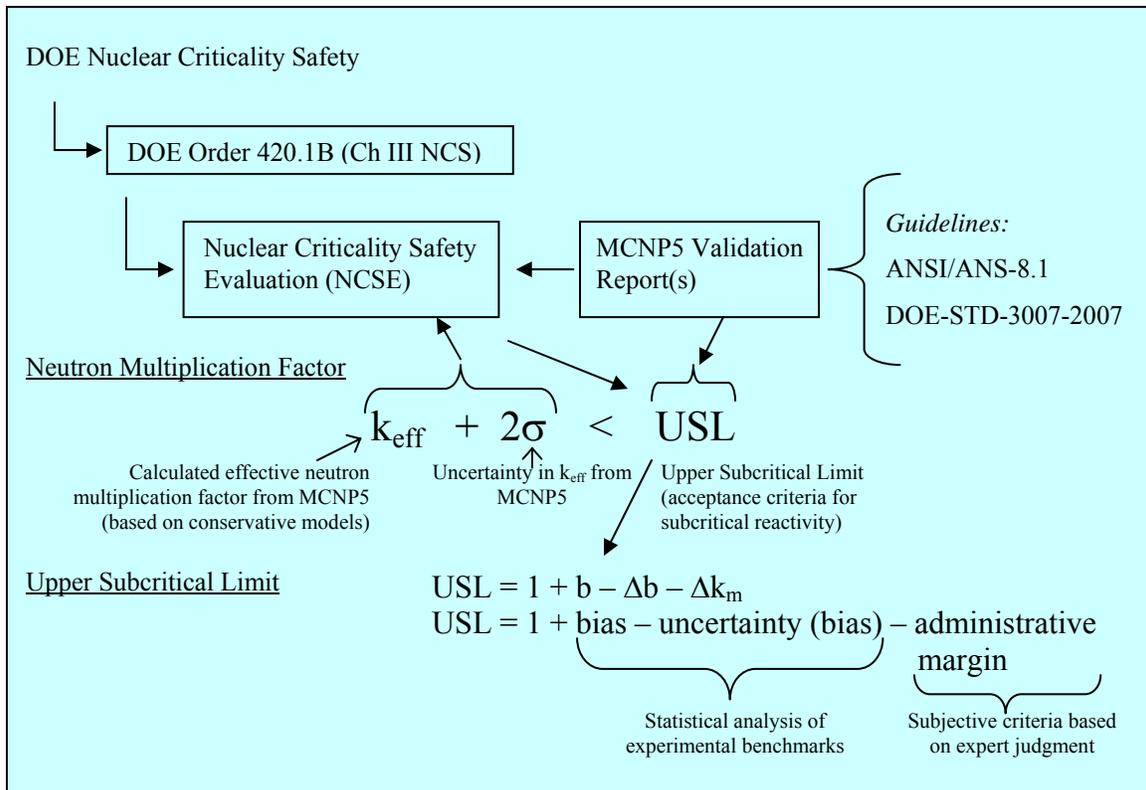


Figure 4-1, Flowchart for use of USL with Monte Carlo Calculations

## 5.0 Process Analysis

In this section, bounding configurations for the receipt, temporary storage in the WHB (aboveground), transfer to the underground in the conveyance, and permanent disposal of shielded containers in the underground repository are evaluated. To conservatively bound the multitude of waste container storage, handling, and disposal configurations, two bounding geometric configurations are evaluated: infinite array configuration with reflection conditions representative of the salt repository, and a two-container model where the fissile masses are close to one another and the containers are surrounded by an infinitely thick reflector (i.e., modeling a thicker reflector would not change  $k_{\text{eff}}$ ). These configurations are modeled in MCNP5 (Larson 2009). The geometry of the waste payloads, underground array, and two-container models are described in Section 5.1, the material compositions used in the models are given in Section 5.2, and the container array and two-container model results are summarized in Sections 5.3 and 5.4, respectively.

### 5.1 Geometry

The geometry of the contents of the various allowed loadings, as modeled in MCNP5, are summarized in Section 5.1.1 for direct loaded waste containing up to 1 weight percent special reflector materials, namely beryllium, Section 5.1.2 for direct loaded waste containing more than 1 weight percent special reflector materials and Section 5.1.3 for machine compacted waste. The

geometry of the infinite array model is described in Section 5.1.4 and the two-container model geometry is discussed in Section 5.1.5.

### 5.1.1 Waste Containing Less Than or Equal to 1 Weight Percent Special Reflectors

For this waste loading, the  $^{239}\text{Pu}$  is mixed with a polyethylene-water moderator, which is 25% by volume polyethylene and 75% by volume water. A mixture of polyethylene and special reflector material fills the remainder of the drum reflecting the fissile mass. The special reflector material is modeled as beryllium based on the evaluation in *Reactivity Effects of Moderator and Reflector Materials on a Finite Plutonium System* (Neeley et al. 2004), which found beryllium to be the most reactive reflector material at infinite thickness for a polyethylene-water moderated  $^{239}\text{Pu}$  system. Polyethylene is modeled at up to a maximum packing fraction of 25% as determined to bound the packing fraction of direct-loaded (non-machine-compacted) waste in the HalfPACT Safety Analysis Report (SAR) (DOE-CBFO 2009a). The amount of beryllium is based on 1 weight percent (wt%) of the maximum gross drum loading limit of 1,000 pounds (DOE-CBFO 2005b) or 4.54 kilograms, which is rounded up to 5 kilograms of beryllium per 55-gallon drum. A beryllium content of 5 kilograms is also modeled in the shielded container. The beryllium is modeled as homogeneously mixed throughout the polyethylene reflector. Note that at 1 wt%, beryllium is slightly more reactive modeled in the reflector than in the moderator as discussed in Section 6.4.3.2.1 of the HalfPACT SAR (DOE-CBFO 2009a).

The shielded container walls are carbon steel (American Society for Testing and Materials [ASTM] A 569), modeled with the composition given in Table 5-3, lining a lead wall, modeled per Table 5-4. The container has a nominal 3-inch-thick steel lid and bottom. The carbon steel is modeled at its theoretical density as degradation of such thick steel pieces will not be a significant fraction of the modeled thickness. Also, scoping calculations showed that modeling the shielded container walls at full thickness and density resulted in the highest reactivity.

The 55-gallon drum dimensions given in Table 2-2 are used in the MCNP5 models. The drum walls are carbon steel (ASTM A 569), which is modeled with the composition given in Table 5-3. The theoretical density of carbon steel is  $7.86 \text{ g/cm}^3$ , but is modeled at 50% of this value, or  $3.93 \text{ g/cm}^3$ , to allow for fabrication tolerances, localized wall thinning or other degradation. Thin layers of steel act as a neutron poison due to the high neutron absorption cross-sections of the material so modeling less steel than is present is conservative and increases reactivity. Section 2.1.2 of the CH-TRAMPAC (DOE-CBFO 2005b) requires that the integrity of the container be visually inspected prior to transport to ensure there is no significant rusting such that the 50% value is conservative.

### 5.1.2 Waste Containing Greater Than 1 Weight Percent Special Reflectors

While transportation of greater than 1 weight percent of special reflector material in a HalfPACT is not currently allowed (see Table 2-1), it is considered in this analysis to define the criticality limits for shielded containers under all possible conditions. [Although the HalfPACT SAR would

have to be revised to include this loading, the NCSE for the WIPP (Larson 2009) contains the necessary analysis and limits.] The special reflector material is modeled as beryllium, which has been shown to result in the highest reactivity when reflecting a plutonium system in unlimited quantity in *Reactivity Effects of Moderator and Reflector Materials on a Finite Plutonium System* (Neeley et al. 2004). For these drums, the beryllium may be in large metal pieces or may be present in particulate form; thus, the beryllium is modeled as either a moderator or a reflector. When beryllium is modeled as a reflector, the plutonium is moderated by 25% by volume polyethylene and 75% by volume water surrounded by beryllium conservatively modeled at 70% of its theoretical density. Reflection by 100% dense beryllium, although bounding, is not possible in these waste drums per *Review of Special Reflectors in the TRU Waste Inventory* (Taggart and Moon 2004). Because the beryllium consists of molds, shapes, chunks, coarse particles, and fines randomly filling the waste container instead of being specifically constructed to surround the fissile material and fill the container with no void, beryllium at 70% of theoretical density, or  $1.295 \text{ g/cm}^3$ , is used given that the maximum theoretical density for randomly packed uniform spheres is 70% (“Recursive packing of dense particle mixtures” [Elliot et al. 2002] and “Is random packing of spheres well defined?” [Torquato et al. 2007]). When modeled as a moderator, the plutonium is homogeneously mixed with the beryllium and the Be/Pu ratio in the mixture is varied to find the maximum reactivity.

### 5.1.3 Machine Compacted Waste

In this loading, the contents are fully compacted and the non-fissile material in the container, modeled as polyethylene, reaches theoretical density. Thus, the fissile mass is moderated with 100% dense polyethylene and reflected by a 100% dense mixture of 5 kilograms beryllium and polyethylene. A denser mixture of polyethylene results in a higher  $k_{\text{eff}}$ . Thus it is conservative to model 100% dense polyethylene even though the compaction process will not achieve a true theoretical density. As another conservatism in this model, the steel wall of the compacted drum is ignored and only the steel of the outer container is modeled.

