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ENGINEERING CHANGE NOTICE

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13a. Description of Change 13b. Design Baseline Document? ☐ Yes ☒ No

Revision 1 incorporates modifications to Revision 0 as a result of DOE review comments, dated August 1999.

14a. Justification (mark one)			
Criteria Change ☒	Design Improvement ☐	Environmental ☐	Facility Deactivation ☐
As-Found ☐	Facilitate Const ☐	Const. Error/Omission ☐	Design Error/Omission ☐

14b. Justification Details

These revisions respond to DOE review comments to Revision 0. These revisions clarify and expand detail to more fully explain assumptions, bases, and results.

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ENGINEERING CHANGE NOTICE				Page 2 of 2	1. ECN (use no. from pg. 1) 647516
16. Design Verification Required	17. Cost Impact			18. Schedule Impact (days)	
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Cog. Eng. B. S. Lew		<u>4/2/98</u>		_____	_____
for Cog. Mgr. J. D. Carlson		<u>9/8/98</u>		_____	_____
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Canister Storage Building Design Basis Accident Analysis Documentation

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Abstract: This document provides the detailed accident analysis to support HNF-3553, *Spent Nuclear Fuel Project Final Safety Analysis Report*, Annex A, "Canister Storage Building Final Safety Analysis Report." All assumptions, parameters, and models used to provide the analysis of the design basis accidents are documented to support the conclusions in the Canister Storage Building Final Safety Analysis Report.

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**CANISTER STORAGE BUILDING DESIGN BASIS
ACCIDENT ANALYSIS DOCUMENTATION**

**SNF-3328
Revision 1**

J. C. Lavender, M.H. Chew
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September 1999

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LIST OF TERMS

ALARA	as low as reasonably achievable
CSB	Canister Storage Building
CVDF	Cold Vacuum Drying Facility
DBA	design basis accident
DOE	U.S. Department of Energy
FFTF	Fast Flux Test Facility
HEPA	high-efficiency particulate air (filter)
MCO	multi-canister overpack
MHM	multi-canister overpack handling machine
NRC	U.S. Nuclear Regulatory Commission
OSTA	overpack storage tube assembly
SNF	spent nuclear fuel
SSC	structure, system, and component
TSR	technical safety requirement

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1.0 INTRODUCTION

The calculations in this document address the design basis accidents (DBAs) selected for analysis in the final safety analysis report for the Canister Storage Building (CSB). The objective is to determine the maximum credible quantity of radioactive particulate available at the CSB and to use that quantity to determine the amount of radioactive material that could be credibly released during the DBAs. The radioactive material released is used to determine dose consequences to receptors. The dose consequences are compared with the appropriate evaluation guidelines and release limits to ascertain the need for preventive and mitigative controls.

1.1 DESIGN BASIS ACCIDENT SELECTION

The hazardous conditions identified by the CSB hazard analysis (HNF-SD-SNF-HIE-001) have been used to select candidate accidents for more detailed analysis. The general selection criteria used were consistent with the U.S. Department of Energy (DOE) standard DOE-STD-3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports*: "The range of accident scenarios analyzed in a SAR should be such that a complete set of bounding conditions to define the envelope of accident conditions to which the operation could be subjected are evaluated and documented."

The selection of candidate accidents was based on characterizing risk from, and developing controls for, a representative set of hazardous conditions. A hazardous condition is generally considered to be representative of other hazardous conditions if it has similar release characteristics and involves similar initiators. Hazardous conditions that represent the most severe consequences and the highest risk (a combination of frequency and consequences) within each set of representative hazards are selected as candidate accidents for further analysis. The representative hazardous conditions bound conditions with lesser but similar potential consequences; represent the highest risk; or, while not necessarily bounding, present some unique but important phenomenological challenge to system safety. The accident selection process comprises five steps.

1. Initial screening. Hazardous conditions with unmitigated offsite consequences or onsite, collocated worker consequences are considered for representative accident selection through a ranking of relative, overall (frequency and consequences) risk.
2. Assignment of release attributes. Each hazardous condition is described with certain release attributes in the case for the CSB (event initiatives and release forms) related to uncontrolled release of the material at risk. At least one candidate accident is selected to represent each unique set of release conditions.
3. Creation of hazardous material release bins. After assigning release attributes, the hazardous conditions are collected to form release categories, or "bins." All hazardous conditions with common initiators and release forms are grouped and ranked by

estimated consequence and frequency. Representative and bounding accidents are chosen to represent all the hazardous conditions within a particular bin.

4. Selection of representative bounding hazardous conditions for each release attribute category. Within each release attribute bin, the most severe hazardous condition is selected. These accidents are the representative and bounding accidents selected for further quantitative analysis as DBAs.
5. Selection of unique hazardous conditions. Hazardous conditions are selected to represent additional unique causes within each release attribute bin. This is done to support development of controls for accidents with similar consequences but with different causes.

The hazardous conditions are grouped by candidate accident to facilitate incorporation of the information and conclusions from the accident analysis into the hazard analysis results when considering controls and hazard classification. An initial set of safety features that would serve to prevent or mitigate the postulated accident scenarios are identified in the hazard analysis, with a final set of safety features identified in these accident analyses. A safety feature that would prevent an accident scenario is defined as one that reduces the expected annual frequency of occurrence for the accident beyond extremely unlikely (less than 10^{-6} per year). The hazard evaluation ranking performed in the hazard analysis identifies hazards and associated events that pose a challenge to offsite and onsite radiological dose evaluation guidelines. This ranking is used to select unique and representative accidents with sufficiently high-risk estimates for further detailed quantitative evaluation as DBAs. Each of the DBAs analyzed represents a bounding case for a category of hazards and accidents. SNF-4042, *Evaluation of Accident Frequencies at the Canister Storage Building*, documents the derivation of the DBA frequency range.

The list of six candidate DBAs resulting from the hazards binning process for the CSB facility is presented in Table 1-1. Chapters 2.0 through 7.0 describe the analyses of these accidents. A category of accidents associated with use of the overpack tubes for the recovery actions are described in Chapter 8.0.

Chapter 2.0 Possible Rearrangement of Multi-Canister Overpack Internals

Principal Analyst	J. C. Lavender
Peer Review	B. S. Lew

The bounding scenario for this accident category describes a physical shear force applied to the multi-canister overpack (MCO) by the MCO handling machine (MHM) such that confinement of the fuel is breached and criticality geometry control is lost. The unmitigated consequences of this event are expected to violate criticality limits. Therefore, safety-class features are identified, consistent with DOE Order 6430.1A, *General Design Criteria*, to prevent this accident. The safety-class features selected for this event include MHM seismic restraints and MHM

Table 1-1. Binned Listing of Candidate Accidents. (2 sheets)

Candidate accident	Risk ranking ^a	Release or change energy ^b	Reference designator
Rearrangement of MCO internals (Chapter 2.0)			
Possible rearrangement of MCO internals due to a drop or shear ^c	9	Medium ^d	OA-E-07
	9	Medium ^d	OA-F-07
	8	Medium ^d	OA-G-03, -13
	9	Low ^d	SA-E-07
	9	Low ^d	SA-F-07b
	9	Low ^d	WS-E-07
	9	Low ^d	WS-F-07
	8	Medium ^d	WS-G-03a, -13
	6	Medium ^d	SA-G-03a, -03b, -13
	9	Medium ^d	TV-G-09
	9	Medium ^d	TV-G-13
	8	Medium ^d	OU-R-01
	6	Medium ^d	OU-P-05
Possible rearrangement of MCO internals due to collision	8	Medium	SA-F-05
Possible rearrangement of MCO internals due to impact from gas cylinder	Note e	Note e	TV-F-06 SA-F-06 WS-F-06
Gaseous release from the MCO (Chapter 3.0)			
Pressurized release from MCO ^e	6	Medium	SA-G-03a, -03b
	5	High	WS-H-06a, -07, -11
	5	Medium	WS-F-02, -05
	Note e	Note e	WS-F-06
	5	Medium	WS-G-03b, -04, -06, -07
Pressurized release from cask-MCO	9	Low	TV-G-13
MCO internal hydrogen explosion (Chapter 4.0)			
Hydrogen deflagration ^c	9	High	WS-J-06a
	9	High	OA-J-06a
	9	High	OA-J-06c
	9	High	SA-J-06a
	7	High	WS-H-06b
MCO external hydrogen explosion (Chapter 5.0)			
External deflagration ^c	5	High	WS-L-11
	5	High	OA-J-06b

Table 1-1. Binned Listing of Candidate Accidents. (2 sheets)

Candidate accident	Risk ranking ^a	Release or change energy ^b	Reference designator
Thermal runaway fuel reactions inside the MCO (Chapter 6.0)			
Runaway reaction	Note f	Note f	WS-H-06b
Fuel exposed to air ^c	9	Medium	WS-E-07
	9	Medium	WS-F-07
	9	Low	SA-E-07
	9	Low	SA-F-07b
	9	Low	OA-E-07
	9	Low	OA-F-07
	8	Low	SA-F-05
Fuel reaction with water	6	High	SA-J-10b
	6	High	OA-J-10b
	6	High	WS-J-10b
Violations of design temperature criteria (Chapter 7.0)			
Violation of design temperature criteria ^c	6	Medium	VL-B-07, -10, -11

^aThe risk ranking is derived from methodology found in DOE-STD-3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports*, which correlates the consequence-frequency pairs assigned by the hazard analysis (HNF-SD-SNF-HIE-001) to a single-scale risk ranking using a figure reproduced in Figure 3-1 of the Spent Nuclear Fuel Project Final Safety Analysis Report.

^b Definition and use of energy release categories (high, medium, low) are based on guidance and examples in DOE-STD-3009-94.

^c Chosen as a representative and bounding accident for further accident analysis development.

^dEnergy was considered that could rearrange the internals of the MCO — falling onto the deck was viewed as higher energy than falling into the service or sample pit with impact absorbers present; falling into the tube with impact absorbers present was viewed as higher energy than falling into the service or the sample pit with an impact absorber present.

^eBefore analysis was performed, the hazard evaluation identified gas storage bottles as a hazard to be evaluated. Subsequent analysis has shown that the passive flow maximum hole diameter in the butt of the valve prevents this hazard.

^fBefore detailed analysis was performed, the hazard evaluation identified WS-H-06b as a serious hazard to be evaluated. Subsequent detailed analysis has shown that thermal runaway reactions are not possible at the Canister Storage Building given limitation of water and resulting temperature.

MCO = multi-canister overpack.

interlocks that ensure that the seismic restraints are applied and that the MHM trolley, bridge, and turret drives cannot operate when the MCO is in a position where it could be subjected to a lateral force. The MHM interlocks and restraints combine to prevent the shear of the MCO. For other safety features selected to prevent or mitigate other binned events within this accident category, see Chapter 2.0 and the associated Table 2-2. This event is prevented by safety structures, systems, and components (SSCs) and controls (SNF-4042 and Chapter A5.0 of HNF-3553, *Spent Nuclear Fuel Project Final Safety Analysis Report*, Annex A, the CSB Final Safety Analysis Report).

Chapter 3.0 Calculations for Gaseous Release from the Multi-Canister Overpack

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Peer Review P. D. Rittmann

Two scenarios have been identified for this accident category. The first accident scenario describes the overpressurization of the MCO by the inert gas system during the reinerting of a monitored MCO after sampling. Violation of the design pressure of the MCO could lead to criticality geometry control violations and thus requires safety-class controls to prevent this accident. Safety-class features required to prevent this accident are redundant pressure safety devices on the inert gas system lines and the sampling system. These prevent the purge gas from pressurizing the MCO above its design pressure. The unmitigated scenario would be brought to a stable state by allowing the inert gas system and MCO to depressurize to atmospheric pressure. Any contaminated areas or equipment would be cleaned consistent with radiation control procedures. The MCO would be handled within recovery activities under operations-related procedures, with the preferred approach being to move the MCO to an overpack storage tube for observation and storage.

The second scenario involves a release of entrained particulate from a pressurized leak of gas from an MCO at the sampling/weld station. The unmitigated consequences of this event do not exceed the offsite release limits but do exceed the onsite evaluation guidelines. Safety-significant features selected for this event include the sample hood and exhaust system, an exhaust flow indicating device, pressure tests to verify the sample connection to the MCO before opening the MCO port valve, and the MHM collision avoidance system (interlock P10) and associated sensors and switches. Mitigated consequences of this event are well below both offsite release limits and onsite evaluation guidelines. For other safety features selected to prevent or mitigate other binned events within this accident category, see Chapter 3.0 and associated Table 3-5. The unmitigated scenario is brought to a stable state by allowing the MCO to

depressurize to atmospheric pressure. Any contaminated areas or equipment would be cleaned consistent with radiation control procedures. The MCO would be handled within recovery operations under operations-related procedures, with the preferred approach being to move the MCO to an overpack storage tube for observation and storage.

Chapter 4.0 Calculations for Multi-Canister Overpack Internal Hydrogen Explosion

Principal Analyst P. D. Rittmann
Peer Review B. S. Lew

The bounding scenario for this accident category describes the ignition and explosion of a hydrogen-oxygen mixture inside an MCO when purge gas contaminated with oxygen is used to inert the MCO after sampling. The unmitigated consequences of this event do not exceed the offsite release limits, but the onsite evaluation guidelines are exceeded. A technical safety requirement (TSR) has been identified for verification of helium purity by the supplier's shipping papers or from a sample. The designated safety features prevent the occurrence of this event; therefore, the onsite evaluation guidelines are satisfied. For other safety features selected to prevent or mitigate less severe events within this accident category, see Table 4-8. The unmitigated scenario is brought to a stable state by allowing the MCO to depressurize to atmospheric pressure. If the MCO is inside the cask, the MHM, or the storage tube, these also are allowed to depressurize to atmospheric pressure. Any contaminated areas or equipment would be cleaned consistent with radiation control procedures. The MCO is handled within recovery operations under operations-related procedures, with the preferred approach being to move the MCO to an overpack storage tube for observation and storage.

Chapter 5.0 Calculations for Multi-Canister Overpack External Hydrogen Explosion

Principal Analyst P. D. Rittmann
Peer Review B. S. Lew

The bounding scenario for this accident category describes the release of hydrogen from an MCO into the sample hood and exhaust system. The hydrogen gas, after mixing with air, ignites and explodes. The unmitigated consequences of this event do not exceed the offsite release limits but do exceed the onsite evaluation guidelines. Safety-significant features selected to prevent this event include the sampling line and connection, the sample hood and exhaust system, verification of a minimum flow rate through the exhaust system, verification of the sample line connection, and pressure testing of the sample line before opening the MCO port valve. The selected safety features prevent the occurrence of this event; therefore, the onsite

evaluation guidelines are satisfied. Additional safety features have been selected to prevent or mitigate less severe events within this accident category and to provide additional defense in depth (see Table 5-8). The unmitigated scenario would be brought to a stable state by allowing the MCO to vent any gas continuing to be generated. If the MCO is inside the cask, MHM, or the storage tube, these volumes would also be allowed to continue venting. Any contaminated areas or equipment would be cleaned consistent with radiation control procedures. The MCO would be handled within recovery activities under operations-related procedures, with the preferred approach being to move the MCO to an overpack storage tube for observation and storage.

Chapter 6.0 Calculations for Thermal Runaway Reactions Inside the Multi-Canister Overpack

Principal Analysts M. G. Piepho, P. D. Rittmann
Peer Review B. S. Lew

Three scenarios have been identified for this accident category. The first scenario describes an accident where the MCO is left in the sampling/weld station for at least 40 days. The analysis shows an increase in MCO temperatures but also shows MCO pressure remains within design limits. Because no release occurs from this event, both offsite limits and onsite evaluation guidelines are satisfied.

The second scenario describes an accident initiated by inadvertently filling an MCO with oxygen at the sampling station. For this scenario, the unmitigated consequences will not violate the safety limit on MCO pressure or violate criticality controls. Because no release occurs from this event, both offsite release limits and onsite evaluation guidelines are satisfied.

The third scenario involves an accident at the sampling/weld station in which the MCO is completely sheared, with the total MCO cross-section exposed to the atmosphere and MCO wall temperatures greater than 100 °C. This scenario is analyzed to illustrate the consequences of a thermal excursion. In the unmitigated scenario, the MCO would be allowed to reach a stable state by cooling at the sample station. The MHM would remain in place providing radiation shielding and high-efficiency particulate air (HEPA) filtration and use of its exhaust system for air cooling if necessary. Any contaminated areas or equipment would be cleaned consistent with radiation control procedures. The MCO would be handled within recovery operations under operations-related procedures. Safety-class features selected to prevent this event include MHM interlocks, controls, and seismic restraints. For other safety features

selected to prevent or mitigate other binned events within this accident category, see Table 6-4.