### 5.1.4 Infinite Array Model Details

The MCNP5 model of the shielded container array is pictured in Figure 5-1. Every shielded container contains 200 FGE. The 55-gallon drums array is modeled in a similar fashion but the fissile mass per seven-pack is reduced to 650 FGE (three drums contain 200 FGE and one drum contains 50 FGE). The underground repository array is modeled as a 3 high stack of containers in a hexagonal arrangement that is infinitely reflected on the six vertical faces to simulate a tight-packed, infinite array in x and y. The bottom of the stack is reflected with nominally 10 feet of salt modeled at 300 centimeters and the top of the stack is reflected by nominally 2 feet modeled at 62.2 centimeters of MgO backed by 300 centimeters of salt. The MgO represents the supersack placed on top of each stack and the salt thickness provides infinite reflection. (MgO between the containers would reduce the interaction between containers and thus reduce the reactivity of the array; reflection by MgO is considered in the two-container model as discussed in Section 5.1.5 to bound supersacks placed amongst the containers or a spill of MgO from a supersack.) Waste container configurations are emplaced on a hexagonal lattice unit with pitch

characteristics typical of a seven-pack of 55-gallon drums. Even though the shielded containers will be emplaced as a three-pack, the three tier high, seven-pack configuration used to model 55-gallon drums is used. This configuration is conservative as it models the shielded containers in a more densely packed arrangement than the three-packs.

Fissile masses are modeled as cylinders, at an optimum height-to-diameter (H/D) ratio of 1, located in the center of the container in the infinite array model. In this centralized configuration, the fissile units are equal distance to all other fissile units in the array. Assuming random placement of the fissile unit in each container, the average center-to-center separation in either the horizontal or vertical direction will be statistically the same as that of the array with all fissile masses centered in the containers, because as two fissile masses are brought closer together, those masses become further separated from the fissile material in other containers. The two-container model discussed in the next section evaluates localized areas of high fissile concentration.

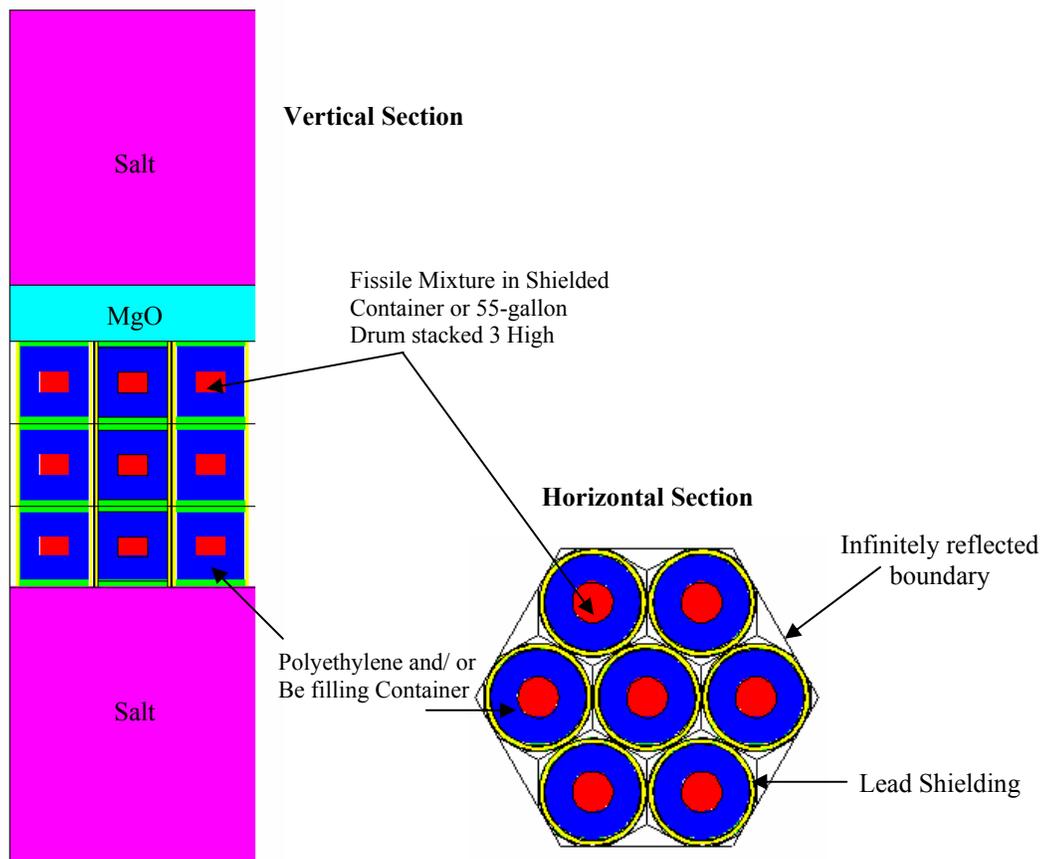
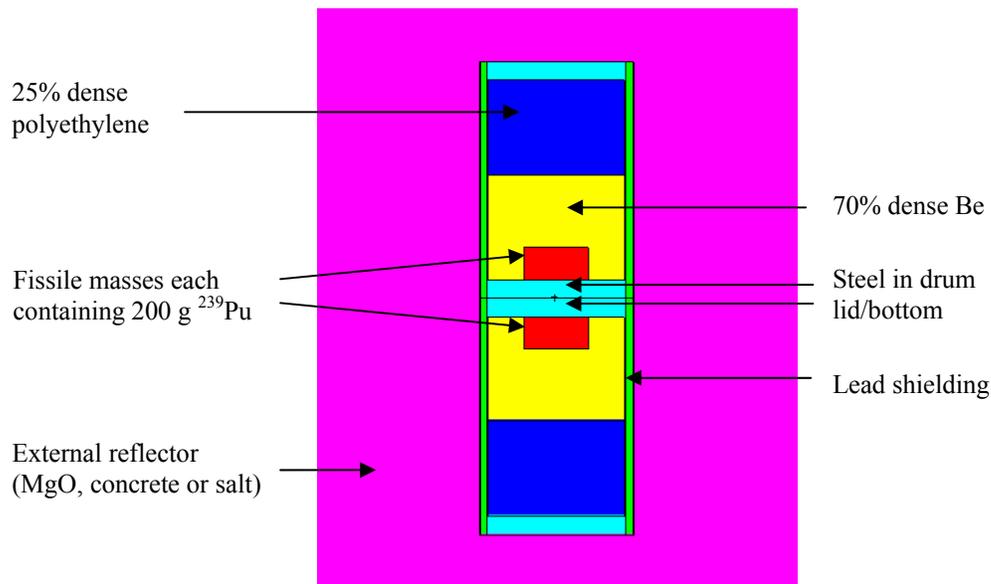


Figure 5-1, Sample Array Model Layout of Shielded Containers

### 5.1.5 Two-container Model Details

The two-container models used in this evaluation consider the different container types and approved loadings that could be stacked on top of one another in a bounding configuration. Whereas the fissile material is centered in each container in the array model, the two-container model considers worst-case fissile placement for maximum interaction between the two containers. The fissile mass in the lower container is located at the top of the container while the fissile mass in the upper container is located at the bottom of the container as shown in Figure 5-2. The fissile mass units form a cylinder with an optimum H/D ratio of 1 and a total mass of two times that allowed per container.

Worst-case reflection conditions that may occur during storage, handling, and disposal are also considered in the two-container model. The stack of two containers is tightly reflected by 300 centimeters of either concrete, MgO, or salt to provide infinite reflection. The concrete is modeled to represent aboveground handling and storage in concrete buildings, the MgO represents close reflection by the MgO supersacks in the underground repository and the salt represents the salt walls. The intent of the two-container analyses is to provide a worst-case, conservative model to ensure that a criticality accident at the WIPP due to the storage, handling, and disposal of CH waste containers is not credible for a localized configuration of concentrated fissile material due to close proximity and/or full reflection conditions.



**Figure 5-2, Typical Shielded Container Two-Container Model showing Payload with > 1 wt% Special Reflector Materials**

## 5.2 Material Compositions

The material compositions used in the MCNP5 models are summarized in this section.

### 5.2.1 Fissile Waste Mixture

The majority of the fissile material to be disposed of at the WIPP is  $^{239}\text{Pu}$  and is the only fissile component considered in the analysis. Other fissile isotopes are allowed at the WIPP, but all are reported as equivalent grams of  $^{239}\text{Pu}$  known as FGE. The  $^{239}\text{Pu}$  density used in determining source mixtures is  $19.848 \text{ g/cm}^3$  (*Handbook of Chemistry and Physics* [CRC 1991-1992] and *Standard Composition Library* [Petrie et al. 2000]) for alpha-phase plutonium metal with a molecular weight of 239.05 (*Nuclides and Isotopes* [GE 1989] and Petrie et al. 2000).

The moderator component of the fissile mixture used in the criticality analyses is dependent on waste category. The moderating material in fully compacted waste streams consists of pure polyethylene at its theoretical density of  $0.923 \text{ g/cm}^3$  or  $0.93 \text{ g/cm}^3$  (both values for 100% dense polyethylene given in Petrie et al. 2000). For all other non-compacted waste streams, the moderator is modeled as a mixture of polyethylene and water, which is 25% by volume polyethylene and 75% by volume water. Tables 5-1 and 5-2 tabulate the fissile mass mixture compositions as a function of hydrogen/plutonium (H/Pu) ratio. For each waste container and payload modeled, calculations varying the H/Pu ratio in the fissile mixture were performed to determine the optimum moderation level (i.e., the H/Pu ratio resulting in the highest reactivity.).

**Table 5-1, Fissile Mixture Parameters for Fully Compacted Waste Versus Hydrogen/Plutonium Ratio**

H/Pu Ratio	$^{239}\text{Pu}$ Concentration (g/L)	Mixture Density ( $\text{g/cm}^3$ )	Wt.% H	Wt.% C	Wt.% Pu
$^{239}\text{Pu}$ Mixed with 100% Dense Polyethylene					
700	44.8428	0.9658	13.7045	81.6522	4.6433
750	41.8596	0.9629	13.7471	81.9057	4.3472
800	39.2485	0.9604	13.7845	82.1289	4.0866
850	36.9441	0.9582	13.8178	82.3268	3.8555
900	34.8953	0.9563	13.8474	82.5035	3.6491
950	33.0617	0.9545	13.8741	82.6623	3.4637
1000	31.4112	0.9529	13.8981	82.8057	3.2962
1050	29.9177	0.9515	13.9200	82.9358	3.1442
1100	28.5598	0.9502	13.9399	83.0545	3.0056

**Table 5-2, Fissile Mixture Parameters for Direct-loaded, Non-compacted Waste Versus Hydrogen/Plutonium Ratio**

H/Pu Ratio	<sup>239</sup> Pu Concentration (g/L)	Mixture Density (g/cm <sup>3</sup> )	Wt.% H	Wt.% O	Wt.% C	Wt.% Pu
<b><sup>239</sup>Pu Mixed with 25% By Volume Polyethylene and 75% By Volume H<sub>2</sub>O</b>						
700	39.548	1.0170	11.4771	65.2466	19.3876	3.8887
800	34.614	1.0123	11.5331	65.5653	19.4823	3.4193
900	30.774	1.0087	11.5771	65.8153	19.5566	3.0509
1000	27.699	1.0057	11.6125	66.0167	19.6165	2.7542
1100	25.184	1.0033	11.6417	66.1824	19.6657	2.5101
1200	23.088	1.0013	11.6661	66.3212	19.7070	2.3058

### 5.2.2 Reflector Material in Waste Container

The reflector material around the fissile mixture used in the criticality analyses is varied to maximize reactivity of the two-container model or the array model. For waste types limited to less than or equal to 1 wt% of special reflector materials, 5 kilograms of beryllium is spread through the reflector region. In the array mode, the remainder of the shielded container or drum is void to increase interaction. In the two-container model, the remainder of the container is 25% dense polyethylene to increase reflection. For payloads with greater than 1 wt% special reflector materials, 100 kilograms of beryllium at 70% density is modeled. The remainder of the container around the beryllium is void in the array model and 25% dense polyethylene in the two-container model. For compacted waste, the remainder of the container is filled with 100% dense polyethylene, resulting from the compaction process, in both the array and two-container models.

### 5.2.3 Container Materials of Construction

The shielded container drawings specify that the steel is carbon steel (WTS 2008). U.S. Department of Transportation specifications require only that the 55-gallon drums be constructed of low carbon or stainless steel (304L). Scoping studies have shown that differences between modeling the wall as 304L versus ASTM A 569 do not have a statistically significant effect on the MCNP5 result. All container structural steel components are modeled with ASTM A 569 low carbon steel (CRC 1991-1992). In the shielded container, the steel wall sandwiching the lead and the thick steel lid and bottom are modeled at the theoretical density of 7.86 g/cm<sup>3</sup> which was shown to maximize reactivity due to its thickness (i.e., 3-inch thick lid and bottom and 1.3-inch combined thickness of steel and lead). Modeling less of the thin steel wall of the 55-gallon drum, on the other hand, was shown to increase reactivity due to high thermal absorption cross-section in steel. Because the WIPP repository is situated in a series of thick salt beds, the environment could cause a degradation of the thin steel drum wall over long periods of time. To avoid imposing controls on the thickness and nature of the drum walls, a reduced density of 50% of

nominal is assumed for the 55-gallon drum walls, lid and bottom and no credit is taken for the additional steel layers of the compacted waste pucks as the thickness of the steel in the compacted puck is uncontrolled and difficult to quantify. The specification for ASTM A 569 low carbon steel modeled is given in Table 5-3.

**Table 5-3, Material Composition for ASTM A 569 Low Carbon Steel**

Element/ Isotope	MCNP5 Library Specification	Wt. Fraction	Element/ Isotope	MCNP5 Library Specification	Wt. Fraction
<b>Density – 7.86 g/cm<sup>3</sup></b>					
C	6000.60c	0.0015	<sup>54</sup> Fe	26054.60c	0.058513
Mn	25055.60c	0.006	<sup>56</sup> Fe	26056.60c	0.90963
P	15031.60c	0.00035	<sup>57</sup> Fe	26057.60c	0.020827
S	16000.60c	0.0004	<sup>58</sup> Fe	26058.60c	0.0027769

The lead in the shielded containers is modeled at its theoretical density of 11.3437 g/cm<sup>3</sup>. Lead consists of four naturally occurring isotopes: <sup>204</sup>Pb, <sup>206</sup>Pb, <sup>207</sup>Pb, and <sup>208</sup>Pb, at the abundances given in Table 5-4. Lead-204, which represents 1.4 atom% of natural lead, is not in the ENDF-VI MCNP5 library; therefore, the abundance of the other isotopes is normalized to 1 to account for the lack of this cross-section.

**Table 5-4, Material Composition for Lead**

Element/ Isotope	MCNP5 Library Specification	Natural Atom%	Atom% Normalized for Lack of <sup>204</sup> Pb Cross-section
<b>Density 11.3437 g/cm<sup>3</sup></b>			
<sup>204</sup> Pb	None	1.4	Not modeled
<sup>206</sup> Pb	82206	24.1	24.442
<sup>207</sup> Pb	82207	22.1	22.414
<sup>208</sup> Pb	82207	52.4	53.144

#### 5.2.4 Reflector Material Outside the Waste Container

To simulate the waste storage, handling, and disposal configurations at WIPP, three different reflectors are used to bound the waste container configurations: concrete, MgO, and salt. Ordinary concrete, at a density of 2.35 g/cm<sup>3</sup> (*Handbook of Health Physics and Radiological Health* [Shleien et al. 1998]), is used as one of the reflecting materials for the two-container models to bound aboveground temporary storage. The composition of the concrete used is summarized in Table 5-5.

**Table 5-5, Material Composition for Concrete**

Element/ Isotope	MCNP5 Library Specification	Wt. Fraction	Element/ Isotope	MCNP5 Library Specification	Wt. Fraction
<b>Density – 2.35 g/cm<sup>3</sup></b>					
H	1001.60c	0.0056	K	19000.60c	0.0192
O	8016.60c	0.4981	Ca	20000.60c	0.0829
Na	11023.60c	0.0171	<sup>54</sup> Fe	26054.60c	0.000725
Mg	12000.60c	0.0026	<sup>56</sup> Fe	26056.60c	0.011377
Al	13027.60c	0.0456	<sup>57</sup> Fe	26057.60c	0.000263
Si	14000.60c	0.3151	<sup>58</sup> Fe	26058.60c	0.000035
S	16000.60c	0.0013	–	–	–

Salt is used as a reflector for the underground array models. Salt is taken as NaCl with a density of 2.165 g/cm<sup>3</sup> with the atomic weights of sodium and chloride being 22.9898 and 35.4527, respectively (CRC 1991–1992). The MgO is modeled as a continuous layer 62.2 centimeters high at a density of 1.45 g/cm<sup>3</sup>. Based on the current specification for the MgO backfill (Ransom 2009), the supersack containing the MgO is a hexagon nominally 155 centimeters (61 inches) across the flats that contains 1,361 ± 22.7 kilograms (3,000 ± 50 pounds) MgO. At the modeled density and thickness, a hexagon 155 centimeters across the flats would hold 1,881.7 kilograms of MgO. Thus more MgO is modeled than is currently planned for use in the underground. This is conservative as including the MgO on top of the waste stacks in the model has been shown to increase the reactivity. Thus, if the MgO is not used on top of the smaller shielded container three-packs, the array will be less reactive than reported in this document. In addition, racks of MgO supersacks may also be placed amongst the waste containers in the underground array or MgO may spill from the supersacks. Thus, full reflection of the two-container model by MgO is considered to bound these conditions. Also by modeling full reflection by MgO, any future change in the MgO super-sack configuration is bounded.

### 5.3 Container Array Results

#### 5.3.1 Baseline Disposal Array Calculations

Calculations were performed to determine the reactivity effect due to the interaction of multiple containers in the underground repository as described in Section 5.1.4 and illustrated in Figure 5-1. These baseline array reactivity results, as summarized in Table 5-6, show that the array reactivity is well below the USL of 0.96. Although the shielded containers will be emplaced in three-packs, a seven-pack array is conservatively modeled as it places the shielded containers in a more densely packed arrangement than the three-packs and does not adversely affect the FGE loading limit. Consequently, this model accounts for areas where two three-packs of shielded containers could be placed next to one another as shown in Figure 2-4.

All shielded containers in the seven-pack model contain 200 FGE whereas three of the 55-gallon drums in the seven-pack model are empty. Even so, the shielded container array result for the payload with less than or equal to 1 wt% special reflectors is only a little higher than the 55-gallon drum result for that payload and the shielded container results are lower than the 55-gallon drum results for the other payloads. These trends indicate that the lead wall reduces interaction between the fissile materials in the shielded containers allowing a much higher fissile density in the array.