Chapter 7.0 Calculations for Violation of Design Temperature Criteria

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Peer Review J. C. Lavender

The bounding scenario for this accident category describes conditions in the CSB safety-class concrete structures that could exceed their design temperatures because of a lack of adequate cooling. This is the thermal buildup at the vault caused by a loss of inlet air flow in the inlet stack. The unmitigated consequences of this event are postulated to cause unacceptable damage to safety-class equipment or structures. Safety-class features selected for this event include the CSB vault, inlet, and exhaust structures. Other safety features are selected to prevent or mitigate other binned events within this accident category (see Table 7-1). The unmitigated scenario is brought to a stable state by restoring cooling and bringing the vault to a stable thermal condition. In this case, any debris would be removed from the air intake and exhaust structures to restore air flow through the vault. Once a stable thermal condition was attained, the vault returned to operational status.

Chapter 8.0 Recovery Actions Related to Gaseous Releases and Explosions from Overpack Storage Tubes

Principal Analyst B. S. Lew
Peer Review J. C. Lavender

This category of accidents is associated with recovery actions associated with the use of the overpack storage tube assemblies (OSTAs) and the tube vent and purge cart. These hazard and accident analyses for recovery actions were performed to identify functions and classify SSCs to achieve an appropriate level of defense in depth (to prevent or mitigate the radiological consequences of postulated hazards and accident events to the collocated onsite worker) and worker safety (to reduce exposure to radiation) for the OSTAs and tube vent and purge cart. The bounding scenario for these accidents is a pressurized release of gases from an MCO into an overpack storage tube caused by either internal MCO pressure or a flammable gas explosion within the MCO. The unmitigated consequences of this event do not exceed the offsite release limits but do exceed the onsite evaluation guidelines. No safety-class features are required to prevent or mitigate this event. Safety-significant features selected to prevent this event include the OSTAs, a program to monitor the overpack storage tubes for pressure and to maintain inert gas within the tube, and a

lockdown device for the overpack storage tube plug. The unmitigated scenario is brought to a stable state by venting and purging the OSTA. The tube vent and purge cart is used until the OSTA has a stable inert atmosphere. Any contamination from the unmitigated event is cleaned consistent with radiation control procedures. The off-normal MCO is handled within recovery operations under emergency response procedures, with the preferred approach being to move the off-normal MCO to another available OSTA for long-term observation and storage. Similarly, the confinement boundary functions of the tube vent and purge cart are identified as safety-significant functions.

The consequences associated with each of the seven bounding DBAs are summarized in Table 1-2. Appendix A contains event tree analysis details for DBAs.

1.2 ACCIDENT ANALYSIS

This section presents the methodology used to develop the potential accidents that are described in Chapters 2.0 through 8.0. The accident analysis for each DBA starts with a description of the accident scenario with the major assumptions identified. The accident source term is then determined. Source terms for the accidents have been obtained through phenomenological and system response calculations. Once a source term has been determined, onsite and offsite consequences are calculated for the atmospheric transport pathway. These consequences are then compared to evaluation guidelines for onsite consequences or release limits for offsite consequences for the identification of safety-class SSCs and TSRs.

1.2.1 Source-Term Composition

The bounding source term used for the accident analyses is based on data for the fuel in the K East and K West Basins given in HNF-SD-SNF-TI-009, *105-K Basin Material Design Basis Feed Description for Spent Nuclear Fuel Project Facilities*. HNF-SD-SNF-TI-009 defines an inventory for safety analysis by considering inventories of Mark IV, Mark IA, and single-pass reactor fuel in the K Basins. High-burnup Mark IV fuel, the fuel type that results in the highest estimated dose to people exposed to the material, was selected as the bounding inventory from the radiological dose perspective. Nuclear accountability records give the basis for the quantity, exposure variation, and decay time variation of the stored fuel. The radionuclide inventory was estimated from these data.

Table 1-2. Summary of Consequences for Bounding Design Basis Accidents.

Accident category	Chapter	Offsite consequences			Onsite consequences		
		Release limit (rem)	Unmitigated (rem)	Mitigated (rem)	Evaluation guideline (rem)	Unmitigated (rem)	Mitigated (rem)
Rearrangement of MCO internals	2	—	NC	Prevented	—	NC	Prevented
Gaseous release from MCO	3	0.5	0.11	1.1 E-04	1.0	300	0.3
MCO internal hydrogen explosion	4	0.5	0.11	Prevented	1.0	300	Prevented
MCO external hydrogen explosion	5	0.5	0.11	Prevented	1.0	300	Prevented
MCO thermal runaway reaction	6	0.5	Beyond extremely unlikely	Beyond extremely unlikely	1.0	Beyond extremely unlikely	Beyond extremely unlikely
Violation of design temperature criteria	7	—	Beyond extremely unlikely	Beyond extremely unlikely	—	Beyond extremely unlikely	—
Use of overpack tube for recovery actions	8	0.5	3.1 E-02	Prevented	1.0	81	Prevented

Note: Offsite release limits and onsite evaluation guidelines cited are for the "anticipated" event frequency category as provided in Sellers, E.D., 1997, *Risk Evaluation Guidelines (REGs) to Ensure Inherently Safer Designs* (Letter 97-SFD-172 to H. J. Hatch, Fluor Daniel Hanford, Incorporated, August 26), U.S. Department of Energy, Richland Operations Office, Richland, Washington.

MCO = multi-canister overpack.

NC = dose calculations provide no additional value because the equipment is already designated safety class for the prevention of the MCO criticality control violation.

The MCO contains finely divided particulate material associated with oxidation of the fuel. This material includes an oxide layer on the fuel and particulate remaining on fuel surfaces and in crevices after fuel washing and racking into the MCO as well as expected increases in oxidation products that occur during queuing at the K Basins and processing at the Cold Vacuum Drying Facility (CVDF). The particulate inventory of the MCO dominates the airborne release. The radionuclide inventory of the sludge also is based on the high-burnup Mark IV fuel, which will be verified when characterization results are available and will be documented in the final safety analysis report.

The spent nuclear fuel (SNF) is primarily uranium metal, which is known to have toxicological effects. Plutonium and other transuranic heavy metals also are present in small quantities but add little to the overall toxicity of the fuel. For example, if the toxic air

concentration limits for uranium are applied to neptunium, plutonium, americium, and curium, the "sum-of-fractions" indicator of toxicity (HNF-SD-SNF-TI-059) increases about 0.2%. Thus, the uranium content of SNF controls the potential health impacts downwind following a postulated accident. Uranium acts like many heavy metals to damage one or more internal organs of individuals exposed to high air concentrations. The toxicity depends on the solubility of the uranium, with more soluble compounds being a greater hazard because they are transferred from the respiratory tract into the blood more quickly.

Because any environmental release of SNF could have toxicological and radiological effects, both should be computed for comparison with consequence guidelines. A detailed comparison (HNF-SD-SNF-TI-059, Section 5.3) of the toxicological and radiological effects of airborne emissions leads to the conclusion that toxicological effects are normally less severe than the radiological effects. The only exceptions are accidents in which new chemical forms are introduced into the CSB and then released into the air. However, scenarios with new chemicals are considered to be beyond extremely unlikely (i.e., the accident frequency is less than 1×10^{-6} per year). The basic assumptions used to show that radiological effects are worse than toxicological effects are listed.

- The safety basis composition of SNF (HNF-SD-SNF-TI-015) was used in the comparison. The chemical forms were chosen to be the most limiting (i.e., smallest air concentration limits).
- The risk acceptance guidelines for chemical hazards are concentration limits for onsite and offsite receptors for three accident frequency categories. The risk acceptance guidelines for radiological hazards are 50-year committed effective dose equivalents for onsite and offsite receptors for the same three accident frequency categories. All combinations of receptor location and accident frequency were evaluated to determine whether chemical or radiological hazards dominated.
- Exposure duration is an important consideration for chemical hazards. For example, the permissible exposure limit—time-weighted average uses an 8-hour exposure time while the emergency response planning guidelines are based on a 1-hour exposure time. In general, the longer the exposure time, the lower the air concentration limit. The comparison analysis, using concentration limits with shorter exposure times, namely 1 minute for corrosives and 15 minutes for noncorrosives, was conservative. These shorter exposure times are based roughly on the physiological response times for the two broad categories of toxic chemicals. However, exposure times from postulated accidents may exceed the times inherent in the concentration limits. In these cases, the concentration limit is reduced proportionately.
- Because SNF contains no corrosive chemicals, only the 15-minute exposure time for noncorrosive chemicals was used in the comparison. This minimum averaging time for the air concentrations downwind leads to the conclusion that puff air transport factors are not appropriate for determining the air concentrations. Puff air transport factors can only be used for release durations of less than 8 minutes.

- The effects of radiological emissions are in all cases modeled using plume air transport factors regardless of the release duration. Because both the toxicological and radiological emissions for a given release duration will use the same air transport factors, the actual air transport factor has no effect on the comparison ratios that were calculated to quantify the relative hazard.

For both the onsite and offsite receptors at all accident frequency categories, the radiological effects are greater than the toxicological effects of an airborne emission. Therefore, the toxicological consequences of the postulated airborne releases will not require mitigating features beyond those required by the radiological consequences.

No routine chemical processes will be conducted in the CSB. Purging and backfilling the MCOs will involve the use of an inert gas (helium). Some chemicals, such as those used for equipment decontamination, may be used occasionally (HNF-SD-SNF-CM-001). However, there are no chemical inventories of concern for safety analysis considerations.

1.2.2 Consequence Analysis

Radiological inhalation dose consequences (D) for each analyzed accident are based on the following factors:

- Mass of respirable material available for release (M)
- Material at risk (MAR)
- Release fraction
- Leak path factor
- Atmospheric transport and dispersion of airborne particles (χ/Q')
- Duration of exposure
- Breathing rates¹ (BR)
- Dose conversion factors (UD).

¹The 12-hour breathing rate is $3.33 \times 10^{-4} \text{ m}^3/\text{s}$, and the 24-hour breathing rate is $2.64 \times 10^{-4} \text{ m}^3/\text{s}$ (HNF-SD-SNF-TI-059).

The radiological dose to a maximum receptor of interest is typically determined by using the following equation:

$$D = M \times \frac{\chi}{Q'} \times BR \times UD$$

where

- D = effective dose equivalent (rem)
- M = mass of respirable airborne material released (g)
- χ/Q' = time-integrated atmospheric transport factor (s/m³)
- BR = breathing rate (m³/s)
- UD = dose per unit mass of radioactive material inhaled (rem/g),
4.38 x 10⁵ rem/g of uranium (HNF-SD-SNF-TI-059).

The quantity of respirable material released (M) is determined by the specific CSB accident scenario. The quantity (M) is a function of the MAR, the release fraction (RF), and the leak path factor of any passive structural enclosure that may cause deposition of an airborne release before the release enters the atmosphere. The leak path factor is based on a time-integrated calculation of aerosol deposition within a release from an enclosure of given dimensions with specified leakage area, pressure, and temperature differentials. The specific value of each parameter is determined in the individual DBA analysis and based on the physical phenomena of the accident; thus, they are specific to the CSB.

The atmospheric transport factor (χ/Q') is based on specific release conditions (e.g., ground level or elevated, long or short duration) and the receptor's distance from the release. While the methodology is common to the SNF Project, the atmospheric transport factor is the time-integrated normalized air concentration at the receptor's location, which is a measured distance from the CSB. The transport factor includes the dilution of an airborne contaminant caused by atmospheric mixing and turbulence. The air transport values used in this report have been generated using the GXQ (WHC-SD-GN-SWD-30002, Version 4.0). GXQ is a FORTRAN program for calculating atmospheric dispersion using site-specific wind data. It uses the Gaussian straight line model for both instantaneous and continuous releases. Several models are available that modify parameters within the Gaussian plume model to account for phenomena such as plume depletion, building wake, plume meander, gravitational settling, and plume rise. The treatment of site wind data is also subject to user controls to allow various frequencies of exceedance to be computed. GXQ is intended to be used by individuals who are knowledgeable of the limits and applicability of the models implemented. The program has been tested and verified to implement its calculational models correctly (WHC-SD-GN-SWD-30003). Table 1-3 shows maximum individual receptor locations and air transport factors for ground-level releases.

Table 1-3. Canister Storage Building Maximum Individual Locations and Air Transport Factors for Ground-Level Releases.

Receptor type	Air transport factors, s/m ³
	<1 hour
Onsite worker 100 m east	3.41 E-02
Highway 240 9,280 m west	2.36 E-05
Hanford Site boundary 17,390 m east	1.30 E-05

Air transport factors were calculated using methods found in U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.145, *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants*. In each wind direction the observed frequencies of particular wind speed and stability class combinations are used to compute χ/Q' . For the accident analysis, the higher of either the 99.5% sector-dependent or the 95% overall value is used. This is repeated for all 16 compass directions to determine the worst-case location. For the SNF Project facilities the sector maximum (0.5%) is always greater than the overall site value (5.0%) for ground-level releases (HNF-SD-SNF-TI-059).

Exposures to the collocated worker onsite are bounded by the individual at the 100 m location. The risk evaluation guidelines apply to this individual. Exposures to members of the public are bounded by the individuals located on Washington State Highway 240 and at the Hanford Site boundary. For assessment purposes, DOE has directed (Sellers 1996) that the Hanford Site boundary be considered the location of the offsite receptor. Consequences at the Highway 240 location are included for reference only. Note that distances to the Hanford Site boundary and to the nearest public access locations onsite were computed using the methodology described in NRC Regulatory Guide 1.145. In this approach, the shortest distance in a 45° sector centered on the direction of interest is chosen for each of the 16 compass directions.

None of the accidents analyzed in this document adjusts the air transport factors for the finite size of the source (i.e., building wake effects) or for the elevation of the release above ground level (the stack is not high enough relative to the operation building to justify using elevated release). It is always conservative to ignore building wake and stack effects because both of these effects serve to disperse the release such that the collocated worker and the offsite receptor will receive a lower estimated dose if the effect is included. As an additional conservatism, all accidents were evaluated using the calculated air transport factors for less than one hour (HNF-SD-SNF-TI-059). However, the duration of the release does affect the air values. Durations less than 1 hour use a point source model. Durations from 1 hour to 2 hours add the effect of plume meander. Air transport factors for longer periods (i.e., 12 and 24 hours) are calculated from the 2-hour and annual average values according to the method in NRC Regulatory Guide 1.145.

For accident analyses without controls, dose calculations for the maximum onsite individual assume that the individual remains at a distance of 100 m (328 ft) for the duration of plume passage up to a maximum of 12 hours. The 12-hour maximum duration is chosen because it is the normal shift for operating personnel. Dose calculations for the maximum offsite individual assume that the individual remains at the worst-case distance for the duration of plume passage up to a maximum of 24 hours. The 24-hour maximum duration is judged to be an appropriate endpoint for consequence calculations based on the premise that the offsite individual can be notified and appropriate corrective action taken within 24 hours of the start of the accident. For accident analysis with controls, a different exposure duration may be used based on a demonstrated ability to detect the accident and protect the receptor.

The dose per unit intake is the 50-year dose commitment for all relevant exposure pathways per gram of radioactive material released (HNF-SD-SNF-TI-059). The major radiation exposure pathway for the identified accidents is inhalation of radioactive material. Dose contributions from the submersion pathway were calculated and found to be negligible with respect to the total dose for the radionuclides of interest (HNF-SD-SNF-TI-059). Doses from groundshine also are expected to be negligible because most of the radionuclides of interest are alpha emitters. Therefore, the doses from groundshine and submersion are not included in the radiological dose calculations.

Potential doses from the ingestion pathway are not considered because DOE, state, and federal emergency preparedness plans limit ingestion of contaminated food in the event of an accident. DOE/RL-94-02, *Hanford Emergency Response Plan*, governs emergency response for all Hanford Site facilities. The primary determinant of exposure from the ingestion pathway is the effectiveness of public health measures (i.e., interdiction) rather than the severity of the accident itself. Ingestion, if it occurs, involves a relatively slow-to-develop pathway and is not considered an immediate threat to an exposed population in the same sense as the inhalation pathway. In addition, calculations in HNF-SD-SNF-TI-059, *A Discussion on the Methodology for Calculating Radiological and Toxicological Consequences for the Spent Nuclear Fuel Project at the Hanford Site*, show that the contribution of ingestion to the total dose is negligible compared to the inhalation contribution.