**Table 5-6, Summary of Underground Array Calculation Results**

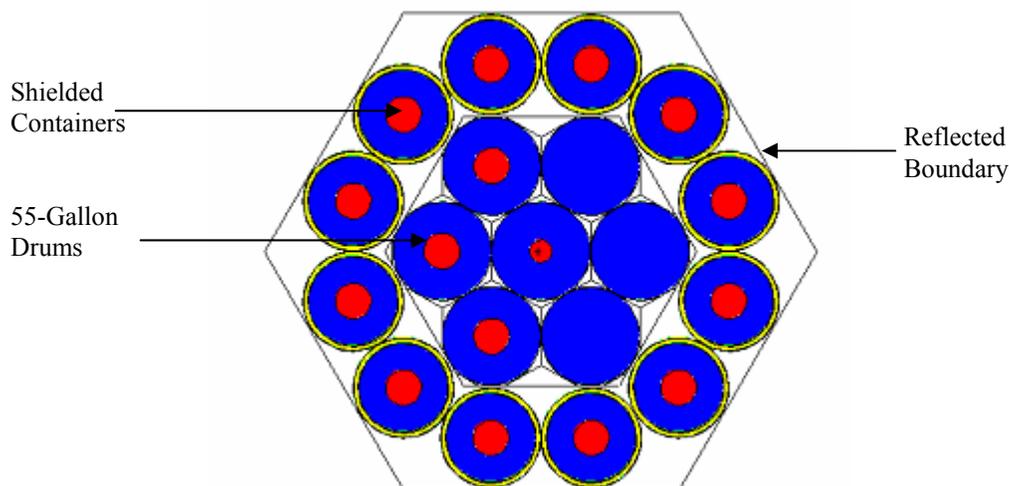
Container Type	Container FGE Limit	FGE Limit per Seven-Pack	Maximum $k_{eff} + 2\sigma$
<b>Direct-loaded Waste Containing <math>\leq 1</math> wt% Special Reflectors</b>			
55-gallon drums	200	650 per seven-pack	0.90096
Shielded containers	200	N/A <sup>(a)</sup>	0.91763
<b>Direct-loaded Waste Containing <math>&gt; 1</math> wt% Special Reflectors</b>			
55-gallon drums	100 + 100 kg Be	N/A <sup>(a)</sup>	0.89169
Shielded containers	100 + 100 kg Be	N/A <sup>(a)</sup>	0.79076
<b>Machine Compacted Waste Containing <math>\leq 1</math> wt% Special Reflectors</b>			
55-gallon drums	200	600 per seven-pack	0.87079
Shielded containers	200	N/A <sup>(a)</sup>	0.86990

(a) All containers modeled with stated container FGE limit such that no seven-pack limit is required.

To determine the effect of lead reflection from the shielded containers on other non-shielded waste containers in a mixed array, an array with shielded containers around a 55-gallon drum seven-pack is also modeled as shown in Figure 5-2. The 55-gallon drum seven-pack contains 650 FGE (200 FGE in three drums and 50 FGE in a fourth). The outer hexagonal surface around the shielded containers is infinitely reflected to model an infinite array. With the reflected boundary, this model also represents the scenario where shielded containers are surrounded by 55-gallon drums; the reflected boundary acts as if a mirror image of the containers shown in the figure is repeated on the other side of the boundary. The shielded containers were modeled with 200 FGE and 5 kilograms beryllium per drum. The fissile mass is in a cylinder located in the center of each drum or container and the containers are stacked three tiers high with MgO and salt reflection. The configuration shown in Figure 5-3 has a  $k_{eff} + 2\sigma$  value of 0.89459. Thus, the presence of shielded containers in the array slightly reduces reactivity from the 55-gallon drum array result shown in Table 5-6 because the lead reduces interaction between containers. An additional model is evaluated that included a stack of two 55-gallon drum assemblies surrounded by shielded containers on the sides and on the third tier. The reactivity of this configuration ( $k_{eff} + 2\sigma$  value of 0.89355) is again slightly lower than the array of 55-gallon drums by themselves. These calculations were repeated with the machine compacted waste payload and again the intermixed arrays had a slightly lower reactivity than the 55-gallon drum array of machine

compacted waste. Thus, intermixing shielded and non-shielded containers is not a criticality safety concern.

Additionally, the reactivity of a configuration with shielded containers placed around 55-gallon drums or other non-shielded containers is bounded by the two-container model of 55-gallon drums (or other non-shielded containers) discussed in the next section. The two-container model has an infinitely thick concrete, MgO, or salt reflector surrounding the 55-gallon drums (see Figure 5-2). The infinitely thick reflector maximizes reactivity in comparison to the 1-inch thick lead wall in the shielded container. Also, the reflecting material in the two-container 55-gallon drum model is tight against the containers with no gaps, which contributes significantly to the reactivity of the system. By comparison, the placement of the shielded containers adjacent to other container types allows for more neutron leakage through the gaps between adjacent packages than is represented in the two-container model. These two features maximize the reactivity of the two-container model for 55-gallon drums relative to the configuration with shielded containers placed around 55-gallon drums.



**Figure 5-3, Drum Array with Shielded Containers, Horizontal Section**

#### **5.4 Two-container Model Results**

The array model assumes the fissile contents are centered in each waste container to represent average fissile spacing based on the random nature of the waste. This model is conservative as it evaluates the waste in pure, concentrated form with optimum moderation instead of spread throughout the waste constituents, as is more likely to occur in waste. However it is possible that the fissile material could be concentrated nearby in two adjacent containers. The two-container model, as described in Section 5.1.5 and illustrated in Figure 5-2, evaluates this possibility.

Table 5-7 summarizes the results of the two-container models. The thick steel lid and bottom of the shielded container provide significant separation between the masses in the two drums and reduce reactivity. As a result, the payloads with less than or equal to 1 wt% beryllium and greater

than 1 wt% beryllium are combined into one case with 200 FGE and 100 kilograms beryllium per shielded container. Even combined, the shielded container results are well below the USL of 0.96. Also, the shielded container two-container result for compacted waste is less than the 55-gallon drum result indicating that 55-gallon drums in the two-container configurations are more reactive than shielded containers.

**Table 5-7, Summary of Two-Container Calculation Results**

Container Type	Container FGE Limit	Maximum $k_{\text{eff}} + 2\sigma$
<b>Waste Containing <math>\leq 1</math> wt% Special Reflectors</b>		
55-gallon drums	200	0.88622
Shielded containers (analyzed with 100 kg Be, such that this case bounds waste with $> 1$ wt% special reflectors)	200 + 100 kg Be	0.90681
<b>Waste Containing <math>&gt; 1</math> wt% Special Reflectors</b>		
55-gallon drums	100 + 100 kg Be	0.92707
Shielded containers	200 + 100 kg Be	0.90681
<b>Machine Compacted Waste</b>		
55-gallon drums	200	0.95284 <sup>(a)</sup>
Shielded containers	200	0.85263

(a) This model credits spacing between fissile masses inherent in the design of the drum lid and recessed bottom that is not credited in any other calculations.

## 6.0 Parameters

The section provides an overview of which parameters important to criticality safety are controlled for the shielded containers. Parameters that are evaluated at their worst case state (i.e., modeling 100%  $^{239}\text{Pu}$  enrichment) do not require control and are noted accordingly. Limits on controlled parameters to ensure criticality safety are summarized in Section 8.0. The contingent events resulting from the loss of each controlled parameter are also given below. These upsets are evaluated in detail in Section 7.0.

### 6.1 Mass

Fissile mass limits are required to maintain the reactivity below the USL, thus mass is controlled. As a contingent condition, an overload to 150% of the mass limit is modeled in one container per stack in the underground array and the stack is infinitely reflected as discussed in Section 7.4.1.

### 6.2 Geometry

The geometry of the fissile region is not controlled. The fissile region is modeled as a cylinder at an H/D ratio of 1 to minimize neutron leakage.

### 6.3 Moderation

Optimum moderation of the fissile region is modeled by varying the H/Pu ratio to determine the most reactive state. Within the container but outside of the fissile region, moderation is shown to reduce reactivity per Section 7.6. Exterior to the container, interstitial moderation is modeled to represent sprinkler activation or flooding as a contingency event in Section 7.5. Thus, moderation is not controlled.

### 6.4 Interaction

Interaction is controlled in that the underground repository array is limited to containers stacked three tiers high. A three-tier-high array of shielded containers is modeled as the bounding configuration. The aboveground array is bounded by the underground array and is also limited to three tiers high for criticality safety (although it is restricted to two tiers high for other reasons).

Interaction is also controlled by the container, which determines the distance between fissile masses. Containers are modeled in contact with one another in an infinite array and the bottom of one container is placed on top of another with only the thickness of the lid or bottom modeled and any recesses ignored.

Four loss of interaction control contingencies are evaluated: (1) dropping containers from the waste hoist in Section 7.1, (2) overstacking the entire array to four tiers high in Section 7.2, (3) underground roof falling resulting in container compaction in Section 7.3, and (4) crushing of the containers on the waste array face as a result of impact by the 41-ton forklift in Section 7.7.

### 6.5 Neutron Absorption

No neutron absorbers are modeled in the shielded container as the thick steel lid/bottom and the steel walls flanking the lead act as reflectors and increase reactivity. In the 55-gallon drum, on the other hand, the thinner, single steel wall acts as a neutron absorber. Thus, the wall, lid, and bottom of the 55-gallon drum are modeled at full thickness but the steel is modeled at 50% of its theoretical density. Section 2.1.2 of the CH-TRAMPAC (DOE-CBFO 2005b) requires that the integrity of the payload container shall be visually inspected prior to transport to ensure that payload container is in good and unimpaired condition (e.g., no significant rusting and of sound structural integrity), where modeling 50% of the steel in the wall is conservative. Thus, neutron absorption is controlled by the transportation requirement. No credible contingency event is identified that would damage more than 50% of the wall thickness over a significant surface area. Therefore, upsets in this parameter are bound by the normal condition using only 50% of the steel wall thickness.

## 6.6 Reflection

### 6.6.1 Internal Container Reflection

Internal container reflection is controlled as mass limits on special reflector materials, namely beryllium, are required to maintain system reactivity below the USL. Unless specifically evaluated, special reflector materials are limited to less than 1 wt% of the payload meaning the waste contains no beryllium or only trace quantities. Mass limits are set for containers with this restriction. An upset condition of exceeding the beryllium restriction is modeled by placing twice as much beryllium in one container per stack. A high beryllium content payload with up to 100 kilograms of beryllium in drums is also evaluated. The corresponding upset condition evaluated one out of every twenty-one containers filled with beryllium as the worst-case credible condition. These upset conditions are evaluation in Section 7.4.2.

### 6.6.2 External Container Reflection

The external reflection is not controlled, and is modeled conservatively compared to actual conditions. In the underground repository, the modeled array is infinite in the x and y directions and reflected by 300-centimeter-thick salt on the top and bottom. The MgO supersack is modeled as a continuous layer of theoretical density MgO directly on top of the container array, and the salt modeled directly on top of that. Scoping calculations confirmed that including the MgO results in a significant increase in reactivity, and modeling it as a continuous layer instead of discrete supersacks on top of individual containers provides conservatism by eliminating the neutron leakage path between supersacks. In the two-container model, the reflectors that the containers may come in contact with (concrete, MgO, and salt) are modeled tight-fitting around the containers at infinite thickness. This configuration is considerably more reactive than the actual condition where the container may be in a corner of a concrete hot cell or salt panel. This tight-fitting reflector around the two-container model also simulates interstitial salt or MgO that could be present between waste containers.

## 6.7 Volume

Volume is not credited in any of the analyses and is not controlled.

## 6.8 Enrichment

Enrichment is not controlled. All fissile material is modeled as  $^{239}\text{Pu}$ , which is conservative as there is always other less reactive isotopes present with  $^{239}\text{Pu}$  including  $^{240}\text{Pu}$ , a strong neutron absorber. Uranium-235 and  $^{233}\text{U}$  can be shipped under these limits using FGE as defined in the CH-TRAMPAC (DOE-CBFO 2005b). The FGE values account for the differences in minimum critical mass between  $^{239}\text{Pu}$  and these isotopes.

## 6.9 Concentration

Concentration is not controlled. The fissile concentration is unrestricted and optimized by varying the H/Pu ratio and consequently the plutonium concentration in the fissile region.

## 7.0 Contingency Evaluation

Credible abnormal conditions that could occur during waste storage, handling, and disposal of waste in shielded containers at the WIPP are assessed in this section. A hazard evaluation was performed to identify the conditions that could lead to a loss of the controlled parameters from Section 6.0. No contingencies are considered for variations in beryllium or polyethylene packing fraction, container wall thickness, reflector parameters, or fissile moderation parameters because the analyses in Section 5.0, along with its subsections, used the worst credible values for these parameters. The limits and controls needed to render a criticality accident not credible are presented in Section 8.0.

The contingency evaluation is based on perturbations of the worst-case normal or nominal configuration infinite array models described in Section 5.3.1. The two-container models are sufficiently conservative as discussed in Section 5.4 to bound any contingency of more realistic or expected conditions involving interaction between small numbers of containers. The array models consider each seven-pack at a fissile loading over 500 FGE, which is greater than the current HalfPACT fissile limit of 325 FGE. The contingencies evaluated in this section are applied to the array models with the fissile material centered in each container.

### 7.1 Loss of Confinement of Fissile Material

The bounding CH event that results in a loss of confinement is the unlikely failure of the waste hoist, such that the CH containers are breached when the load falls down the waste shaft into the waste shaft sump. However, the failure of the waste hoist has been evaluated (DOE-CBFO 2009b) to be beyond extremely unlikely (i.e., frequency of less than  $10^{-6}$ /yr and thus not credible in criticality safety terminology) due to the robust design of the waste hoist with redundant brakes and six ropes.

### 7.2 Exceeding Disposal Array Vertical Stacking Limit

#### 7.2.1 Exceeding Array Vertical Stacking Limit in the Underground Repository

By design, the WIPP panels are mined to a ceiling height that will accommodate up to the nominal height of three 55-gallon drums. This configuration allows adequate space for the MgO supersack to be placed on top of the waste column and still allow adequate space for the airflow rate required by the Hazardous Waste Facility Permit for WIPP (NMED 2007). Waste handling procedures at WIPP administratively control waste stacks in the disposal array to be stacked no greater than the equivalent of three drum assemblies. However, ground control activities to ensure mine safety have resulted in areas of the disposal rooms being mined to a height greater

than 13 feet, such that it is possible to stack containers greater than three tiers high including the MgO.

To determine the impact on the disposal array reactivity if an overstacking event occurred in the repository, a fourth tier of containers is added to the following arrays: (1) direct-loaded 55-gallon drums containing less than or equal to 1 wt% special reflectors, (2) direct-loaded 55-gallon drums containing greater than 1 wt% special reflectors, and (3) 100-gallon drums of fully compacted waste. Shielded containers are also evaluated stacked four tiers high with the payload containing up to 1 wt% beryllium as this payload had the highest reactivity in the 55-gallon drum array. Modeling containers at four tiers high through the entire infinite array is very conservative as only localized areas have been mined to allow stacking to this height and stacking is administratively limited to three tiers high.

The results of the base array and the overstacked array are compared in Table 7-1. A larger reactivity increase over the three-tier array is seen for non-compacted waste than for compacted waste as the higher polyethylene density in the compacted waste acts to isolate the fissile material in the various tiers. The cases with high special reflector content also exhibit a large increase for the four-tier array as the array model considers the plutonium spread through the beryllium at the beryllium/plutonium ratio that resulted in the highest  $k_{\text{eff}}$  value. If the 100 kilograms of beryllium in each drum are modeled purely as a reflector around the fissile material, it would isolate the fissile material in the tiers from one another and little increase would be seen as demonstrated in the compacted waste results. All results are below the USL of 0.96 except for the loading with high beryllium content. Overstacking of the entire array without noticing the error, while at the same time placing the MgO supersack on top of the fourth tier, would require multiple operator errors. Also, although areas of disposal rooms have been mined to a height greater than 13 feet, the entire disposal panel being mined to a height that allows room to create an infinite four-tier array with MgO is unlikely. As such, a four-tier array of drums containing 100 FGE and 100 kilograms of beryllium is modeled without the MgO supersack but with the drums in contact with the salt ceiling. As shown in Table 7-1, the  $k_{\text{eff}} + 2\sigma$  value is less than 0.89. The four-tier drum array height is 11.1 feet without the MgO supersack and 13.15 feet with the supersack emplaced on top of the drums. Based on the significant reduction in reactivity without the supersack on top of the array and the small clearance between the worst-case mining height and the four-tier array with MgO, it is not considered credible to create an infinite overstacked array that would result in a critical configuration. In addition, note that each drum in the array is modeled at the FGE limit (whereas the average FGE per drum currently emplaced in the underground is less than 40 FGE\*).

---

\* Based on query of WIPP Waste Information System (WWIS) database for average FGE per container with 200 FGE limit performed by WWIS Database Administrator on June 1, 2009.

**Table 7-1, Evaluation of Stacking Containers Four Tiers High in the Underground Repository**

Container and Waste Loading	Array Height	$k_{\text{eff}} + 2\sigma$
55-gallon drums of direct-loaded waste with $\leq 1$ wt% special reflectors	3 tiers	0.90096
	4 tiers	0.94913
55-gallon drums of direct-loaded waste with $> 1$ wt% special reflectors	3 tiers	0.89169
	4 tiers with MgO	0.96628 <sup>(a)</sup>
	4 tiers without MgO	0.88973 <sup>(b)</sup>
Shielded containers of direct-loaded waste with $> 1$ wt% special reflectors	3 tiers	0.79076
	4 tiers	0.79354
100-gallon drums of fully compacted waste	3 tiers	0.86925
	4 tiers	0.87247

(a) An infinite four-tier-high array plus MgO is not considered credible.

(b) Modeled with the MgO supersack removed from the infinite four-tier-high array.

### 7.2.2 Exceeding Interim Drum Storage Array Stacking Limit

Waste containers may be stored aboveground while awaiting processing and/or transport to the underground facility. Stacking in aboveground storage arrays is administratively limited to the height of two containers. Waste containers are required to be stored on facility pallets in the WHB. The load limit of the facility pallet is such that drums will not be stacked higher than two containers. Up to four CH drum or shielded container assemblies are stored on a pallet. Overstacking on the surface is unlikely even though forklifts are capable of stacking containers higher because the surface stacking configuration is designed to minimize any additional handling prior to placing waste on the waste shaft conveyance for transfer to the underground. Any overstacking event is bounded by the calculation performed in Section 7.2.1 (recall that concrete reflection is comparable to salt and/or MgO reflection).

### 7.3 Underground Roof Fall

A roof fall impacting all of the containers in the array during the operational phase of a disposal panel is unlikely due to the historic behavior of the salt repository and WIPP's safe mining practices. [The WIPP safety analysis (DOE-CBFO 2009b) considers a roof fall breaching 30 waste assemblies as an anticipated event but this analysis considers the unlikely event of a roof fall impacting the entire infinite array or waste assemblies.] If a roof falls, vertical compaction of 15 inches to the bottom tier of drums is postulated in the *Analysis of Roof Fall and Methane Gas Explosions in Closed Rooms and Panels* (PLG 1997). For machine compacted waste, the result is bounded by the normal condition models since the reflector density considered in these models is already 100% of theoretical. A number of runs are performed to evaluate this scenario for non-compacted waste. The compaction is modeled by reducing the height of the bottom row of drums by 15 inches and then centering the fissile material in the shortened drum. This effect is modeled in the following arrays: (1) direct-loaded 55-gallon drums containing less than or equal to 1 wt%

special reflectors, (2) shielded containers containing less than or equal to 1 wt% special reflectors, and (3) direct-loaded 55-gallon drums containing greater than 1 wt% special reflectors. Modeling the bottom row of containers crushed through the entire infinite array is conservative as the roof fall may only occur over a localized area. The results of the base array and the compacted array are summarized in Table 7-2. The compaction has a small effect on the reactivity of the array, and all results remain below the USL of 0.96.

In addition to compaction due to roof fall, it is possible that the MgO sacks could break such that MgO would fall between drums in an assembly or between columns of waste assemblies. This condition is bounded by the full MgO reflection evaluated around the two-container models, as the MgO would provide reflection and act to decouple the fissile masses in the array. Again, a large roof fall is not expected during the operational pre-closure phase of a disposal room or panel.