Table 1-4 shows the composition of the K Basins fuel used to determine the committed effective dose equivalent per gram of respirable release. Nuclides with minor contributions (less than 0.1 mrem/g) are not shown. Isotopes of plutonium, americium, and curium constitute 99.5% of the total inhalation dose. The specific dose for the safety analysis inventory is 4.38×10^5 rem/g. The values shown for the dose per unit respirable radioactive material inhaled (UD) are the product of the activity and the dose conversion factor found in EPA Federal Guidance Report Number 11, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*. The dose conversion factor for tritium was increased by 50% to account for skin absorption (ICRP Publication 30). The committed effective dose equivalent for ^{85}Kr is the submersion dose factor from EPA Federal Guidance Report Number 12, *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents*, divided by the light activity breathing rate.

Table 1-4. Composition of K Basins Fuel and the Dose per Unit of Intake. (2 sheets)

Radionuclide	Activity (Ci/MTU) ^a	CEDE per unit intake ^b (rem/g)
³ H	2.61 E+01	2.5 E-03
¹⁴ C	5.53 E-01	1.2 E-03
⁶⁰ Co	2.09 E+00	4.6 E-01
⁸⁵ Kr	3.70 E+02	4.9 E-04
⁹⁰ Sr ^c	6.93 E+03	1.7 E+03
⁹⁹ Tc	2.19 E+00	1.8 E-02
^{113m} Cd	2.78 E+00	4.3 E+00
¹³⁴ Cs	6.47 E+00	3.0 E-01
¹³⁷ Cs ^c	9.66 E+03	3.1 E+02
¹⁴⁷ Pm	1.09 E+02	4.3 E+00
¹⁵¹ Sm	1.02 E+02	3.1 E+00
¹⁵² Eu	8.45 E-01	1.9 E-03
¹⁵⁴ Eu	1.13 E+02	3.2 E+01
¹⁵⁵ Eu	1.06 E+01	4.4 E-01
²³⁴ U	3.84 E-01	5.1 E+01
²³⁵ U ^c	1.27 E-02	1.6 E+00
²³⁶ U	7.16 E-02	9.0 E+00
²³⁸ U ^c	3.31 E-01	3.9 E+01
²³⁷ Np ^c	4.66 E-02	2.5 E+01
²³⁸ Pu	1.33 E+02	5.2 E+04
²³⁹ Pu	1.73 E+02	7.4 E+04
²⁴⁰ Pu	1.37 E+02	5.9 E+04
²⁴¹ Pu ^c	6.82 E+03	5.6 E+04
²⁴² Pu	8.71 E-02	3.6 E+01
²⁴¹ Am	4.34 E+02	1.9 E+05
^{242m} Am ^c	3.72 E-01	1.6 E+02
²⁴³ Am ^c	2.78 E-01	1.2 E+02

Table 1-4. Composition of K Basins Fuel and the Dose per Unit of Intake. (2 sheets)

Radionuclide	Activity (Ci/MTU) ^a	CEDE per unit intake ^b (rem/g)
²⁴⁴ Cm	4.47 E+00	1.1 E+03
⁵⁵ Fe	5.41 E-01	1.5 E-03
⁶³ Ni	3.47 E+00	2.2 E-02
⁷⁹ Se	6.54 E-02	6.4 E-04
⁹³ Zr	2.95 E-01	9.5 E-02
^{93m} Nb	1.93 E-01	5.6 E-02
¹⁰⁶ Ru ^c	2.56 E-02	1.2 E-02
¹⁰⁷ Pd	1.56 E-02	2.0 E-04
^{121m} Sn ^c	6.27 E-02	7.2 E-04
¹²⁶ Sn ^c	1.29 E-01	1.3 E-02
¹²⁹ I	5.16 E-03	9.0 E-04
¹³⁵ Cs	6.04 E-02	2.8 E-04
¹⁴⁴ Ce ^c	7.91 E-04	3.0 E-04
²⁴⁴ Cm	4.47 E+00	1.1 E+03
Total	—	4.38 E+05

^aCombined K Basins inventories decayed to May 31, 1998: 1.0 Ci = 3.7×10^{10} Bq.

^bFifty-year committed effective dose equivalent. The total was calculated by spreadsheet retaining three significant figures.

^cThe following short-lived progeny nuclides are not shown in the table: ⁹⁰Y, ^{137m}Ba, ¹⁰⁶Rh, ¹²¹Sn, ^{126m}Sb, ^{144m}Pr, ¹⁴⁴Pr, ²³¹Th, ²³⁴Th, ²³³Pa, ²³⁴Pa, ^{234m}Pa, ²³⁷U, ²³⁸Np, ²⁴²Am, and ²⁴²Cm. These nuclides are found in secular equilibrium with the parent nuclide. Their dose contributions are included in the CEDE value shown for the parent nuclide.

MTU = metric ton of uranium.

CEDE = committed effective dose equivalent.

1.2.3 Toxicological Effects

The SNF is primarily uranium metal, which is known to have toxicological effects. Plutonium and other transuranic heavy metals also are present in small quantities but add little to the overall toxicity of the fuel. For example, if the toxic air concentration limits for uranium are applied to neptunium, plutonium, americium, and curium, the "sum-of-fractions" indicator of toxicity increases about 0.2% (HNF-SD-SNF-TI-059). Thus, the uranium content of SNF controls the potential health impacts downwind following a postulated accident. Uranium acts like many heavy metals to damage one or more internal organs of individuals exposed to high air concentrations. The toxicity depends on the solubility of the uranium, with more soluble compounds being a greater hazard because they are transferred from the respiratory tract into the blood more quickly. The chemical form of radiological isotopes that is most soluble (toxic) was assumed when determining the toxicological effects.

No routine chemical processes are conducted in the SNF Project facilities. Purging and backfilling the MCOs involves the use of an inert gas (helium). Some chemicals, such as those used for equipment decontamination, may be used occasionally (HNF-SD-SNF-CM-001). However, there are no chemical inventories of concern for safety analysis considerations.

1.2.4 Risk Guidelines

The DOE-recommended radiological risk evaluation guidelines (Sellers 1997) are shown in Table 1-5. These criteria for identifying safety-class SSCs implement the guidance of DOE Order 6430.1A, Section 1300-1.4, "Guidance on Limiting Exposure of the Public," and are consistent with the graded approach to safety required by DOE Order 5480.23, *Nuclear Safety Analysis Reports*.

Table 1-5. Radiological Evaluation Guidelines and Limits.

Event category	Frequency range (per year)	Onsite risk evaluation guidelines,* rem	Offsite accident release limits,* rem
Anticipated	1.0 E-01 to 1.0 E-02	1 (5)	0.5 (0.5)
Unlikely	1.0 E-02 to 1.0 E-04	10 (25)	5.0 (5)
Extremely unlikely	1.0 E-04 to 1.0 E-06	25 (100)	5.0 (25)

Note: All doses are committed effective dose equivalents.

*This terminology is consistent with Tables 1 and 2 of Sellers, E. D., 1997, *Risk Evaluation Guidelines (REGs) to Ensure Inherently Safer Designs* (Letter 97-SFD-172 to H. J. Hatch, Fluor Daniel Hanford, Incorporated, August 26), U.S. Department of Energy, Richland Operations Office, Richland, Washington. These SNF Project guidelines are more conservative than the values in HNF-PRO-705, *Safety Basis Planning, Documentation, Review, and Approval*, Fluor Daniel Hanford, Incorporated, Richland, Washington (shown in parentheses).

As stated in HNF-PRO-704, *Hazard and Accident Analysis Process*, satisfaction of its radiological evaluation guidelines meet the goals of SEN-35-91, *Nuclear Safety Policy*. However, the guidelines used by the SNF Project (Sellers 1997) are more conservative and are bounded by the guidelines specified in HNF-PRO-704, Table D-1. As such, satisfaction of the SNF Project radiological evaluation guidelines (Sellers 1997) will meet the goals of SEN-35-91. As discussed in future sections, the mitigated DBAs using the identified preventive and mitigative SSC features met the SNF Project radiological evaluation guidelines (Sellers 1997) and, consequently, the goals of SEN-35-91.

1.2.5 Limiting Design Basis Accident Assumptions

Based on limiting values assumed in the hazard and DBA analyses, the interface between the CVDF and the CSB requires that an MCO delivered from the CVDF to the CSB contain less than 200 g of free water and confine combustible hydrogen gases within the mechanically sealed MCOs. In addition, the CSB hazard and DBA analyses rely on the interface between the K Basins facility and the CVDF that requires the SNF delivered from the K Basins to the CVDF and the CSB to be sufficiently clean fuel (i.e., with cladding surfaces sufficiently free of aluminum hydroxides, uranium hydrides, uranium dioxides, and other surface contaminants) and the fuel loading to be controlled (e.g., the number of scrap baskets loaded into each MCO). The assumptions associated with the K Basins and CVDF performance are identified in Table 1-6. Safety-related performance documentation from the K Basins and the CVDF is relied on to ensure that the as-received content and condition of the MCO is as required for safety basis properties.

Table 1-6. Key K Basins and Cold Vacuum Drying Facility Performance Assumptions.

Facility	Performance parameter	Parameter	
		Value	Equivalent water mass
K Basins	Maximum mass of aluminum hydroxide in an MCO delivered to the CSB	49 kg*	16.8 kg*
K Basins	Maximum mass of uranium hydrates in an MCO delivered to the CSB	10.6 kg	0.56 kg
K Basins	Maximum number of scrap baskets in an MCO delivered to the CSB	2 scrap baskets	NA
K Basins	Maximum removable, not strongly adherent, UO ₂ particulate in an MCO delivered to the CSB	34 kg of UO ₂ particulate	NA
CVDF	Maximum free water in an MCO delivered to the CSB	200 g	200 g
CVDF	Leak rate of internal gas from MCO	<10 ⁻⁵ standard cm ³ /s	NA
CVDF	MCO pressurized with inert gas	1.5 atm helium at <25 °C	
CSB	Quantities of water moisture introduced into the MCO during sampling operations do not exceed "equivalent water mass" from aluminum hydroxide and uranium hydrates in an MCO delivered to the CSB per above	Quantities resulting in "equivalent water mass" from aluminum hydroxide and uranium hydrates in an MCO delivered to the CSB per above	17.56 kg

*This is the maximum based on long-term radiolysis; the thermal runaway case uses the HNF-SD-SNF-TI-015, 1997, *Spent Nuclear Fuel Project Technical Databook*, Rev. 0, Rev. 2, and ECN 645061, Fluor Daniel Hanford, Incorporated, Richland, Washington, value of 10.65 kg Al(OH)₃ which corresponds to 3.73 kg water.

CSB = Canister Storage Building.

CVDF = Cold Vacuum Drying Facility.

MCO = multi-canister overpack.

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2.0 REARRANGEMENT OF MULTI-CANISTER OVERPACK INTERNALS

2.1 PURPOSE AND OBJECTIVES

If the multi-canister overpack (MCO) were to be subjected to an accidental drop, impact, or shear force of sufficient magnitude, then the MCO or the cask-MCO could be damaged in such a way as to breach the MCO or to substantially rearrange its internal geometry. A number of potential accidents have been identified at the Canister Storage Building (CSB) and are listed in Section 2.2. Five of these accidents are selected for further discussion or evaluation. While some of the cases could lead to radiological dose consequences or to a violation of criticality geometry control criteria, these scenarios are either prevented or mitigated so that no violation or significant release may occur, or are determined to occur so infrequently ($<10^{-6}/\text{yr}$) that they do not need to be considered. These cases are prevented or significantly mitigated by design and control features associated with the CSB or MCO handling machine (MHM). Required controls for each accident are summarized in Section 2.6.

2.2 SCENARIO DEVELOPMENT

At the CSB the MCO is hoisted by both the receiving crane and the MHM. The MCO could be dropped, either when it is inside the transportation cask or when it is outside the cask. Objects (e.g., the transportation cask lid) also are hoisted above the MCO, creating the potential for a drop onto the MCO. Other building equipment could move and collide with the MCO or the transportation cask. Several different scenarios that could cause rearrangement of MCO internals were considered, all of which were considered potentially serious hazards to the MCO in the CSB hazard analysis (HNF-SD-SNF-HIE-001). These scenarios include the following:

- Cask-MCO drop from the receiving crane
- Cask lid drop onto the MCO
- Drop of an MCO by the MHM
- Shear of an MCO by the MHM.

The translational movement of the CSB receiving crane and the MHM and the rotational movement of the MHM turret provide mechanisms for applying lateral or shear forces to the side of the MCO. If the MHM were operated without the provided interlocks, sufficient rotational or translational forces could damage the MCO by the MHM because of operator error (requesting translational or rotational drive operation at an inappropriate time), MHM malfunction (drive actuation without operator request), or an earthquake. These shear forces could be applied when the MCO extends across two regions that can translate or rotate with respect to one another, such as when the MCO is partially lowered below the CSB deck into a storage tube or partially lowered below the MHM turret-base interface. An accident in which lateral forces are applied to the MCO, resulting in possible breach of confinement and loss of criticality geometry control of the fuel, is considered to be the bounding impact force design basis accident for the accident grouping involving the rearrangement of MCO internals.

Simple calculations have not demonstrated that the MCO could withstand shearing forces generated during any of the above-listed unmitigated accidents; therefore, each accident is assumed to result potentially in a complete shear of the MCO. MCO containment and geometry must not be allowed to be breached or significantly altered because an MCO provides both primary containment and nuclear criticality configuration control of the spent nuclear fuel. Equipment or controls that protect the MCO and prevent violations of criticality limits are considered safety class (DOE Order 6430.1A). Because such equipment and controls must be designated safety class, it is not necessary to perform radiological consequence analysis for accidents that could violate criticality limits. Dose consequence analysis could not prescribe more stringent safety classifications than those already required to protect the MCO and to protect against criticality contingencies.

An MCO must continue to meet several conditions during any drop, impact, or shear accident. Three geometry constraints must be satisfied to maintain criticality control: (1) the axis of the basket center criticality insert (6.6-in. pipe) must be maintained within 2 in. of the MCO centerline, (2) the inside MCO circumference must not exceed 73.04 in., and (3) the spent nuclear fuel contents in the MCO must be maintained within the MCO (HNF-SD-SNF-CSER-005). Because the MCO does not contain significant water while at the CSB, a criticality will not occur because any or all of these geometry controls are violated (double contingency is satisfied).

All MCO lateral force (shear) accidents with potentially unacceptable consequences have been prevented by safety-class MHM interlock controls. A discussion of the MHM interlocks is included in HNF-3553, *Spent Nuclear Fuel Project Final Safety Analysis Report*, Annex A, "Canister Storage Building Final Safety Analysis Report," Chapter A4.0, "Safety Structures, Systems, and Components."

A shear of an MCO by the MHM was identified in the CSB hazard analysis (HNF-SD-SNF-HIE-001) as a potentially significant accident (designator: SA-E-07, SA-F-07b, OA-E-07, OA-F-07, WS-E-07, WS-F-07). Because such an accident has the potential to cause the most damage to an MCO in terms of its fuel confinement and containment safety functions, it is considered to bound the consequences of all other accidents that could rearrange the MCO internals. Shear forces could be applied to the MCO during an unmitigated accident by MHM rotational or translational movement resulting from operator error, MHM malfunction or failure, or a seismic event. It is also postulated that the turret rotation could shear the MCO hoist cable and result in a drop of the MCO. Neither of these turret rotation accidents can occur unless one of several safety-class MHM interlocks (P6, P80, P9) is defeated. MHM interlock P9 ensures that the turret seismic restraints are applied before operating the MCO hoist. MHM interlocks P6 and P80 ensure that the turret seismic restraints cannot be disengaged and that power is not supplied to the turret rotate motor unless the MCO is fully raised in the MHM. Shear of an MCO by the MHM may be possible during a seismic event if the MCO is partially inserted in a storage tube, a pit, or the transport cask. Lateral movement of the massive MHM during a design basis earthquake could shear the MCO. Seismic restraints on the MHM trolley and gantry will prevent significant lateral movement when the restraints are applied. The MHM also could apply significant lateral forces against an MCO if the bridge or trolley drives were activated by operator error or MHM malfunction while the MCO was partially lowered from the MHM. MHM interlock P21 prevents the raising or lowering of the MCO hoist unless the bridge and

trolley seismic restraints are applied. MHM interlocks (P3, P6, P8, P26, P80) prevent the disengagement of the bridge and turret seismic restraints and interrupts bridge and trolley drive motor power unless the MCO is fully raised.

Consistent with credible drop scenarios developed from the CSB hazard analysis, MCO and cask-MCO drop analyses have been performed for different conceivable drop events. These analyses have been performed for a representative set of identified drop events that are not prevented by safety features. Drop event analyses have been performed for different orientations of the MCO (or dropped object) and assuming different material properties to ensure that the calculated effects of the drop events were thoroughly investigated and well understood. To demonstrate that all possible drop/shear scenarios have been considered and either explicitly analyzed or bounded by similar analyzed events, each process step during the MCO lifetime at the CSB is listed chronologically in Table 2-1 with any considered drop/shear scenarios. Drop accident scenarios that could occur during transportation to or from the CSB are discussed in HNF-SD-TP-SARP-017, *Safety Analysis Report for Packaging (Onsite) Multicanister Overpack Cask*.

2.2.1 Cask-Multi-Canister Overpack Drop from Receiving Crane

Conceivable cask-MCO drop events from the receiving crane were identified in the CSB hazard analysis (HNF-SD-SNF-HIE-001) as potential significant accidents (designator: TV-G-09, TV-G-13, SA-G-03b). The CSB receiving crane has been designated a safety-significant and important-to-safety piece of equipment. The crane only provides a single-load path but is rated for twice the load required for a safety-significant hoist. The crane is used to lift the cask-MCO from the transport trailer using a yoke. The crane is then translated to place the cask-MCO above the service station pit, and the cask-MCO is lowered into the pit. The cask-MCO could be dropped from the receiving crane at any location the crane travels while suspending the cask-MCO. Drops 3 through 8, listed in Table 2-1, represent each distinct drop event possible during a receiving crane operation. Any of these drop events could occur as a result of a failure in the lift system (e.g., the hook, hoist rope, cask yoke) or as a result of improper connections of the load to the hoist. Because the crane is designed to ASME NOG-1, *Rules for Construction of Overhead and Gantry Cranes (Top Running Bridge, Multiple Girder)*, Type I criteria, the crane load should remain suspended during and after a design basis earthquake event. The drop from the receiving crane that impacts the transporter and results in a horizontal slap-down of the cask-MCO onto the concrete receiving area is the bounding unmitigated scenario for all possible receiving crane drops and provides the bounding unmitigated consequences. Recently, however, the Spent Nuclear Fuel (SNF) Project has implemented a prevention system for this drop. The cask transfer safety system is designed to prevent a dropped cask-MCO from impacting the floor during offloading from the transport trailer. The absorbing material collapses if a cask is dropped on it and cushions the cask. The restraints prevent the cask from tipping and falling on its side (slap down) in an unlikely event that the cask is dropped. The cask transfer safety system provides protection for the cask-MCO as it is being transferred from the transporter to the receiving pit. Other drops from the receiving crane that could have worse consequences have been reduced in frequency sufficiently to claim that they have been prevented.

Table 2-1. Multi-Canister Overpack Process Steps and Possible Drop, Shear, or Impact Scenarios. (5 sheets)

Drop shear	Process step or event	Drop/shear/impact description	Credible	Analyzed	MCO fail	Prevented	Safety controls, consequences, and comments
1	Cask-MCO transported to CSB	See the safety analysis report for packaging ^a					See the safety analysis report for packaging. ^a
2	Remove tractor	None	N				NA
3	Cask-MCO moved by the receiving crane to the MCO service station pit	Cask-MCO drop onto trailer edge with horizontal slap-down onto floor. Drop height: 40 in.	Y	Y	N	Y	Cask transfer safety system. ^b
4		Cask-MCO vertical drop directly onto concrete floor	Y	Y	N	Y	Cask transfer safety system. ^c
5		Cask-MCO drop onto edge of service pit with slap-down	Y	Y	N	N	The consequences for this drop are bounded by analyses for the drop onto trailer edge with horizontal slap-down (drop 3).
6		Cask-MCO drop into service pit	Y	Y	N	N	This drop is not expected to violate MCO containment or criticality geometry control. ^c
7		Cask-MCO shear by moving receiving crane while partially lowered into pit	Y	Y	N	N	Shear forces not sufficient to significantly damage the MCO because of the transportation cask. ^d
8		Cask-MCO drop onto edge of maintenance pit with horizontal slap-down into pit floor	Y	N	Y	Y	This drop could lead to a 2 in. deflection of the MCO center tube, violating a criticality safety criteria. A resolver and interlock on receiving crane movement will prevent this event.
9		MHM shears the MCO by colliding with the crane and cask-MCO as the cask-MCO is lowered into the pit	Y	N	N	Y	Interlocks do not allow the MHM to enter the service area while the receiving crane is present. Analysis demonstrates that, in this accident, the transportation cask prevents unacceptable MCO damage. ^d
10	Cask yoke removal	Drop yoke onto cask lid	Y	N	N	N	Insufficient force to damage MCO through cask lid.

Table 2-1. Multi-Canister Overpack Process Steps and Possible Drop, Shear, or Impact Scenarios. (5 sheets)

Drop shear	Process step or event	Drop/shear/impact description	Credible	Analyzed	MCO fail	Prevented	Safety controls, consequences, and comments
11	Cask lid removal using service station gantry hoist	Drop cask lid onto MCO	Y	Y	N	N	Analysis of this drop demonstrates that the structural containment of the MCO is not breached and that criticality geometry control is not compromised. ^{b,c} The port cover-to-flange seal may be broken. If the rupture disk were to release from over-pressurization, an MCO blow-down could occur.
12	Seismic event	CSB facility structure falls on MCO	N	N	Y	Y	The CSB facility is seismically qualified. ^e This drop is incredible.
13	Tent removal and radiation survey	None	N	N	N	NA	NA
14	MCO retrieved from cask in service pit into the MHM ^f	Drop service pit plug onto MCO	N	N	N	Y	The design of plug and pit shield make it geometrically impossible for this drop to impact the MCO.
15		Drop MCO onto edge of cask	N	Y	N	Y	This drop is not expected to violate MCO containment or criticality geometry control. ^e Drop likelihood is reduced by MHM interlocks (P61, P62, P66) and grapple design.
16		Drop MCO back into cask. Could be caused by shear of MCO hoist by improper turret rotation	N	Y	N	Y	This drop is not expected to violate MCO containment or criticality geometry control. ^e Drop likelihood is reduced by MHM interlocks (P61, P62, P66) and grapple design. Consequences of a drop from shear of hoist are bounded by drop 11.
17	Seismic event	Shear MCO by moving MHM with MCO only partially retrieved into the MHM cask	N	N	Y	Y	This shear is prevented by MHM SC interlocks (P3, P8, P6, P9, P21, P26, P80).
18		Shear MCO while partially inserted into service station pit or storage tube during a DBE.	Y	N	Y	Y	This shear is prevented by MHM SC seismic restraints and SC interlocks (P3, P6, P8, P21, P26, P80).
19		Cause MHM to fall onto operating deck, resulting in major structural damage to deck	Y	Y	N	Y	This drop is prevented by the MHM seismic restraints and SC interlocks (P3, P21) that ensure their operation.

Table 2-1. Multi-Canister Overpack Process Steps and Possible Drop, Shear, or Impact Scenarios. (5 sheets)

Drop shear	Process step or event	Drop/shear/impact description	Credible	Analyzed	MCO fail	Prevented	Safety controls, consequences, and comments
20	MCO transported to storage tube or sampling/weld station	Shear MCO by rotating turret with MCO only partially retracted into MHM cask	Y	N	N	Y	This shear is prevented by MHM SC interlocks (P9, P6, P80).
21		Drop MCO within MHM MCO cask tube onto MHM turret deck	Y	N	N	Y	Drop likelihood is reduced by MHM interlocks (P61, P62, P66) and grapple design. Consequences bounded by drop 28.
22		Drop MCO onto CSB deck or over empty tubes or over empty pits (i.e., maintenance pit, exchange facility pit)	Y	N	Y	Y	Drop into pits is prevented by MHM SC interlocks (P3, P8, P26, P85, P80) and grapple design.
23	Install intermediate impact absorber on MCO	Drop limiter on MCO - reduce limiter effectiveness	Y	N	N	Y	Drop likelihood is reduced by MHM interlocks (P61, P62, P66) and grapple design. Limiter effectiveness should not be greatly reduced.
24	MCO placed in storage tube or sampling/weld station	Shear MCO or MHM grapple cable by translating MHM with MCO only partially deployed into the storage tube	Y	N	Y	Y	This shear is prevented by MHM SC interlocks (P3, P8, P6, P21, P26, P80).
25		Shear MCO by rotating MHM turret with MCO only partially retracted into MHM cask	Y	N	N	Y	This shear is prevented by MHM SC interlocks (P6, P9, P80).
26		Drop MCO onto impact absorber in storage tube	N	N	N	Y	Drop likelihood is reduced by SC MHM interlocks (P61, P62, P66) and grapple design. Consequences are prevented by SC impact absorber. Drop frequency is determined to be incredible.
27		Drop MCO into empty storage tube (no impact absorber)	N ^r	N	Y	Y	Impact absorber is integral part of storage tube design and fabrication. This drop scenario is considered incredible.
28		Drop MCO onto another MCO in storage tube (no intermediate limiter)	N ^r	N	Y	Y	Drop likelihood is reduced by MHM interlocks (P61, P62, P66) and grapple design. Consequences are prevented by SC impact absorber under original MCO. This drop scenario is considered incredible.

Table 2-1. Multi-Canister Overpack Process Steps and Possible Drop, Shear, or Impact Scenarios. (5 sheets)

Drop shear	Process step or event	Drop/shear/impact description	Credible	Analyzed	MCO fail	Prevented	Safety controls, consequences, and comments
29		Drop MCO onto impact absorber above existing MCO	N ^f	N	N	Y	Drop likelihood is reduced by MHM interlocks (P61, P62, P66) and grapple design. Consequences are mitigated by SC impact absorber under original MCO. Consequences are further reduced by intermediate impact absorber. This drop scenario is considered incredible.
30		Drop MCO onto storage tube plug	Y	N	Y	Y	Drop likelihood is reduced by MHM interlocks (P61, P62, P66) and grapple design. Consequences are bounded by MCO blow-down.
31		Drop MCO onto edge of storage tube	N ^f	N	Y	Y	Drop likelihood is reduced by MHM interlocks (P61, P62, P66) and grapple design. Consequences are bounded by MCO blow-down. This drop scenario is considered incredible.
32		Drop storage tube plug onto MCO	N	N	N	Y	Design of plug and tube embed make it geometrically impossible for this drop to impact MCO.
33	Seismic event	MCO (1 or 2) experiences unacceptable damage from impact forces during seismic event while stored in storage tube	Y	Y	N	Y	Storage tube assembly design and construction will withstand DBE forces and protect the MCO from unacceptable damage. ^g
34	MCO retrieved from storage tube or sampling/weld station	Shear MCO or MHM grapple cable by moving MHM with MCO only partially retrieved from the storage tube	Y	N	Y	Y	This shear is prevented by MHM SC interlocks (P3, P8, P6, P21, P26, P80).
35		Shear MCO by rotating turret with MCO only partially retracted into MHM cask	Y	N	N	Y	This shear is prevented by an MHM SC interlocks (P6, P9, P80).
36		Drop MCO onto impact absorber in storage tube	N ^f	N	N	Y	Drop likelihood is reduced by MHM SC interlocks (P61, P62, P66) and grapple design. Consequences are prevented by SC impact absorber. This drop scenario is considered incredible.

Table 2-1. Multi-Canister Overpack Process Steps and Possible Drop, Shear, or Impact Scenarios. (5 sheets)

Drop shear	Process step or event	Drop/shear/impact description	Credible	Analyzed	MCO fail	Prevented	Safety controls, consequences, and comments
37		Drop MCO onto a previously crushed impact absorber (MCO was dropped when originally inserted)	N ^f	N	Y	Y	Drop likelihood is reduced by MHM interlocks (P61, P62, P66) and grapple design. Previously crushed impact absorber may still provide some mitigation of MCO damage. This drop scenario is considered incredible.

Note: MHM SC interlock descriptions may be found in HNF-3553, 1999, *Spent Nuclear Fuel Project Final Safety Analysis Report*, Annex A, "Canister Storage Building Final Safety Analysis Report," Chapter A4.0, "Safety Structures, Systems, and Components," Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^aHNF-SD-TP-SARP-017, 1997, *Safety Analysis Report for Packaging (Onsite) Multicanister Overpack Cask*, Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^bHNF-SD-SNF-DP-010, 1997, *Cask and MCO Drop onto the Transport Trailer Edge with Subsequent Horizontal Slap Down onto the CSB Receiving Area Floor*, Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^cHNF-SD-SNF-DP-007, 1997, *Multi-Canister Overpack/Cask Drop Analysis File Documentation*, Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^dPetersen, S. L. 1998, *MHM Collision with Cask/MCO* (Transmittal FDT-137 to A. S. Daughtridge, D&ES Hanford, November 30), Fluor Daniel Hanford, Incorporated, Richland, Washington.

^eWHC-SD-SNF-DB-009, 1996, *Canister Storage Building Natural Phenomena Hazards*, Rev. 4, Westinghouse Hanford Company, Richland, Washington.

^fThese drops recently were considered incredible per SNF-4087, *The Frequency of a Multi-Canister Overpack (MCO) Drop by the Multi-Canister Overpack Handling Machine (MHM)*, Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^gCSB-S-0007A, 1996, *Storage Tube Analysis Confirmation*, Fluor Daniel Hanford, Incorporated, Richland, Washington.

CSB = Canister Storage Building.

DBE = design basis earthquake.

MCO = multi-canister overpack.

MHM = multi-canister overpack handling machine.

N = No.

NA = not applicable.

SC = safety class.

Y = Yes.

A drop of the cask-MCO from a height of 40 in. with a subsequent slap-down onto the CSB receiving area concrete floor (drop 3) has been shown to result in no releases of radioactivity and no loss of criticality configuration control (HNF-SD-SNF-DP-010). The cask transfer safety system prevents or mitigates this drop.

The consequences of a cask-MCO drop by the receiving crane into the maintenance pit (drop 8, height greater than 40 in.) with a slap-down have not been determined. Based on the results from a similar analysis (HNF-SD-SNF-DP-007), it is expected that such an accident would damage the MCO center tube geometry sufficiently to cause a criticality specification violation. While definitive supporting calculations do not exist, no radiological releases or associated onsite (100 m) or offsite dose consequences are expected from such an accident because of the structural protection provided by the cask. This accident frequency is reduced to beyond extremely unlikely by a safety-class receiving crane resolver and associated interlock. The resolver tracks the east-west position of the receiving crane. Before the receiving crane reaches the west side of the Fast Flux Test Facility (FFTF) pit, the interlock removes power from the drive motors. Power may only be restored to the crane by both the use of a supervisor-controlled fortress key at a remote station and the operator depressing an override button on the crane. While this interlock does not reduce the drop frequency, it does reduce the frequency of drops into the FFTF or maintenance pits. A technical safety requirement (TSR) program will not allow the interlock to be overridden when a cask-MCO is suspended by the crane.

2.2.2 Cask Lid Drop onto Multi-Canister Overpack

A drop of the cask lid onto the MCO was identified in the CSB hazard analysis (HNF-SD-SNF-HIE-001) as a potentially significant accident (designator: SA-G-03a). When the MCO transportation cask lid is removed from the cask, the lid could be dropped from the service station gantry hoist onto the top of the MCO or its port covers. While it has been demonstrated that such drops (5 ft or less drop height) do not violate the structural integrity of the MCO (HNF-SD-SNF-DP-010, HNF-SD-SNF-DP-007), it is likely that the seal between the port cover and the MCO is ruptured. Below one port is a rupture disk. This disk is not expected to be disturbed by the drop. However, if the seal is broken on the MCO rupture disk port and the MCO pressurizes above the rupture disk relief pressure (10 atm), then a blow-down of the MCO would occur. The maximum internal MCO pressure at the CSB is 5.2 atm (HNF-SD-SNF-TI-015). Overpressurization of the MCO above the rupture disk relief pressure is considered incredible because insufficient water is available in the MCO to generate the required gas. It is physically not possible to lift the transportation cask lid more than 5 ft above the MCO using the service station gantry hoist.