**Table 7-2, Evaluation of Compaction Caused by Roof Fall in the Underground Repository**

Container and Waste Loading	Compaction	$k_{\text{eff}} + 2\sigma$
55-gallon drums of direct-loaded waste with $\leq 1$ wt% special reflectors	None	0.90096
	15 in. in bottom row	0.92034
Shielded containers of direct-loaded waste with $\leq 1$ wt% special reflectors	None	0.91763
	15 in. in bottom row	0.92001
55-gallon drums of direct-loaded waste with $> 1$ wt% special reflectors	None	0.89169
	15 in. in bottom row	0.89792

## 7.4 Exceeding Mass Limits

### 7.4.1 Exceeding the Fissile Mass Limit for a Container

Exceeding the fissile mass for a container is unlikely, as non-destructive analysis (NDA) is performed at the waste generator site and confirmed prior to preparing containers for shipment to WIPP. CH-TRAMPAC requirements (DOE-CBFO 2005b) indicate that the mass estimate must include two times the uncertainty in the NDA measurement. In addition, the underground disposal fissile mass limits are often higher than the limits for transport of the containers in the HalfPACT shipping containers. To model this upset condition, the fissile mass in one container per three-tier stack of seven-packs is increased to 1.5 times the fissile mass limit. Thus, one container out of every twenty-one containers exceeds the criticality safety limits which will be incorporated into the WIPP WAC. In addition, since the HalfPACT individual container limits are the same as the WIPP WAC, an overbatch to this magnitude would require more than one out of three shipments to exceed the transportation SAR requirements (DOE-CBFO 2009a). Also, all containers around the overbatched container are filled to the underground repository limits, which would also require exceeding the current total payload fissile mass limits for the transportation package. Thus, exceeding the modeled condition is not considered credible.

The results of the overbatching contingency are tabulated in Table 7-3. The computational results indicate that multiple overbatching events will not result in the USL of 0.96 being exceeded.

**Table 7-3, Fissile Mass Overbatching Contingency Results**

Container and Waste Loading	Overbatch Scenario	$k_{\text{eff}} + 2\sigma$
Shielded containers of direct-loaded waste with $\leq 1$ wt% special reflectors	None	0.91763
	1 container at 300 FGE	0.93015
Shielded containers of direct-loaded waste with $> 1$ wt% special reflectors	None	0.79076
	1 container at 150 FGE with 100 kg Be	0.85063
Shielded containers of machine compacted waste	None	0.86990
	1 container at 300 FGE	0.95919

#### 7.4.2 Exceeding the Beryllium Mass Limit for a Container

The beryllium overbatching contingency is similar to the fissile mass overbatching event in that one drum in the modeled three-tier stack of containers exceeds its mass limit. In this case, one container with a 5-kilogram beryllium limit is double-batched to 10 kilograms, and one container with a 100-kilogram limit is modeled volumetrically filled with beryllium, which results in over 200 kilograms beryllium in the container. The results of the overbatching contingency are tabulated in Table 7-4, which shows that the system  $k_{\text{eff}} + 2\sigma$  values are well below the USL and double-batching the beryllium has only a minor effect. In some cases, the  $k_{\text{eff}} + 2\sigma$  value for the overbatched beryllium case is less than the base case result. This is due to the statistical nature of MCNP5 calculations and the values are statistically the same.

**Table 7-4, Beryllium Overbatching Contingency Results**

Container and Waste Loading	Overbatch Scenario	$k_{\text{eff}} + 2\sigma$
55-gallon drums of direct-loaded waste with $\leq 1$ wt% special reflectors	None	0.90096
	1 drum at 10 kg Be	0.90056
55-gallon drums of direct-loaded waste with $> 1$ wt% special reflectors	None	0.89169
	1 drum filled with Be ( $> 300$ kg)	0.88842
Shielded containers of direct-loaded waste with $> 1$ wt% special reflectors	None	0.79076
	1 container filled with Be ( $> 200$ kg)	0.79108

#### 7.5 Sprinkler Activation in the Waste Handling Building

The WHB is equipped with a fire sprinkler system. This contingency addresses activation of the sprinkler system resulting in interspersed moderation between the waste containers. Although containers are only stacked a maximum of two high aboveground, a three-tier stack of seven-packs of shielded containers or 55-gallon drums is modeled for conservatism. The ceiling and

floor are modeled as 2-foot-thick concrete, while the sides are mirrored for infinite reflection. The cases are evaluated at the maximum mass limits and optimum H/Pu ratio for the base array. Thus, the shielded containers of non-compacted waste are modeled with 200 FGE per drum, 55-gallon drums of machine compacted waste is modeled with 200 FGE in three of the 55-gallon drums in the seven-pack, and 55-gallon drums of non-compacted waste are modeled with 200 FGE in three drums, 50 FGE in one drum, and three drums empty. Water mist from sprinkler activation is allowed to fill the interstitial spaces between the containers. The water density is varied from 0 to 1 g/cm<sup>3</sup> with the results as shown in Figure 7-1. Interstitial water reduces the reactivity of containers of non-compacted waste, but has little effect on containers of compacted waste as the high-density polyethylene in the drum isolates the fissile masses in the drums from one another such that the material between the containers has little effect. The same result would be true for containers with greater than 1 wt% special reflectors as the beryllium also provides isolation. Thus, these calculations bound shielded containers containing compacted waste or greater than 1 wt% special reflectors. All results are significantly below the USL and the addition of interstitial water reduces reactivity.

Water ingress into the WIPP underground is observed at the shafts and not in the disposal area during the operational period. The same reactivity trend seen for sprinkler activation would occur if water is somehow available in the underground repository, and the  $k_{eff}$  would not increase above the analyzed dry condition.

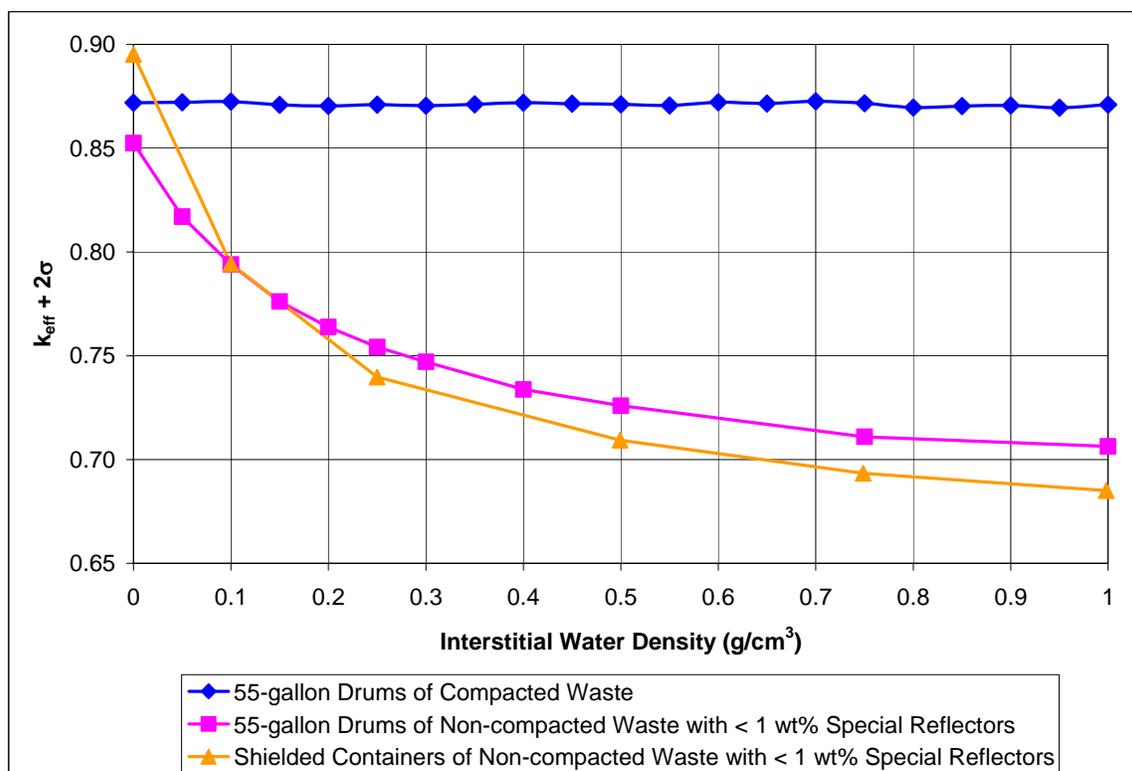


Figure 7-1, Results with Interstitial Water between Containers

## 7.6 Excess Liquid in Waste Containers

This contingency evaluates waste containers with more than 1% liquid present, which could occur from a generator site error or water intrusion into the containers. Although the underground is not subject to flooding, the analysis considers all containers in the underground array containing excess water at various densities up to the point where water fills all void space in the container. Only non-machine compacted waste with loose polyethylene dunnage mixed with 1% special reflector material is considered, since waste forms with large quantities of special reflector materials, or since machine compacted waste will be less reactive if water is substituted for the special reflector material or the polyethylene. The H/Pu ratio in the fissile material is varied at each water density considered to ensure the optimum condition is modeled.

The calculation results are summarized in Table 7-5 for 55-gallon drums and shielded containers of direct-loaded waste with less than or equal to 1 wt% special reflector materials. Shielded container results show a peak in reactivity at a 25% polyethylene/75% water mixture in the container but all flooded container results are less than the results for the normal condition with no polyethylene or water around the fissile material. Thus, excess liquid in the containers has no impact from a criticality safety perspective.