2.2.3 Drop of a Multi-Canister Overpack by the Multi-Canister Overpack Handling Machine

Drops of the MCO by the MHM were identified in the CSB hazard analysis (HNF-SD-SNF-HIE-001) as potential significant accidents (designator: OA-G-03, -13,

SA-G-03b, -13, WS-G-03a and b, -13). The safety-class interlocks on the MHM and the mechanics of the grapple associated with the MHM hoist combine to greatly reduce the likelihood that any MCO drop from the MHM will occur. MHM descriptions may be found in HNF-3553, Annex A, Chapter A2.0, "Facility Description." The MHM hoist has a single-failure-proof load path. The MHM grapple is designed with a mechanical lock that, when properly engaged, uses the weight of the MCO to help maintain a nearly fault-proof grip on the MCO. Interlocks prevent the grapple jaws from being opened unless the grapple is no longer loaded and the grapple is at a height corresponding to a permitted MCO set-down location (interlock P66). The most credible failure of this locking mechanism requires that the sensors that detect when the grapple has closed fully be miscalibrated, so that the grapple engages the MCO but does not engage its mechanical locking mechanism. Because the sensors are calibrated at the same time, miscalibration would be a common mode failure of this double-channel interlock. Even with this grapple interlock compromised, the MCO must be physically disturbed (possibly a seismic event) or another MHM interlock (such as P66) must fail and allow the operator to fully open the grapple under load before a drop would result. Recent calculations confirm that frequency of this drop is incredible ($<10^{-6}/\text{yr}$) (SNF-4087).

Another possible accident that could lead to a drop is the shear of the MCO hoist cables by rotation of the MHM turret or by lateral movement of the MHM during a seismic event. Rotation of the turret while lowering the MCO is prevented by a safety-class interlock (P6). The MHM may not be rotated to the MCO hoist unless the MHM crane bridge and trolley seismic restraints have been applied (interlock P21). These seismic restraints prevent the MHM from shearing the hoist cables in a design basis earthquake. Drop of the MCO at a location other than a pit or tube where the MCO would normally be raised or lowered is considered incredible, because not only do the grapple and its interlocks have to fail but the interlock (P26), which prevents the turret from rotating and the turret seismic restraints from disengaging without lowering the shield skirt, must also fail. Recent calculations confirm that frequency of this drop is incredible ($<10^{-6}/\text{yr}$) (SNF-4087).

Because drops into the service pit, sampling/weld station pit, or storage tube are not considered beyond extremely unlikely accidents, each of these locations are fitted with an impact absorber. These impact absorbers are required to limit the deceleration of a maximum weight MCO dropped from the maximum height to less than 35 g. The MCO and internal baskets are designed to maintain confinement, containment, and subcriticality under all design basis drops with decelerations limited below 35 g (HNF-S-0426). These same MCO safety functions are maintained for some drops where this deceleration is exceeded. No consequence analyses are performed for any MCO drops from the MHM because they all are either incredible or their consequences have been mitigated such that no radiological release is expected.

2.2.4 Shear of a Multi-Canister Overpack by the Multi-Canister Overpack Handling Machine

A shear of an MCO by the MHM was identified in the CSB hazard analysis as a potentially significant accident (designator: SA-E-07, SA-F-07b, OA-E-07, OA-F-07, WS-E-07, WS-F-07)

(HNF-SD-SNF-HIE-001). Because this accident has the potential to cause the most damage to an MCO in terms of its fuel confinement and containment safety functions, it is considered to bound the consequences of all other accidents that could rearrange the MCO internals. Simple analysis has demonstrated that the turret will not shear the MCO during rotation. It is also possible that the turret rotation could shear the MCO hoist cable and result in a drop of the MCO. Neither of these turret rotation accidents can occur unless one of several safety-class MHM interlocks (P6, P80, P9) is defeated. MHM interlock P9 ensures that the turret seismic restraints, the base, and the turret locking pins are applied before operating the MCO hoist. MHM interlocks P6 and P80 ensure that the turret seismic restraints cannot be disengaged and that power is not supplied to the turret rotate motor unless the MCO is fully raised in the MHM. Shear of an MCO by the MHM may be possible during a seismic event if the MCO is partially inserted in a storage tube, a pit, or the transport cask. Lateral movement of the massive MHM during a design basis earthquake could shear the MCO. Seismic restraints on the MHM trolley and gantry will prevent significant lateral movement when the restraints are applied. The MHM also could apply significant lateral forces against an MCO if the bridge or trolley drives were activated by operator error or MHM malfunction while the MCO is partially lowered from the MHM. MHM interlock P21 prevents the raising or lowering of the MCO hoist unless the bridge and trolley seismic restraints are applied. MHM interlocks (P3, P6, P8, P26, P80) prevent the disengagement of the bridge and turret seismic restraints and interrupts bridge and trolley drive motor power unless the MCO is fully raised.

Shear of the MCO also could be possible if the MHM were to enter the service area while the MCO is being lowered into the service pit by the receiving crane (SA-F-05). The MHM could collide with the crane or directly with the partially lowered MCO, causing the MCO to be sheared. An MHM interlock (P5) inhibits the MHM from entering the service area "overlap zone" if the receiving crane is located in this area. Because the failure of the receiving crane sensor and striker deployment system that activates the MHM limit switches associated with interlock P5 is not incredible, analysis has been performed to assess the damage to the MCO in this accident scenario. Analysis demonstrates that such an accident would not cause unacceptable damage to the MCO (Petersen 1998). The transportation cask will adequately protect the MCO so that it is not breached and no criticality geometry control contingencies are violated.

No consequence analyses are performed for MCO shears caused by the MHM because the controls to prevent such an event are robust and sufficient to consider this accident incredible.

2.2.5 Cask-Multi-Canister Overpack Shear by the Receiving Crane

If the receiving crane were to be moved (translated) while the cask-MCO were partially lowered into the service pit, a shear force would be applied to the outer transportation cask. The lateral forces exerted upon the cask in this scenario are expected to be bounded by those experiences by the cask during a collision with the MHM (Petersen 1998). Because of the substantial design of the cask, engineering judgement is that such an event would not damage the MCO within the cask. Only superficial damage to the outer cask is considered to be likely.

No consequence analyses are performed for any MCO shears caused by the receiving crane because the cask is expected to be able to fully protect the MCO from damage.

2.3 SOURCE TERM ANALYSIS

Those accidents that could breach the MCO such that geometry control or containment of the SNF may be lost require safety-class mitigation to prevent violation of criticality contingencies. Because the development of radiological source term and dose consequences could not lead to more restrictive safety classification and controls, no source term is developed.

2.4 CONSEQUENCE ANALYSIS

A consequence analysis was not performed for MCO shears caused by the MHM because the controls to prevent such an event are robust and sufficient to make this accident frequency beyond extremely unlikely. Any drop, impact, or shear accidents that were deemed to have the potential to violate the MCO criticality geometry control safety functions, including breach of MCO containment, have been assigned preventive features that make their occurrence beyond extremely unlikely.

2.5 COMPARISON TO GUIDELINES

The consequences of a cask-MCO drop by the receiving crane into the maintenance pit with a slap-down have not been determined. Based on the results from a similar analysis (HNF-SD-SNF-DP-007), it is expected that such an accident would damage the MCO center tube geometry sufficiently to cause a criticality specification violation. While definitive supporting calculations do not exist, no radiological releases or associated onsite (100 m) or offsite dose consequences are expected from such an accident because of the structural protection provided by the cask. The receiving crane will be instrumented with an absolute resolver (to measure and report current crane location) and an interlock scheme that only will allow the crane to travel west of the FFTF pit without requiring a key-operated override switch be used to allow power to the crane drive. Because this accident could lead to the violation of a criticality control limit, this receiving crane interlock and associated electronics will need to be classified safety class.

No dose consequences are expected from a drop of the transportation cask lid onto the MCO. Dose consequences could result only if the MCO rupture disk were damaged or failed. Because MCO internal pressures above the rupture disk actuation pressure (150 lb/in² gauge) are not credible at the CSB (HNF-SD-SNF-TI-015), a blow-down of the MCO and associated radiological release are not possible.

The drop of the MCO by the MHM could have safety-class consequences because of the potential to violate criticality control limits. No dose consequence estimates are needed to determine structure, system, and component (SSC) or TSR classification. Impact absorbers that

mitigate drop consequences must be safety class. This drop has been recently determined to be incredible (SNF-4087).

The shear of the MCO by the MHM could have safety-class consequences because of the potential to violate criticality geometry control limits. No dose consequence estimates are needed to determine SSC or TSR classification. Mechanical equipment and MHM control system interlocks, sensors, relays, and power contractors that prevent a shear must be safety class.

The drop of the cask-MCO by the receiving crane from heights greater than 40 in. could have safety-class consequences because of the potential to violate criticality geometry control limits. No dose consequence estimates are needed to determine SSC or TSR classification. Equipment used to prevent a drop into the maintenance pit or from heights greater than 40 in. onto the receiving area floor must be safety class. Recently, a safety-class cask transfer system has been implemented to prevent these drops.

2.6 SUMMARY OF SAFETY STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

The SSCs and TSR controls designated to prevent the loss of criticality control and associated dose consequences resulting from the rearrangement of MCO internals caused by a shear accident are as follows:

2.6.1 Possible Rearrangement of Multi-Canister Overpack Internals Because of Shear

1. Lateral MHM Movement

- Safety-class SSCs
 - MHM interlock (P21) and sensors — Ensure that the MCO hoist cannot operate unless the bridge seismic clamps and trolley seismic restraints are applied when an MCO is in the MHM; the interlock circuitry includes relays, contractors, and sensors (limit switches)
 - MHM interlocks (P3, P6, P8, P26, P80), sensors, and switches — Prevent the seismic restraints from disengaging and power being applied to the bridge and trolley drive motors unless the MCO hoist is fully raised when an MCO is in the MHM; the interlock circuitry includes contractors, relays, and sensors (resolvers, limit switches, photoelectric switches)
 - MHM seismic restraints, rails, and rail frogs — Prevent translational movement of the MHM whenever engaged when an MCO is in the MHM (restraints must be engaged before MCO hoist operation)

- Seismic detection and MHM power-disconnect system — Detects seismic events (magnitude 0.25 g horizontal [0.74 g/3] and 0.16 g vertical [0.49 g/3]) and removes all power to the MHM; removal of power to prevent operation of the MCO hoist, disengagement of seismic restraints, and MHM translational movement (While the MHM interlocks are not seismically qualified, they ensure that the MHM maintains itself and the MCO in a state such that, under the loss of electrical power, it is not possible for the MCO to sustain unacceptable damage. An MCO being handled by the MHM will be safe during the design basis earthquake because the seismic-detection and MHM power-disconnect system removes power from the MHM before improper MHM function could occur because of potential interlock failure)
 - MHM rails and rail frogs — Prevent inadvertent movement and/or structural failure of the MHM, with collateral damage to safety-class structures or an MCO
- Safety-significant SSCs
 - MHM and MHM MCO hoist — Required by Letter 97-SFD-172, *Risk Evaluation Guidelines (REGs) to Ensure Inherently Safer Designs* (Sellers 1997), and U.S. Nuclear Regulatory Commission (NRC) equivalency important-to-safety Category B for SSCs that handle SNF
- TSR
 - Operability of MHM interlocks (P3, P6, P8, P21, P26, P80) and seismic-detection and MHM power-disconnect system; the interlock circuitry includes relays, contractors, and sensors (resolvers, limit switches, photoelectric switches).

2. Rotation of the MHM Turret

- Safety-class SSCs
 - MHM interlock (P9) and sensors — Ensure that the MCO hoist cannot operate unless the turret seismic restraints are applied when an MCO is in the MHM; the interlock circuitry includes power contractors, relays, and proximity sensors
 - MHM interlocks (P6, P80) and sensors — Prevent the seismic restraints from disengaging and power being applied to the turret drive assembly unless the MCO hoist is fully raised when an MCO is in the MHM; the interlock circuitry includes power contractors, relays, and sensors (resolver, limit switch, photoelectric switch)

- MHM seismic restraints — Prevent rotational movement of the MHM whenever engaged when an MCO is in the MHM (restraints must be engaged before MCO hoist operation)
- Seismic detection and MHM power-disconnect system — Detects seismic event (magnitude 0.25 g horizontal [0.74/3 g] and 0.16 g vertical [0.49/3 g]) and removes all power to the MHM; removal of power to prevent operation of the MCO hoist, disengagement of seismic restraints, and MHM rotational movement (MHM interlocks are not seismically qualified)
- Safety-significant SSCs
 - MHM and MHM MCO hoist — Required by Letter 97-SFD-172 (Sellers 1997) and NRC equivalency important-to-safety Category B for SSCs that handle SNF
- TSR
 - Operability of MHM interlocks (P6, P9, P80) and seismic-detection and MHM power-disconnect system; the interlock circuitry includes power contractors, relays, and sensors (resolvers, limit switches, photoelectric switches, proximity sensors).

The SSCs and TSR controls designated to prevent the loss of criticality control and the dose consequences of the rearrangement of MCO internals caused by a shear accident are summarized in Table 2-2. In accordance with Title 10, *Code of Federal Regulations*, Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste," Section 72.3, "Definitions" (10 CFR 72.3), SSCs also have been identified that are considered important to safety. This important-to-safety classification is further delineated using a graded approach provided by NUREG/CR-6407, *Classification of Transportation Packaging and Dry Spent Fuel Storage System Components According to Importance to Safety*. NRC important-to-safety designations are identified in Table 2-2 for the rearrangement of MCO internals accidents. Defense-in-depth features also are included for each specific accident in Table 2-2.

The suite of safety SSCs and TSR controls necessary and sufficient to prevent the two design basis MCO shear accidents do not address some of the other accidents in the rearrangement of MCO internals accident category. Table 2-2 also lists the safety SSCs and TSR controls needed to prevent or mitigate these accidents. Because these accidents are substantially different in development and progression from the design base accidents, each scenario and the corresponding controls are described below also.

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
Possible rearrangement of MCO internals because of a shear or drop				
1. Lateral MHM movement	SA-F-07b OA-F-07 WS-F-07 OU-R-01	Prevent MCO translational shear	<p><u>Safety-class SSCs:</u></p> <ul style="list-style-type: none"> MHM interlock (P21), sensors, and switches MHM interlocks (P3, P6, P8, P26, P80), sensors, and switches MHM seismic restraints, rails, and rail frogs Seismic detection and MHM power-disconnect system MHM rails and rail frogs <p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> MHM structural components and MHM MCO hoist and grapple <p><u>TSR:</u></p> <ul style="list-style-type: none"> Operability of MHM interlocks (P3, P6, P8, P21, P26, P80), seismic detection and MHM power-disconnect system; MHM interlock <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> Personnel are trained in sitewide and facility-specific emergency response procedures. The MHM provides active, filtered ventilation at its open interface with both the service station and the sampling/weld station. The MHM is designed to ASME NOG-1° to preclude tipping. The MHM has an auditory indication of its movement (i.e., alarms). The MHM is limited to relatively slow movement (maximum 40 ft/min, creep 1.0 ft/min).^d The MHM is provided with a backup grapple disengagement capability. Personnel are trained to procedures detailing the safe sequence of operations; these procedures prohibit interferences between the receiving crane and the MHM 	<p>A</p> <p>A</p> <p>A</p> <p>A</p> <p>A</p> <p>B</p>

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
2. Rotation of the MHM turret	SA-E-07 OA-E-07 WS-E-07 OU-R-01	Prevent MCO rotational shear	<u>Safety-class SSCs:</u> <ul style="list-style-type: none"> MHM interlock (P9), sensors, and switches MHM interlocks (P6, P80), sensors, and switches MHM seismic restraints Seismic detection and MHM power-disconnect system 	A
			<u>Safety-significant SSCs:</u> <ul style="list-style-type: none"> MHM structural components and MHM MCO hoist and grapple <u>TSR:</u> <ul style="list-style-type: none"> Operability of MHM interlocks (P6, P9, P80) and seismic detection and MHM power-disconnect system, and interlock circuitry <u>Defense in depth:</u> <ul style="list-style-type: none"> Personnel are trained in sitewide and facility-specific emergency response procedures The MHM provides active, filtered ventilation at its open interface with both the service station and the sampling/weld station The MHM is designed to ASME NOG-1^c to preclude tipping The MHM has an auditory indication of its movement (i.e., alarms) The MHM is limited to relatively slow movement The MHM is provided with a backup grapple disengagement capability Personnel are trained to procedures detailing the safe sequence of operations; these procedures prohibit interferences between the receiving crane and the MHM 	B

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
3. Drop of cask-MCO from the receiving crane ^a	TV-G-09 TV-G-13 SA-G-03a SA-G-13	Prevent the MCO from sustaining damage exceeding the allowable level ^f	<p><u>Safety-class SSCs^g:</u></p> <ul style="list-style-type: none"> • Transportation cask • Service station impact absorber • Receiving crane height limiting devices • MCO^g <p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> • Receiving crane structure and hoist • Setting crane height limiting device setpoints to ensure crane lift height with yoke attached does not exceed 40 in. • Cask transfer safety system^h <p><u>TSRs:</u></p> <ul style="list-style-type: none"> • Use of proper yoke to lift the cask-MCO • Impact absorber is installed in the MCO service station pit and is functional • Setting crane height limiting device setpoints to ensure crane lift height with yoke attached does not exceed 40 in. <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> • The operators of the receiving crane are trained and qualified to perform their duties safely, which includes following procedures for safe handling of the transportation cask • Regular maintenance is performed on the transporter to ensure it is in good working orderⁱ • Maintenance and operations manuals and details are provided by crane vendorsⁱ • The hoist design includes <ul style="list-style-type: none"> - Interlocks to preclude lift and horizontal motion at same time - Dual brakes - No free fall capacity 	<p>A</p> <p>A</p> <p>A</p> <p>A</p> <p>NA</p> <p>B</p> <p>B</p>

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
4. Drop of MCO back into the cask or onto the cask rim by the MHM	SA-G-03a SA-G-13	Prevent the MCO from sustaining damage exceeding the allowable level ^f	<u>Safety-class SSCs:</u> • MCO ^g	A
			<u>Safety-significant SSCs:</u> • MHM structural components and MHM MCO hoist and grapple	A
			• MHM hoist height limiting devices - limit lift to 21 ft, 2 in.	B
5. Drop of the MCO from the MHM into the MHM maintenance pit	SA-G-03a SA-G-13	Prevent the MCO from sustaining damage exceeding the allowable level ^f	<u>Defense in depth:</u> • The MHM grapple is designed with a mechanical lock such that it should not be able to open while a load is suspended from it • Lifting devices used at the CSB are designed to handle the loads they will carry • Personnel are trained to facility-specific procedures in the proper handling of the transportation cask, MCO, receiving crane, gantry, and MHM • Regular maintenance of the MHM is performed to ensure it is in good working order ^k • Qualified operators	
			<u>Safety-class SSCs:</u> • MHM interlocks (P3, P8), sensors • MHM interlocks (P26, P80, P85), sensors	A A
			<u>Safety-significant SSCs:</u> • MHM structural components and MHM MCO hoist and grapple	B
			<u>TSR:</u> • Operability of interlocks (P3, P8, P26, P80, P85)	
			<u>Defense in depth:</u> • The MHM grapple is designed with a mechanical lock such that it should not be able to open while a load is suspended from it • Lifting devices used at the CSB are designed to handle the loads they will carry • Personnel are trained to facility-specific procedures in the proper handling of the transportation cask, MCO, receiving crane, gantry, and MHM • Regular maintenance of the MHM is performed to ensure it is in good working order ^k • Qualified operators	

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
6. Drop of the cask-MCO from the receiving crane into the FFTF or MHM maintenance pit	SA-G-03b SA-G-13	Prevent the MCO from sustaining damage exceeding the allowable level ^f	<p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> Receiving crane positioning/interlock control system <p><u>TSRs:</u></p> <ul style="list-style-type: none"> Administrative use of the supervisor-controlled fortress key for movement of receiving crane over or east of the FFTF pit when there is no cask-MCO load Operability of receiving crane positioning/interlock control system <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> Lifting devices used at the CSB are designed to handle the loads they will carry Personnel are trained to facility-specific procedures in the proper handling of the transportation cask, MCO, receiving crane, gantry, and MHM Qualified operators Maintenance and operations manuals and details are providedⁱ 	B
7. Drop of CSB structural component onto an MCO or other safety-class structure OR MHM fall onto the operating deck	OU-R-01	Prevent collapse of CSB structures or loss of structural integrity of the facility when there is SNF in the facility during NPH events	<p><u>Safety-class SSCs:</u></p> <ul style="list-style-type: none"> Standard and overpack storage tubes, carbon steel basemat embeds, tube base assemblies, operating area deck (including sampling/weld area and load-in/load-out area), and vault <p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> Operating area shelter Rail frogs, rails, MHM seismic restraints, MHM (structural) <p><u>TSR:</u></p> <ul style="list-style-type: none"> Double verification that rail frogs are installed and secure <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> Personnel are trained in sitewide and facility-specific emergency response procedures The facility provides shelter for workers 	A B B

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
8. Break of exterior water line	OU-P-05	Detect water leak to prevent washout of compacted soil near the CSB to protect building seismic analysis assumptions	<u>Safety-class SSCs:</u> <ul style="list-style-type: none"> • None <u>TSRs:</u> <ul style="list-style-type: none"> • Walkdowns of the facility after design basis earthquakes <u>Defense in depth:</u> <ul style="list-style-type: none"> • None 	None

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
9. Drop of an MCO into or onto the storage tube	OA-G-03 OA-G-13	Limit impact forces on the MCO, tube, and associated structures to acceptable levels	<p><u>Safety-class SSCs:</u></p> <ul style="list-style-type: none"> Storage tube bottom impact absorber Interface guide ring funnel MHM drop prevention interlocks (P61, P62, P63, P66) sensors <p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> Standard storage tube intermediate impact absorber MHM structural components and MHM MCO hoist and grapple <p><u>TSRs:</u></p> <ul style="list-style-type: none"> Bottom impact absorber is installed in each storage tube prior to placing an MCO in the storage tube Intermediate impact absorber is installed in each storage tube prior to placement of a second MCO in that storage tube The interface guide ring funnel is in place before the MHM is brought over the standard storage tube location to place or retrieve an MCO Operability of interlocks (P61, P62, P63, P66) <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> The MHM grapple is designed with a mechanical lock such that it should not be able to open while a load is suspended from it MHM grapple is designed to handle the loads they will carry Personnel are trained to facility-specific procedures in the proper handling of the MCO and MHM Qualified operators Regular maintenance of the MHM is performed to ensure it is in good working order^k The hoist design includes <ul style="list-style-type: none"> Interlocks to preclude lift and horizontal motion at same time Dual brakes No free fall capacity 	A NA B

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
10. Drop of an MCO into the sampling/weld station	WS-G-03a WS-G-13	Limit impact forces on the MCO to acceptable levels	<p><u>Safety-class SSCs:</u></p> <ul style="list-style-type: none"> • Sampling/weld station impact absorber • MHM drop prevention interlocks (P61, P62, P63, P66) sensors <p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> • MHM structural components and MHM MCO hoist and grapple <p><u>TSR:</u></p> <ul style="list-style-type: none"> • Sampling/weld station impact absorber is installed in the pit prior to placing an MCO in the sampling/weld station • Operability of interlocks (P61, P62, P63, P66) <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> • The MHM grapple is designed with a mechanical lock such that it should not be able to open while a load is suspended from it • MHM grapple is designed to handle the loads they will carry • Personnel are trained to facility-specific procedures in the proper handling of the transportation cask, MCO, receiving crane, and MHM • Qualified MHM operators • Regular maintenance of the MHM is performed to ensure it is in good working order^k • The hoist design includes <ul style="list-style-type: none"> - Interlocks to preclude lift and horizontal motion at same time - Dual brakes - No free fall capacity 	A

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
Possible rearrangement of MCO internals due to collision				
11. MHM collision with cask-MCO (while cask-MCO is not fully inserted into the service pit)	SA-F-05	Provide passive structural protection for the MCO	<u>Safety-class SSCs:</u> <ul style="list-style-type: none"> Transportation cask <u>Defense in depth:</u> <ul style="list-style-type: none"> Personnel are trained to procedures detailing the safe sequence of operations; these procedures prohibit interferences between the receiving crane and the MHM Rail frogs The receiving crane is limited to relatively slow movement (maximum bridge speed is 36 to 44 ft/min)¹ Regular maintenance is performed on the receiving crane to ensure it is in good working order¹ From the bottom of the girder to the top of the tent, there is 0.5 ft of clearance (Figure A2-9) 	A
Possible rearrangement of MCO internals due to impact from gas cylinder				
12. Gas cylinder missile impacts	TV-F-06 SA-F-06 WS-F-06	Prevent compressed gas cylinders from becoming a missile hazard	<u>Design feature:</u> <ul style="list-style-type: none"> Maximum hole diameter in the butt of the valve in the neck of all gas cylinders. <u>TSR:</u> <ul style="list-style-type: none"> A TSR is not required. <u>Defense in depth:</u> <ul style="list-style-type: none"> Operators are trained in the proper handling of compressed gas cylinders according to established procedures Gas cylinders that supply the inert gas system other than those on the tube vent and purge cart and cylinders used for maintenance are located outside of the CSB 	

Table 2-2. Summary of Safety Features Required to Prevent Rearrangement of Multi-Canister Overpack Internals. (10 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
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^aChecklist designators are from HNF-SD-SNF-HIE-001, 1999, *Canister Storage Building Hazard Analysis Report*, Rev. 1, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^bSSCs are classified per their function in mitigating or preventing specific accidents. SSCs may have other classifications based on their functions in other events.

^cASME NOG-1, 1995, *Rules for Construction of Overhead and Gantry Cranes (Top Running Bridge, Multiple Girder)*, American Society of Mechanical Engineers, New York, New York.

^dESL/R(96)065, 1998, *MCO Handling Machine 100% Design Report*, Rev. 0, GEC Alsthom Engineering Systems Ltd, Leicester, England.

^eImpact absorber specification requires that the deceleration of a maximum-weight MCO dropped from the maximum height (40 in. above the floor to the top of the impact absorber) is less than 35 g.

^fAllowable level of damage means that calculations were performed to determine that the impacts did not violate design or performance specification criteria.

^gThe following are safety-class features of the MCO and not CSB facility features; however, these MCO features provide structural capability to the MCO during this event:

- MCO shell, locking ring, and shield plug — Provide structural protection, criticality geometry control (73 in. circumference), and confinement of SNF should the cask-MCO drop from the receiving crane
- MCO Mark IA fuel and scrap baskets including center post — Provide criticality geometry control of the SNF (maximum 2-in. deflection from MCO centerline) should the MCO drop from the receiving crane.

^hTSR controls are not required for those safety-significant SSCs resulting from only NRC equivalency requirements.

ⁱDE&S, 1999, *SNF CSB Operations & Maintenance Manual*, Volume 12, "MCO Receiving Crane," Rev. 0, DE&S Hanford, Incorporated, Richland, Washington.

^jThe following are safety-class features of the MCO and not CSB facility features; however, these MCO features provide structural capability to the MCO during this event:

- MCO shell, locking ring, and shield plug — Provide structural protection, criticality geometry control (73 in. circumference), and confinement of SNF should the MCO drop from the MHM at the MCO service station pit
- MCO Mark IA fuel and scrap baskets including center post — Provides criticality geometry control of SNF (maximum 2-in. deflection from MCO centerline from any credible drop).

^kDE&S, 1999, *SNF CSB Operations & Maintenance Manual*, Volume 15, "MCO Handling Machine," Rev. 0, DE&S Hanford, Incorporated, Richland, Washington.

^lSNF-W379-PAT-012, 1998, *Preoperational Acceptance Test Procedure (PAT) Cask Receiving Crane*, Rev. 0, DE&S Hanford, Incorporated, Richland, Washington.

CSB = Canister Storage Building.

FFTF = Fast Flux Test Facility.

ITS = important to safety.

MCO = multi-canister overpack.

MHM = multi-canister overpack handling machine.

NA = not applicable to ITS category classification.

NPH = natural phenomena hazard.

NRC = U.S. Nuclear Regulatory Commission.

SNF = spent nuclear fuel.

SSC = structure, system, and component.

TSR = technical safety requirement.

2.6.2 Possible Rearrangement of Multi-Canister Overpack Internals Because of Drops

Several drop accidents were evaluated and are listed here along with specific safety SSCs and TSR controls to prevent or reduce the severity of the described drop accident.

3. Drop of Cask-MCO from the Receiving Crane

The drop of the cask-MCO from the receiving crane onto the load-in/load-out area floor or into the MCO service station pit could lead to the loss of criticality geometry control of the fuel in the MCO. Analysis has demonstrated that the cask-MCO structural and criticality control features are sufficient to remain intact if the cask-MCO is dropped onto the concrete from a height less than 40 in. The SSCs and TSR controls selected prevent the cask-MCO from being hoisted more than 40 in. above the underlying concrete and provide for impact absorption to reduce the forces on the MCO in case of a drop. The following are the specific safety SSCs and TSR controls relied on to prevent the MCO from sustaining unacceptable damage during this drop event:

- Safety-class SSCs²
 - MCO transportation cask — Provides structural protection to the MCO from drops from the receiving crane when the MCO is inside the cask
 - Receiving crane height limiting devices — Limit lift height above the floor (maximum of 40 in.) when lifting yoke is attached
 - MCO service station pit impact absorber — Limits deceleration forces to less than 35 g for a maximum-weight MCO if the cask-MCO is dropped from receiving crane into the MCO service station pit
- Safety-significant SSCs
 - Receiving crane and hoist — Required by Letter 97-SFD-172 (Sellers 1997) and NRC equivalency important-to-safety Category B for SSCs that handle SNF

²The following are safety-class features of the MCO and not CSB facility features; however, these MCO features provide structural capability to the MCO during this event:

- MCO shell, locking ring, and shield plug — Provide structural protection, criticality geometry control (73 in. circumference), and confinement of SNF should the cask-MCO drop from the receiving crane
- MCO Mark IA fuel and scrap baskets including center post — Provide criticality geometry control of the SNF (maximum 2-in. deflection from MCO centerline) should the MCO drop from the receiving crane.

- Cask transfer safety system — The impact absorber mitigates the impact of a cask–MCO drop onto the floor and its mechanical pivoting safety rails prevent the cask–MCO from falling on its side. Neither of these occurrences leads to unmitigated dose consequences nor loss of criticality geometry. This is safety significant because it is NRC equivalency important-to-safety Category B for SSCs that apply to SNF
- TSRs
 - TSR controls are not required for those safety-significant SSCs resulting only from NRC equivalency requirements
 - Use of proper yoke (length) to lift the cask-MCO ensures lift height above the floor is a maximum of 40 in.
 - Setting crane height limiting devices setpoints to ensure crane lift height with yoke attached does not exceed 40 in.
 - Impact absorber is installed in the MCO service station pit and is functional.

4. Drop of MCO Back into the Cask or onto the Cask Rim by the MHM

The drop of the MCO from the MHM back into or onto the rim of the transportation cask has been analyzed for damage to the MCO. Calculations have been completed that demonstrate that the MCO will not sustain unacceptable damage from this drop accident from the maximum height possible from the MHM MCO hoist and that this drop is incredible. An MCO that drops back into the cask will not be damaged in such a way that it cannot be retrieved from the cask using the MHM (HNF-SD-SNF-DP-007, HNF-SD-SNF-SARR-005). The following are the specific safety SSCs that prevent this event:

- Safety-significant SSCs
 - MHM and MHM MCO hoist — Required by Letter 97-SFD-172 (Sellers 1997) and NRC equivalency important-to-safety Category B for SSCs that handle SNF
 - MHM hoist height limiting devices — Limit lift height to 21 ft, 2 in.
- TSRs
 - Setting MHM hoist height limiting devices setpoints to ensure MCO is not lifted to a height greater than 21 ft, 2 in. above the cask bottom.

5. Drop of the MCO from the MHM into the MHM Maintenance Pit

The drop of the MCO from the MHM into the MHM maintenance pit could lead to the loss of criticality geometry control of the fuel in the MCO. This has been determined recently to be incredible. The following are the specific safety SSCs and TSR controls that prevent this event:

- Safety-class SSCs
 - MHM interlocks (P3, P8) and sensors — Ensure that the MHM turret is rotated to the navigate (TV camera) position before allowing power to the bridge or trolley drive motors when an MCO is in the MHM; the interlock circuitry includes contractors, relays, switches, and sensors (resolver, limit switches)
 - MHM interlocks (P26, P80, P85) and sensors — Prevent the MHM from rotating to the MCO position while over the maintenance pit when an MCO is in the MHM; the interlock circuitry includes contractors, relays, and sensors (limit switches, photoelectric switches)
 - MHM hoist height limiting devices — Limit lift height to 21 ft, 2 in.
- Safety-significant SSCs
 - MHM and MHM MCO hoist — Required by Letter 97-SFD-172 (Sellers 1997) and NRC equivalency important-to-safety Category B for SSCs that handle SNF
- TSR
 - Operability of interlocks and sensors (P3, P8, P26, P80, P85); the interlock circuitry includes contractors, relays, and sensors (resolvers, limit switches, photoelectric switches).
 - Setting MHM hoist height limiting devices setpoints to ensure MCO is not lifted to a height greater than 21 ft, 2 in. above the cask bottom.