**Table 7-5, Excess Liquid Contingency Results**

Container and Waste Loading	Poly Density in Container (% of Theoretical)	Water Density in Container (% of Theoretical)	$k_{\text{eff}} + 2\sigma$
55-gallon drums of waste with $\leq 1$ wt% special reflectors	0	0	0.90096
	25	0	0.74767
	25	18.75	0.76707
	25	37.5	0.78482
	25	56.25	0.80061
	25	75	0.81173
Shielded containers of waste with $\leq 1$ wt% special reflectors	0	0	0.91763
	25	18.75	0.77266
	25	37.5	0.78678
	25	56.25	0.81180
	25	75	0.81294
	15	85	0.81164
	5	95	0.81112

## 7.7 Forklift Accident Crushes Containers

This contingency simulates an accident condition where the 41-ton waste handling forklift impacts an array of seven-packs of 55-gallon drums containing CH waste in the underground repository. The 41-ton forklift is not used to move CH waste containers but is used to move the

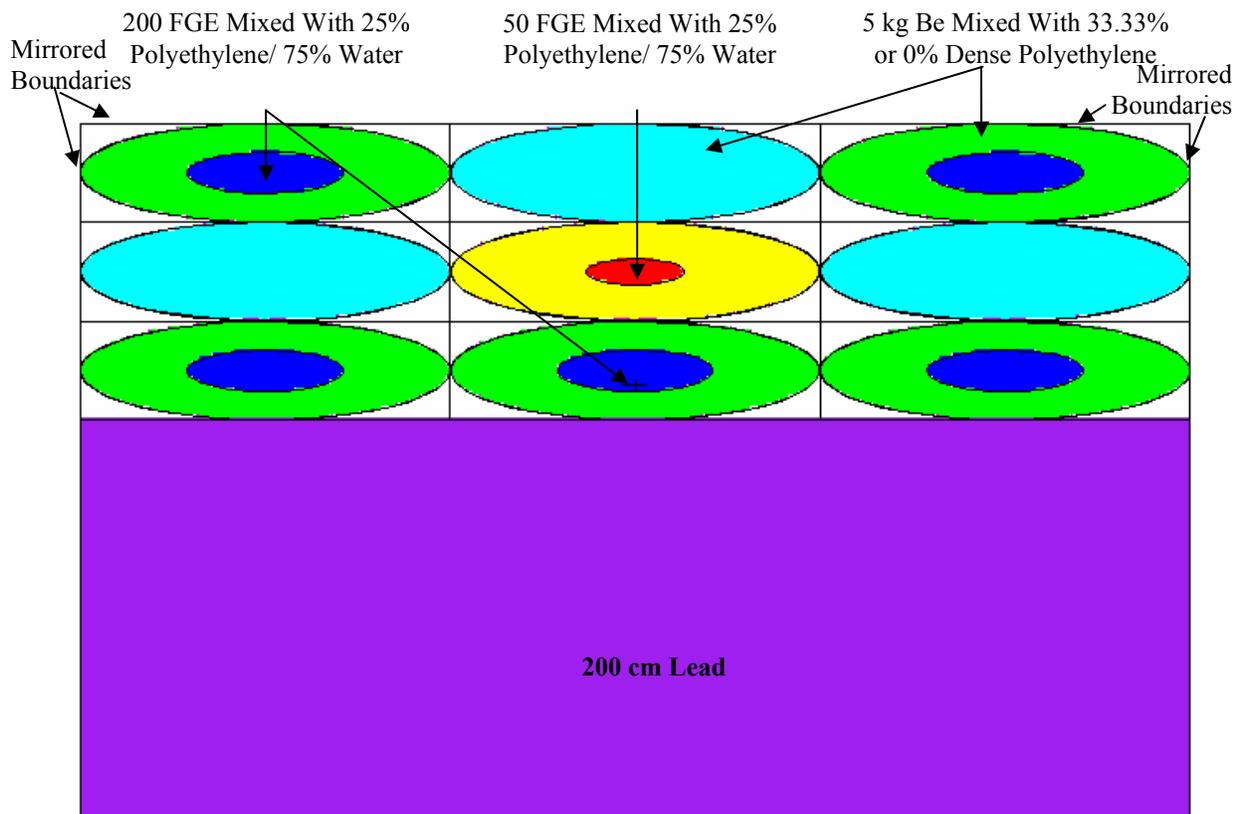
lead-shielded facility cask containing RH waste containers, as well as the shielded, heavy portions of the horizontal emplacement retrieval equipment, as described in the *Waste Isolation Pilot Plant Documented Safety Analysis* (DOE-CBFO 2009b). The 41-ton forklift can also be used to move other large, heavy underground equipment from the waste hoist. The forklift is not normally near the CH waste face because the RH waste is typically emplaced into boreholes in the salt walls before the CH waste is emplaced nearby. The RH horizontal emplacement waste handling equipment is typically placed between the CH waste face and the approaching 41-ton forklift. The documented safety analysis considers a forklift accident that breaches 16 waste assemblies an anticipated event. This analysis considers the unlikely event where the forklift accident breaches all of the waste assemblies in the modeled infinite array. This evaluation bounds impacts between smaller forklifts and CH waste containers as smaller forklifts would impact less waste containers with less force.

The 55-gallon drum of direct-loaded waste is chosen as the worst case container and loading combination for this contingency because the interaction between the fissile material in the crushed containers is maximized for two reasons. First, the 55-gallon drum is the smallest CH waste container and thus will create the tightest array when crushed. Second, this container and waste type does not have significant internal reflection which would reduce interaction between the fissile masses. The high density polyethylene in machine compacted waste, the high beryllium content in waste with a large amount of special reflectors, and the lead wall in the shielded waste all reduce interaction. To simulate the effects of a high-energy impact on the waste drums, it is assumed that the collision expels some of the air volume from the 55-gallon drums leaving the drums permanently deformed. In particular, it is assumed that the volume of the 55-gallon drums is reduced to 75% of its initial volume. Since some air is expelled, the internal reflector mass around the moderated fissile mass will compress and the density will increase. It is assumed that the polyethylene, which makes up the bulk of the dunnage around the fissile mass, is compressed from a maximum of 25 to 33% of its theoretical density. Furthermore, the model assumes that the geometry of 55-gallon drums is deformed into an elliptical shape with the ratio of the major to minor axes being 2. In this configuration, the elongated fissile mass and internal reflector waste in the 55-gallon drums are moved closer together and become more reactive. In order to minimize the distance between fissile masses in the array, the model uses a rectangular array since the waste packages and drums are elliptical cylinders. Finally, to maximize the reactivity state of the system and at the same time not restrict the number of seven-packs involved in the accident, mirror boundary conditions are used on three of the four lateral boundaries simulating an infinite array. The fourth boundary uses a reflector made up of 200 centimeters of lead to bound the steel structure of the forklift and the lead shielding on the RH facility cask that it could be carrying. In the vertical plane, the upper tier is reflected by an MgO layer (approximately 62 centimeters thick) placed on top of the 55-gallon drums and the whole stack is then reflected by 300 centimeters of salt above and below. Figure 7-2 shows a top view of the model used in the analysis.

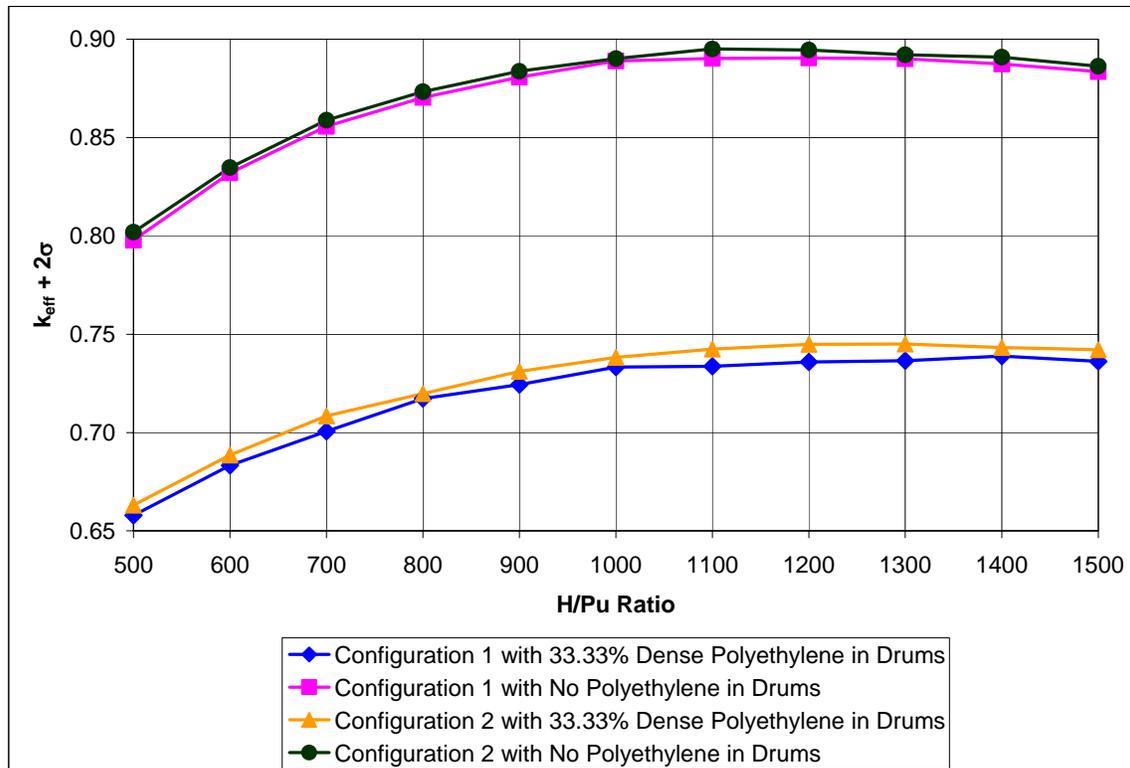
Two drum configurations are considered. The first configuration assumes that three 200-FGE drums are impacted by the forklift and the whole seven-pack stack is crushed and displaced into

the surrounding seven-packs. The resulting arrangement is a 3-by-3 array with three 200-FGE drums in the first row, one 50-FGE drum in the middle of the second row with one non-fissile bearing drum on either side, and one non-fissile bearing drum in the middle of the last row with one 200-FGE drum on either side. The two 200-FGE drums in the last row originate from the surrounding seven-packs. The boundaries that are not reflected by lead are infinitely reflected to model an infinite array of crushed seven-packs as shown in Figure 7-2. The second configuration is similar to the first except the fissile contents in the drums in the first and last rows are exchanged. Finally, to maximize the interaction effects, a computation is also performed where the polyethylene in the internal reflector is removed and only the beryllium remained in the reflector zone of the “crushed” drums.