6. Drop of the Cask-MCO from the Receiving Crane into the FFTF Pit or the MHM Maintenance Pit

The drop of the cask-MCO from the receiving crane into the FFTF pit or the MHM maintenance pit could lead to the loss of criticality geometry control of the fuel in the MCO. The following are the specific safety SSCs and TSR controls that prevent this event:

- Safety-significant SSCs
 - Receiving crane positioning/interlock control system — Prevent accidental drop of cask-MCO in specific areas where the drop height exceeds 40 in. and no impact absorbers are provided. Remove power to the receiving crane to prevent the receiving crane from traveling over the FFTF or maintenance pit when the receiving crane is carrying an MCO loaded with SNF
- TSRs
 - Administrative use of the supervisor-controlled fortress key for movement of receiving crane over or east of the FFTF pit when there is no cask-MCO loaded with SNF suspended from the crane
 - Operability of receiving crane resolver and interlock.

7. Drop of a CSB Structural Component onto an MCO or other Safety-Class Structure OR the MHM Falling onto the Operating Deck

The drop of a CSB structural component onto an MCO or other safety-class structure could lead to the loss of criticality geometry control of the fuel in the MCO. The following are the specific safety SSCs and TSR controls that prevent this event:

- Safety-class SSCs
 - Standard and overpack storage tubes, carbon steel base slab embeds, tube base assemblies, operating area deck (including sampling/weld area and load-in/load-out area), and vault — Provide criticality geometry control and passive cooling and are seismically qualified to ensure structural integrity for all design basis natural phenomena hazards
- Safety-significant SSCs
 - Operating area shelter — Seismically qualified and tornado hardened to provide structural integrity for all design basis natural phenomena hazards
 - Rail frogs, rails, MHM seismic restraints, MHM (structural) — Prevent the MHM from falling onto the operating deck during design basis accident seismic events

- TSR
 - Double verification that the rail frogs are installed and secure.

8. Break of an Exterior Water Line

The break of an exterior water line and the subsequent erosion and softening of soil around the CSB would weaken the structural integrity of the building such that it may no longer be able to withstand a seismic event. The following are the specific safety SSCs and TSR controls that prevent this event:

- Safety-class SSCs
 - None
- TSRs
 - Walkdowns of the facility after operating basis earthquakes.

9. Drop of an MCO into or onto the Edge of a Storage Tube

The drop of an MCO into or onto the edge of a storage tube could lead to the loss of criticality geometry control of the fuel in the MCO. These drops are both mitigated by the installation of one or more impact absorbers in each storage tube. These impact absorbers limit the deceleration of a maximum weight MCO dropped from the maximum height in the MHM to less than 35 g. This has been determined recently to be incredible. The following are the specific safety SSCs and TSR controls that prevent this event:

- Safety-class SSCs
 - Storage tube bottom impact absorber — Limits deceleration forces to less than 35 g for a maximum-weight MCO if the MCO is dropped from the MHM into or onto the storage tube
 - Interface guide ring — Limits forces on the standard storage tube, operating deck, and the MCO within acceptable criteria during MCO drop events (eccentric)
 - MHM interlocks (P61, P62, P63, P66) and sensors — Inhibit the MCO hoist operator to prevent MCO drop from the MHM; the interlock circuitry includes contractors, relays, and sensors (e.g., limit switches, switches)

- Safety-significant SSCs
 - MHM and MHM MCO hoist — Required by Letter 97-SFD-172 (Sellers 1997) and NRC equivalency important-to-safety Category B for SSCs that handle SNF.
 - Storage tube intermediate impact absorber — Limits forces to the bottom of the dropped MCO and the top of the bottom MCO if a second MCO is dropped into a storage tube
- TSRs
 - Bottom impact absorber is installed in each storage tube before placing an MCO in the storage tube
 - Intermediate impact absorber is installed in each storage tube before placement of a second MCO in that storage tube
 - The interface guide ring funnel is in place before the MHM is brought over the standard storage tube location to place or retrieve an MCO.
 - Operability of interlocks and sensors (P61, P62, P63, P66); the interlock circuitry includes contractors, relays, and sensors (resolvers, limit switches, and switches).

10. Drop of an MCO into the Sampling/Weld Station

The drop of an MCO into the sampling/weld station could lead to the loss of criticality geometry control of the fuel in the MCO. This drop is mitigated by the installation of an impact absorber in the sampling/weld station pit that limits the deceleration of a maximum weight MCO dropped from the maximum height in the MHM to less than 35 g. The following are the specific safety SSCs and TSR controls that prevent this event:

- Safety-class SSCs
 - Sampling/weld station impact absorber — Limits deceleration forces to the MCO if the MCO is dropped from the MHM into the sampling/weld station pit
 - MHM interlocks (P61, P62, P63, P66) and sensors — Inhibit the MCO hoist operator to prevent MCO drop from the MHM; the interlock circuitry includes contractors, relays, and sensors (e.g., limit switches, switches)

- Safety-significant SSCs
 - MHM and MHM MCO hoist — Required by Letter 97-SFD-172 (Sellers 1997) and NRC equivalency important-to-safety Category B for SSCs that handle SNF
- TSR
 - Sampling/weld station impact absorber is installed in the pit before placing an MCO in the sampling/weld station
 - Operability of interlocks and sensors (P61, P62, P63, P66); the interlock circuitry includes contractors, relays, and sensors (resolvers, limit switches, and switches).

2.6.3 Possible Rearrangement of Multi-Canister Internals Because of Collision

11. MHM Collision with Cask-MCO

A collision of the MHM with the transportation cask when the cask is partially inserted into the service station pit by the receiving crane could lead to the loss of criticality geometry control of the fuel in the MCO. Calculations demonstrate that the cask provides adequate protection to the MCO in this accident (Petersen 1998). The following is the specific safety SSC that prevents this event:

- Safety-class SSCs
 - Transportation cask — Provides structural protection for the MCO when the MCO is inside the cask.

No TSR controls are needed for this accident.

2.6.4 Possible Rearrangement of Multi-Canister Internals Because of Gas Cylinder Impact

12. Compressed Gas Cylinder Missile Impacts

The impact of a compressed gas cylinder (missile) with the cask-MCO or an exposed portion of the MCO presents an unknown hazard to the MCO. All compressed gas cylinders contain a flow-limiting orifice installed within the neck of the bottle so that the bottle may not become a missile unless this orifice is deliberately removed. No calculations were performed to determine the damage that an MCO might sustain if it were struck by a damaged compressed gas cylinder that

did not contain a flow-limiting orifice, but the hazard analysis assumed that such damage might lead to a gaseous release with safety-significant consequences. No credible accident will remove the flow-limiting orifice, so these cylinders will not present missile hazards. The following is the specific programmatic control that prevents this event:

- Design Features
 - Maximum hole diameter in the butt of the valve in the neck of all gas cylinders — Limits the thrust produced by escaping gas to an amount that cannot accelerate the cylinder to dangerous velocity; this feature provides protection against accidental breaking-off of the valve body on top of the cylinder.

2.7 REFERENCES

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3.0 CALCULATIONS FOR GASEOUS RELEASE FROM THE MULTI-CANISTER OVERPACK

3.1 PURPOSE AND OBJECTIVES

At the Cold Vacuum Drying Facility (CVDF), the multi-canister overpack (MCO) is backfilled to a prescribed pressure, using helium, just before it is sealed for shipment to the Canister Storage Building (CSB). The MCO's internal pressure can increase, as a function of time, because of the radiolytic decomposition of water and aluminum hydroxide inside the MCO and the release of hydrogen from the chemical reaction of water with metallic fuel. Uncontrolled release of this MCO internal gas pressure, referred to as a gaseous release, is an operational accident resulting from failure of MCO sampling system equipment and/or operator error during the MCO sampling process. The purpose of this section is to calculate the potential gaseous release dose consequences from an MCO in the CSB sampling/weld station. The accident analyzed is a release of MCO internal gases resulting from failure of sampling system pressure bounding integrity during the time that a sample is being taken from an MCO.

The design basis accident in Chapter 3.0 bounds the accident analyzed in HNF-SD-SNF-SARR-005, *Multi-Canister Overpack Topical Report*, Section 11.3.3.

3.2 SCENARIO DEVELOPMENT

The CSB hazard analysis (HNF-SD-SNF-HIE-001) identifies and categorizes a series of potential accidents as MCO pressurized gaseous release accidents. The general sequence of events leading to a gaseous release event is shown in Figure 3-1. The gaseous release accidents, illustrated in Figure 3-2, include leaks in the process system caused by dropping or crashing equipment into the process system equipment, by random failures of the process equipment, or by operator error. These gaseous release events specifically include four potential events:

- Shear of sampling lines connected to the MCO because of collision (e.g., with crane, service cart) (hazard analysis checklist entry WS-F-05)
- Shear of sampling lines connected to the MCO because of impact of a gas cylinder that becomes a missile (hazard analysis checklist entry WS-F-06)
- Damage to the MCO, when the cover port is removed for sampling, because of dropped equipment (e.g., hoods, sampling equipment, pit covers) (hazard analysis checklist entry WS-G-03b)
- Overpressurization of the MCO, sampling system, and/or inerting system because of high gas pressure resulting from failure of the sampling system helium supply pressure regulator (hazard analysis checklist entry WS-H-06a).

This set of accidents involves a pressurized MCO exhausting, ultimately, to the environment as a result of an upset condition during the MCO sampling process. All accidents in this set have been assigned the same severity and frequency categories (S2/F2).

MCOs arrive at the CSB from the CVDF in a mechanically sealed configuration and having no pressure safety devices. The majority of the MCOs will be placed in interim storage after being welded closed, but a relatively small fraction of them will be designated as monitored MCOs.

A monitored MCO is transferred by the MCO handling machine (MHM) from the storage tube to the sampling/weld station for sampling. At the sampling/weld station, the MCO wall temperature is checked via an optical pyrometer, the MCO gas pressure and temperature are checked, and the MCO gas stream is sampled for hydrogen and oxygen and for radiological particulate and gases. After sampling is completed, the MCO gas pressure is re-established to the prescribed pressure with inert gas if the MCO pressure is less than the prescribed pressure. The MCO mechanical seal and cover plate seal then can be leak-tested to confirm seal integrity.

Once the sampling program has been completed, the monitored MCOs eventually will be transferred back to the sampling/weld station to have the cover cap welded in place. The MCO cover cap encloses all of the potential leak paths from the MCO through mechanical seals on the shield plug and process valves. MCOs not designated for monitoring activities will have the cover cap welded on immediately after receipt at the CSB; they will go directly from the MCO service station to the sampling/weld station and will not be installed in storage tubes before welding.

Accidents identified in the CSB hazard analysis as checklist entries WS-F-05 and WS-F-06 are gaseous release events resulting from failures of the MCO sampling system or sampling system process that result in blowing down a pressurized MCO (HNF-SD-SNF-HIE-001). The conceptual design of the MCO sampling/weld station (Petersen 1998), which includes the MCO sampling system, specifies that one process line will be connected to the short tube process port of the MCO (under cover plate 2). This line will be used to draw a sample of gas from within the MCO and to repressurize the MCO to a prescribed pressure using helium from the 120 lb/in² gauge CSB helium supply system. The sampling system piping between the refill valve and the MCO will be pressurized to a maximum of the prescribed pressure value during this MCO refill operation. A rupture of this process line while the line is connected to the MCO and the MCO process valve is open would result in blowdown of the MCO. Because only one process line is connected to the MCO, it is not possible to establish a flow path through the MCO so as to feed and bleed the MCO and remove particulate from the MCO for an extended period of time. To get a substantial release from the CSB, the MCO internal filter must be failed open and the break must occur in a section of process piping upstream of the sampler's high-efficiency particulate air (HEPA) filter (or the sampler's HEPA filter must be assumed to be failed open for a break location downstream of the sampler's HEPA filter). The entire sampling process is a manual operation, and the technician taking the sample is present at all times.

Hazard analysis checklist entry WS-G-03b involves equipment dropping onto the top of the MCO during the short time that the port cover is removed and the valve operator is not installed (HNF-SD-SNF-HIE-001). To cause a release, the dropped object must be small enough to fit into the MCO shield plug cavity and hit the port valve and massive enough to damage the valve to the extent that a substantial leak ensues. Such equipment has not been identified, so this event is considered not credible.

Hazard analysis checklist entry WS-H-06a involves pressurizing the MCO from the CSB helium supply system to the extent that the MCO design pressure is exceeded, thereby failing the MCO (HNF-SD-SNF-HIE-001). This event requires (1) a failure of the pressure regulator that regulates the sampling system inert gas supply pressure to 120 lb/in² gauge, (2) a failure of the safety relief valve (set to relieve at $135 \pm 10\%$ lb/in² gauge), and (3) an undetected failure of the sampling system refill regulator. If the MCO is pressurized because of regulator failures, the pressurized helium supply piping of the sampling system could carry helium to the safety relief valve but there would be no flow path through the MCO. The safety valve will close when the helium supply is exhausted or interrupted, and there will be no release of radioactive material from the MCO. Therefore, this event is not considered for dose calculations.

Conditions required to develop the design basis gaseous release accident at the sampling/weld station are shown in Figure 3-1. This accident could be caused by dropping or crashing equipment into the process system equipment, by random failures of the process equipment, or by operator error. The sequence of events leading up to and following the accident and possible mitigating features are depicted in Figure 3-2. The bounding gas release event is, therefore, failure of the sampling system pressure bounding during sampling. The magnitude of the radioactive release and subsequent dose associated with this type of accident is a function of the MCO's particulate loading at the time of the event.

The sampling process begins when the MHM lowers the selected monitored MCO into the sampling/weld station pit. The surface temperature of the MCO is monitored. If the surface temperature of the top of the MCO exceeds a worker safety range, then the MCO can be cooled using the sampling/weld station cooling cap to reduce the temperature consistent with standard industrial safety regulations. After installing temporary radiation shields and guard rails, the sampling hood is installed on the MCO to confine possible airborne contamination generated by an accidental release during sampling. The MCO sampling cart is connected to the local distributed control system and inert gas connections. The sampling cart's piping to the sample gas accumulator is connected to the sampling hood's HEPA filter outlet using a quick-disconnect, and the sample cart vent's flexible hose is connected to the sampling hood discharge, which dumps to the exhauster. This exhaust system fan is turned on to establish a negative pressure relative to the operating area atmosphere inside the sampling hood to maintain air contamination control around the top of the MCO.

An MCO process valve operator is installed on the short tube port of the MCO (port 2) after the cover plate is removed. The process valve operator is connected, with a quick-disconnect coupling, to a flexible hose that connects to the inlet of the sampler's HEPA filter. The remainder of the sample system piping is (1) the flexible pipe that connects the outlet of the

sampler's HEPA filter to the sample cart and (2) the rigid pipe in the sample cart that attaches to the sample valve and the sample accumulator.

A leak in the confines of the sample hood would be exhausted quickly through the sampling/weld station HEPA filter or exhaustor to the CSB exhaust system plenum and out to the environment through the CSB stack. Leaks from the sample system outside of the sample hood would be to the CSB atmosphere.

The effective leak flow area is bounded by the flow area of the path through the MCO shield plug, which is a 1.0-in.-diameter hole. All of the sampling system piping outside of the sampling hood is ≤ 0.75 -in. diameter except the sample line to the cart, which is 1 in. in diameter. The flexible hose inside the sample hood is nominal 1.0-in. diameter; a break of that hose could result in an approximately 1.0-in. diameter flow path from the MCO. This maximum area leak path could occur also if the valve operator body is improperly secured to the top of the MCO. If the valve operator body is improperly secured to the top of the MCO, then the leak path flow area around the valve could be large enough to make the flow area of the shield plug the limiting flow area. Therefore, the largest leak flow path area would be a leak into the sample hood. Sampling system leaks outside of the sample hood would have smaller flow area paths and would have traveled through the sampler's HEPA filter.