Figure 7-3 summarizes the results of the contingency calculation. The maximum system  $k_{eff} + 2\sigma$  value is 0.89501, which occurred with the polyethylene removed from the crushed drums, thereby increasing the interaction amongst the close fissile masses. This value is below the base 55-gallon drum array  $k_{eff} + 2\sigma$  value of 0.90096. The reduction in  $k_{eff}$  results from the fact that the front face of the waste is reflected by lead instead of other fissile waste drums in the base case infinite array model. Thus, a criticality accident from a loss of interaction control caused by the impact of a large object, such as a 41-ton forklift, with an array of CH waste packages is not credible.



**Figure 7-2, Top View of Model for the 41-ton Forklift Impact with an Array of 55-Gallon Drums Seven-Packs (Configuration 1)**



**Figure 7-3, System Reactivity Resulting from a 41-ton Forklift Impact with 55-Gallon Drums Seven-Packs**

## 7.8 Contingency Analysis Conclusion

The previous subsections have shown that the operations will remain subcritical after each contingent condition occurs. The base cases for the array models is such that the fissile content for each drum assembly is nominally twice that allowed by the shipping packages. There are many other conservatisms in the base case including: modeling all containers at the FGE limit when the average FGE content per drum in WIPP is less than 40 FGE (see Section 7.2.1); modeling the fissile material in a pure form at the optimum moderation level in a compact form instead of spread throughout the drum intermixed with other waste; and modeling the remainder of the drum contents using the most reactive materials, just to name a few. The contingency upset conditions are evaluated additively to the already conservative base case models.

However, to demonstrate that a criticality event is not credible, combinations of events must be evaluated. First, note that the load drop in the shaft is shown not to be a credible event, and the sprinkler activation, water intrusion, and forklift crushing contingencies each resulted in a reduction in array reactivity. Thus, none of these events need to be further analyzed. Also, roof fall is extremely unlikely in the active operational phase prior to closure of the panel, which is the scope of the array. The highest risk is judged to result from a container that exceeds the fissile mass limit being placed in a four-tier-high array. The overstacking contingency discussed in Section 7.2.1 is modeled with each drum assembly containing almost twice the fissile mass allowed in the transportation package. This configuration is extremely unlikely based on the

actual conditions. Further, a mining or waste handling error to the extent of allowing a whole panel of containers to be stacked four high with MgO on top is also not credible. In reality, only limited areas would be mined higher than normal to allow a four-tier array. Also, the 55-gallon drum array modeled four high without MgO on top, which is still conservative compared to the mined height, showed little reactivity change compared to the three-high array. Thus, an overbatched container in a four-tier array will have a comparable reactivity to that given in the overbatching evaluation in Section 7.4, and the array will remain subcritical even with both upset conditions. Thus, a criticality accident at the WIPP is deemed not credible, and a criticality detection system is not required.

## **8.0 Design Features and Administratively Controlled Limits and Requirements**

A summary of the credited design features and administrative limits and requirements for criticality safety are provided in the following sections.

### **8.1 Design Features**

Washington TRU Solutions maintains configuration control at the WIPP facility. Revision to significant design features requires an unreviewed safety question determination to verify that the change will remain within the approved safety basis. For the purposes of this evaluation, the shielded container is the design feature that provides spacing between the fissile contents of the TRU waste.

### **8.2 Administrative Limits and Requirements**

The controls below are required to ensure that a criticality accident is not credible for shielded containers of CH waste at the WIPP.

1. Container arrays are limited to three tiers, where a drum or shielded container occupies one tier.
2. Waste approved for shipment to and disposal at WIPP are required to meet the WIPP WAC. The WAC shall contain the shielded container limits in Table 8-1.

**Table 8-1, Summary of Limits Imposed on Shielded Containers**

Container Type	Container Fissile Mass Limit	Container Geometry Requirements	Non-Fissile Material Limits
<b>Direct-loaded Waste Containing <math>\leq 1</math> wt% Special Reflectors</b>			
Shielded containers	$\leq 200$ FGE	Shielded container nominal dimensions per Figure 2-5	Special reflector mass $\leq 1$ wt%
<b>Direct-loaded Waste Containing <math>&gt; 1</math> wt% Special Reflectors</b>			
Shielded containers	$\leq 100$ FGE	Shielded container nominal dimensions per Figure 2-5	Special reflector mass $\leq 100$ kg per container
<b>Machine Compacted Waste</b>			
Shielded containers	$\leq 200$ FGE	Shielded container nominal dimensions per Figure 2-5	Special reflector mass $\leq 1$ wt%

## 9.0 Conclusions

The criticality safety analysis has evaluated the handling, storage, and disposal processes for the various waste types in the shielded containers allowed at the WIPP. The limits on fissile mass and special reflectors meet or exceed the limits on containers allowed to be transported to the facility in the HalfPACT shipping package. The modeled configurations are very conservative compared to expected fissile mass per container, the moderation level, and the geometric configuration of the waste within the container.

Conclusions are based on bounding analysis which uses several conservative assumptions. A seven-pack array of shielded containers is analyzed in a more densely packed arrangement than the three-pack configuration for the shielded containers anticipated for use. Using the Monte Carlo computational method, two bounding geometric configurations were evaluated, an infinite array and a two-container model. An additional geometry modeled is a stack of two 55-gallon drum seven-pack assemblies surrounded by shielded containers on the sides and on the third tier. This analysis showed that intermixing of shielded and non-shielded containers does not pose a criticality safety concern.

The analysis used waste container storage and disposal configurations that result in worst case criticality scenarios. Credible abnormal conditions have been identified, evaluated and shown to result in a subcritical configuration in Section 7.0. With the controls listed in Section 8.0, no credible accidental criticality scenarios involving shielded containers exist for the WIPP. Therefore, there is no need for a criticality accident alarm system or a criticality detection system.

## 10.0 References

ASTM A 569. *Standard Specification for Steel, Carbon (0.15 Maximum, Percent), Hot-Rolled Sheet and Strip Commercial*, American Society for Testing and Materials, West Conshohocken, PA.

CRC, 1991–1992. *Handbook of Chemistry and Physics*, 72nd Edition, 1991-1992, CRC Press, Boca Raton, FL.

DOE, 2005. *Facility Safety*, DOE O 420.1B, Chapter III, Nuclear Criticality Safety, December 22, 2005, U.S. Department of Energy, Washington, DC.

DOE, 2007. *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities*, DOE-STD-3007-2007, February 2007, U.S. Department of Energy, Washington, DC.

DOE-CBFO, 2005b. *Contact-Handled Transuranic Waste Authorized Methods for Payload Control (CH-TRAMPAC)*, Revision 2, May 2005, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, NM.

DOE-CBFO, 2009a. *HalfPACT Safety Analysis Report*, Revision 5, February 2009, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, NM.

DOE-CBFO, 2009b. *Waste Isolation Pilot Plant Documented Safety Analysis*, DOE/WIPP-07-3372, Revision 1, February 2009, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, NM.

Elliot J.A., A. Kelly, and A.H. Windle, 2002. “Recursive packing of dense particle mixtures,” *J. Mat. Sci. Lett.* 21:1249–1251; 2002.

GE, 1989. *Nuclides and Isotopes*, Chart of the Nuclides, 14th Edition, GE Nuclear, San Jose, CA.

LANL, 2005. *MCNP—A General Monte Carlo N-Particle Transport Code*, Version 5, LA-UR-03-1987, October 3, 2005, Los Alamos National Laboratory, Los Alamos, NM.

Larson, S.L., 2009. *Nuclear Criticality Safety Evaluation for Contact-Handled Transuranic Waste at the Waste Isolation Pilot Plant*, July 2009, WIPP-016 Revision 1, Washington TRU Solutions, Carlsbad, NM.

Neeley, G.W., D.L. Newell, S.L. Larson, and R.J. Green, 2004. *Reactivity Effects of Moderator and Reflector Materials on a Finite Plutonium System*, SAIC-1322-001, Revision 1, May 2004, Science Applications International Corporation, Oak Ridge, TN.

NMED, 2007. *Waste Isolation Pilot Plant Hazardous Waste Facility Permit*, NM4890139088, February 2007, New Mexico Environment Department, Santa Fe, NM.

Petrie, L.M., P.B. Fox, and K. Lucius, 2000, *Standard Composition Library*, ORNL/NUREG/CSD-2/V3/R6, Volume 3, Section M8, March 2000, Oak Ridge National Laboratory, Oak Ridge, TN.

PLG, 1997. *Analysis of Roof Fall and Methane Gas Explosions in Closed Rooms and Panels*, PLG-1167, August 1997, PLG Incorporated, Newport Beach, CA.

Ransom, C., 2009, *Specification for Prepackaged MgO Backfill*, Specification D-0101, Revision 8, January 2009, Washington TRU Solutions LLC, Carlsbad, NM.

Shleien, B., L.A. Slaback, Jr., and B. Birky, 1998, *Handbook of Health Physics and Radiological Health*, 3rd Edition, Scinta Publishing, Silver Spring, MD.

Taggart, D.P. and J.U. Moon, 2004. *Review of Special Reflectors in the TRU Waste Inventory*, LA-UR-04-0857, February 2004, Los Alamos National Laboratory, Los Alamos, NM.

Torquato, S., T.M. Truskett, and P.G. Debenedetti, 2007. "Is random packing of spheres well defined?" *Phys. Rev. Lett.* 84:2064–2067; 2000.

WTS, 2008. *Shielded Container Assembly*, Drawing 165-F-026-W1 through -W5, Revision B, June 2008, Washington TRU Solutions LLC, Carlsbad, NM.