3.3 SOURCE TERM ANALYSIS

Section 4.4.2.3.2, page 4-73, of DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions/Rates for Nonreactor Nuclear Facilities*, documents airborne release fractions and respirable fractions. These fractions are derived from experiments in which pressurized gases are vented through fine uranium oxide powders. The airborne release fraction for venting through a powder is considered bounding or representative of an MCO blowing down through a significant leak in the MCO sampling system pressure boundary. Based on the data reported in DOE-HDBK-3010-94 for pressures of 0.17 MPaG and less, a conservative release fraction of 2×10^{-3} is assessed to be bounding. The bounding release fraction for this lower pressure regime is considered appropriate because high pressure gas will not be escaping directly through a powder-covered opening. During gaseous release accident, the gases escaping from the MCO entrain particulate from the surfaces of the spent nuclear fuel (SNF) as they flow past them toward the leak in the MCO. The speed of the gas at the SNF surfaces is much lower than at the pressurized opening, where the particulate was available during the experimental measurements. The rate of particulate entrainment is strongly dependent on the airspeed. This bounding airborne release fraction is commensurate with the value from DOE-HDBK-3010-94 for accelerated airflow parallel to a powdered surface, which could be the dominant effect for low-pressure venting powder.

For the gaseous release accident, the particulate available for release would be generated after the fuel is washed and could be very similar to powder lying on a heterogeneous surface. The contents of the MCO are intact fuel elements tightly packed in the fuel baskets and the pieces of fuel elements housed in the scrap basket. Particulate matter swept up by the streams of flowing

gas within the MCO does not simply enter the general CSB airspace to be available for dispersion in the environment. Once a particle is swept up by the flowing gas, it must take a tortuous path through the rest of the MCO and through the MCO shield plug to exit the MCO.

The MCO gaseous release accident could happen only within the first year after an MCO is loaded, based on the schedule for sampling MCOs. HNF-3048, *Post Fuel-Cleaning Corrosion of Uranium within MCO Payloads*, states that the bounding value for the mass of particulate at the end of the first year is 34.0 kg of uranium dioxide, which contains 30.0 kg of uranium.

The gaseous release event with the bounding particulate release from the MCO would be that which results from a leak close to the MCO through a leak path with a flow area greater than or equal to the flow area through the MCO shield plug. This could be the result of a complete severance of the pipe or flexible tubing within the sampling/weld station sample hood or failure to tighten the hold down bolts on the MCO port valve operator. For a leak path flow area of this size, the MCO would depressurize to atmospheric pressure in less than a minute (SNF-2770, Figure 7-4), even for an MCO pressure of about 75 lb/in² gauge. The MCO would depressurize in a much shorter time for MCO pressure values less than 10 lb/in² gauge, which are very likely to be the case.

The MCO gases and any radioactive particulate matter released from the MCO during this event would be released through the MCO shield plug port, which contains the internal HEPA filter. Because the internal HEPA filter is not testable, it is assumed to be failed open for this event and not inhibiting entrained particulate matter escaping from the MCO into the sampling/weld station sample hood. The MCO sampling/weld station heating, ventilation, and air conditioning system draws air through the sampling/weld station hood at the rate of 100 to 250 ft³/min into a filter train and then blows the air into the CSB exhaust system plenum. This air then goes up the exhaust stack and is released to the environment.

The amount of respirable material released during the blowdown from the MCO will be calculated using the following formula:

$$Q = (MAR)(RF)(LPF)$$

where

MAR = material at risk (30.0 kg)
 RF = release fraction (2×10^{-3})
 LPF = leak path factor (conservatively set to 1.0)
 Q = amount of respirable material released.

For this event, the amount of respirable radionuclide material released is

$$\begin{aligned} Q &= (30.0 \text{ kg})(1,000 \text{ g/kg})(1.0)(2 \times 10^{-3})(1.0) \\ &= 60. \text{ g.} \end{aligned}$$

3.4 CONSEQUENCE ANALYSIS

The radiological dose (effective dose equivalent) to a receptor is calculated by using the following equation:

$$\text{EDE} = (M) \left(\frac{\chi}{Q'} \right) (\text{BR})(\text{UD})$$

where

- EDE = the effective dose equivalent, rem
- M = the respirable quantity released into the air, grams
- χ/Q' = the air transport factor, s/m³ (see Table 3-1)
- BR = the average inhalation rate during the release, m³/s
- UD = the committed effective dose equivalent per unit gram inhaled.

Table 3-1. Maximum Individual Locations and Air Transport Factors Used in the Calculations.

Receptor location	Acute (<1 hour)
Onsite (100 m ESE)	3.41 E-02
Highway 240 (9,280 m W)	2.36 E-05
Hanford Site boundary (17,390 m E)	1.30 E-05

Note: Air transport factors are for ground-level releases, and the units are s/m³. Values are taken from Table 1 of HNF-SD-SNF-TI-059, 1999, *A Discussion on the Methodology for Calculating Radiological and Toxicological Consequences for the Spent Nuclear Fuel Project at the Hanford Site*, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington.

Radiological inhalation dose consequences for each set of accident conditions are analyzed based on the following assumptions:

- Breathing rate (BR) – The light activity breathing rate of 3.33×10^{-4} m³/s, as specified in HNF-SD-SNF-TI-059, *A Discussion on the Methodology for Calculating Radiological and Toxicological Consequences for the Spent Nuclear Fuel Project at the Hanford Site*, is used for all receptors.
- Dose conversion factor (UD) – The dose per unit of respirable material inhaled is 4.38×10^5 rem/g of fuel as specified in HNF-SD-SNF-TI-059. All the material released from the building is treated as respirable (i.e., <10 µm aerodynamic diameter).

The actual duration of the release is expected to be less than one hour for all receptors; therefore, the applied χ/Q value is conservatively chosen for a 1-hour duration. All of the air transport factors used in this analysis are summarized in Table 3-1. Using the respirable radionuclide release quantities and the air transport factors (see Table 3-1), doses to various receptors are calculated as demonstrated below.

For the onsite collocated worker

$$\begin{aligned} EDE_{\text{Onsite}} &= (60.00 \text{ g}) \left(3.41 \times 10^{-2} \frac{\text{s}}{\text{m}^3} \right) \left(3.33 \times 10^{-4} \frac{\text{m}^3}{\text{s}} \right) \left(4.38 \times 10^5 \frac{\text{rem}}{\text{g}} \right) \\ &= 300.00 \text{ rem (3.0 Sv)} . \end{aligned}$$

3.5 COMPARISON TO GUIDELINES

The U.S. Department of Energy-recommended radiological risk evaluation guidelines (Sellers 1997) are shown in Table 3-2. The annual frequency of a helium leak in the sampling system is estimated to be the sum of the frequency of a leak from the MCO sampling system pressure boundary configuration that exists during sampling. This includes (1) a leak resulting from failure to properly seal the MCO valve operator at the sampling/weld station; (2) leaks from the process line inside the sample hood; and (3) leaks from the process line outside the sample hood, which includes the piping in the sample cart (see Appendix A):

$$(1 \times 10^{-2}) + (1.6 \times 10^{-5}) + (1.6 \times 10^{-5}) \approx 1 \times 10^{-2}/\text{year}.$$

This places this event into the anticipated category.

The unmitigated radiological dose to the onsite worker from the gaseous release accident is calculated to be greater than the onsite risk evaluation guidelines for anticipated events. The dominant features of the CSB design in reducing doses associated with sampling system leak accidents are the HEPA filter train of the sample hood air system, which discharges to the CSB general exhaust system, and the HEPA filter on the sample line located on the sample hood. These filters will mitigate releases associated with breaches of the sample line inside and outside of the sample hood. All CSB HEPA filters will be required, upon initial procurement, to meet an operating efficiency of 99.9%. Safety analysis will require only that post-installation testing demonstrate that the filters meet the operating efficiency of 99.9% assumed in the safety analysis to reduce the likelihood that a filter, after some use, will not meet the minimum desired efficiency. The respirable quantity released into the air is therefore reduced by a minimum factor of 1,000. The resultant mitigated dose for the bounding gaseous release accident is provided in Table 3-3.

Table 3-2. Radiological Evaluation Guidelines and Limits.

Event category	Frequency range (per year)	Onsite risk evaluation guidelines,* rem (Sv)	Offsite accident release limits,* rem (Sv)
Anticipated	1.0 E-01 to 1.0 E-02	1.0 (0.01)	0.5 (0.005)
Unlikely	1.0 E-02 to 1.0 E-04	10.0 (0.1)	5.0 (0.05)
Extremely unlikely	1.0 E-04 to 1.0 E-06	25.0 (0.25)	5.0 (0.05)

Note: All doses are committed effective dose equivalent.

*This terminology is consistent with Tables 1 and 2 of Sellers, E. D., 1997, *Risk Evaluation Guidelines (REGs) to Ensure Inherently Safer Designs* (Letter 97-SFD-172 to H. J. Hatch, Fluor Daniel Hanford, Incorporated, August 26), U.S. Department of Energy, Richland Operations Office, Richland, Washington.

Table 3-3. Dose Calculation Summary for a Bounding Gaseous Release Event at the Sampling/Weld Station.

Receptor location (distance, direction)	Duration (hours)	Unmitigated dose ^a , rem (Sv)	Evaluation guideline ^b / release limits, rem (Sv) anticipated ^c	Safety-significant mitigated dose, rem (Sv)
Onsite (100 m E)	<1	300 (3.0)	1.0 (1.0 E-02)	0.3 (0.003)
Highway 240 ^d (9,280 m W)	<1	2.1 E-01 (2.1 E-03)	--	2.1 E-04
Hanford Site boundary (17,390 m E)	<1	1.1 E-01 (1.1 E-03)	0.5 (5.0 E-03)	1.1 E-04

^aFifty-year committed effective dose equivalent.

^bEvaluation guideline for onsite (100 m) receptor only.

^cAnticipated event frequency is >0.01 to ≤0.1 per year.

^dProvided for information only.

3.6 SUMMARY OF SAFETY STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

The following safety-class and safety-significant equipment and Technical Safety Requirement (TSR) controls are designated to mitigate the dose consequences of the bounding gaseous release accidents.

3.6.1 Gaseous Release during the Multi-Canister Overpack Sampling Operation

The release of MCO gases during the MCO sampling operation is a result of a leak from the sampling system. Such a leak could result from the sampling/weld station gantry crane, the MHM, or some other equipment moving horizontally into the sampling/weld station components and causing a shear of the piping or otherwise failing the sampling system pressure boundary. The following are the specific safety features and controls that reduce the frequency of or mitigate this event:

- Safety-significant structures, systems, and components (SSCs)
 - MHM interlock (P10), sensors, and switches (MHM collision avoidance system) — Remove power from MHM bridge trolley drive motors upon collision with the MCO sampling/weld station
 - Seismic restraints on the sampling/weld station gantry crane — Prevent motion of the gantry crane when the gantry crane is in position over the MCO for sampling, the MCO is connected to the sampling system, and the MCO port valve is open
 - Sampling/weld station gantry crane bumper — Activates the MHM collision avoidance system
- TSRs
 - Verify operability of MHM interlock (P10), sensors, and switches
 - Verify application of the seismic restraint on the gantry crane before connecting the sampling line to the MCO
 - Check HEPA filter operating efficiency in accordance with ASME N510, *Testing of Nuclear Air Cleaning Systems*.

3.6.2 Gaseous Release from Overpressurization of the Multi-Canister Overpack

The release of MCO gases resulting from overpressurization of the MCO is caused by the inert gas system during reinerting of a monitored MCO after sampling. This accident is initiated by failure of the pressure regulator on the helium supply system while an MCO is in the sampling/weld station undergoing the MCO helium backfill operation. The following are the specific safety features and controls that reduce the frequency of or mitigate this event:

- Safety-class SSCs
 - Pressure safety devices — Are provided to prevent the exceedance of MCO safety limits and provide protection from pressure internal to the MCO from exceeding design value of 150 lb/in² gauge when sampling the MCO; there shall

be at least two independent safety devices, each with the flow capacity to relieve the maximum flow rate of gas through a failed open pressure regulator

- Safety-significant SSCs
 - Pressure safety device — Is provided to prevent releases from the sampling system when sampling the MCO. This pressure safety device will maintain pressure to less than design value (150 lb/in² gauge)
- TSR
 - Three pressure safety devices, one on the MCO sampling system and two on the helium supply system, must be installed and operable.

In addition, the maintenance of gas cylinders is assumed to be controlled by the site/project maintenance program. This program will verify that the gas cylinders have orifice flow restrictors that prevent excessive gas flow from the cylinders. As such, a TSR is not required.

The SSCs and TSR controls designated to mitigate gaseous release accidents are summarized in Table 3-4. U.S. Nuclear Regulatory Commission important-to-safety category SSCs and defense-in-depth features also are included.

The suite of safety SSCs and TSR controls necessary and sufficient to reduce the frequency of occurrence of the two gaseous release accidents to beyond extremely unlikely do not address some of the other accidents in the same accident category. Table 3-4 also lists the safety SSCs and TSR controls needed to prevent or mitigate these accidents. Because these accidents are substantially different in development and progression from the design basis accidents, each scenario and the corresponding controls are also described below.

3.6.3 Pressurized Release Caused by a Cask Lid Drop or Drop from Multi-Canister Overpack Handling Machine

When at the service area, the transportation cask lid can be dropped onto the cask-MCO or the MCO can be dropped from the MHM either back into the transportation cask or onto the edge of the cask as the MCO is being raised out of the cask into the travel position in the MHM. If the MCO is dropped onto the edge of the cask, the falling distance from the maximum possible elevation of the MCO in the MHM to the top of the transportation cask is approximately 8 ft. The MCO is designed to maintain its integrity following such a drop (HNF-SD-SNF-DP-010). The MCO also can be dropped from the maximum possible height in the MHM to the bottom of the transportation cask; a distance of about 21.2 ft. An impact absorber in the MCO service station pit, located under the cask, will absorb energy of the falling MCO and prevent damage to the MCO that could result in the release of MCO gas (HNF-SD-SNF-DP-010). The following are the specific safety features and controls that reduce the frequency of or mitigate this event:

Table 3-4. Summary of Safety Features Required to Mitigate the Consequences of a Gaseous Release Design Basis Accident. (4 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
Pressurized release from MCO				
1. Gaseous release during MCO sampling operations	WS-F-02 WS-F-05	Prevent equipment, moving horizontally, from damaging the sampling system	<u>Safety-significant SSCs:</u> <ul style="list-style-type: none"> • MHM interlock (P10), sensors, and switches (MHM collision avoidance system) • Seismic restraints on the sampling/weld station gantry crane • Sampling/weld station gantry crane bumper <u>TSRs:</u> <ul style="list-style-type: none"> • Verify operability of MHM interlocks, sensors, and switches (P10) • Verify application of the seismic restraint on the gantry crane prior to connecting the sampling line to the MCO • HEPA filter operating efficiency <u>Defense in depth:</u> <ul style="list-style-type: none"> • Personnel are trained to procedures detailing the safe sequence of operations. • The operators of the MHM are trained and qualified to perform their duties safely, which includes following procedures for safe operation. • Regular maintenance is performed on the MHM to ensure it is in good working order.^c 	NA NA NA
2. Gaseous release from overpressurization	WS-H-06a WS-H-07 WS-H-11	Protect the sampling system piping and the MCO from internal pressure that exceeds design pressure	<u>Safety-class SSCs:</u> <ul style="list-style-type: none"> • Helium supply system pressure safety devices (two) <u>Safety-significant SSCs:</u> <ul style="list-style-type: none"> • Pressure safety device (one) on sampling system <u>TSR:</u> <ul style="list-style-type: none"> • Three pressure safety devices, one on the MCO sampling system and two on the helium supply system, must be installed and operable 	A

Table 3-4. Summary of Safety Features Required to Mitigate the Consequences of a Gaseous Release Design Basis Accident. (4 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
3. Pressurized release caused by cask lid drop or by drop from MHM	SA-G-03a	Prevent the MCO from structural deformation that results in a leak of MCO internal gases from the MCO	<p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> • MCO service station impact absorber • MCO^d <p><u>TSRs:</u></p> <ul style="list-style-type: none"> • Impact absorber is installed in the MCO service station pit and is operable • Cask lid may only be removed by a crane and hoist lifting device that physically cannot lift the lid more than 5 ft above the top of the MCO. <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> • The MHM grapple is designed with a mechanical lock such that it should not be able to open while a load is suspended from it. • Personnel are trained to facility-specific procedures in the proper handling of the transportation cask, MCO, receiving crane, gantry, and MHM. • Lifting devices used at the CSB are designed to handle the loads they will carry. 	NA NA
4. Drops of objects onto the sampling/weld station	WS-G-03b WS-G-04 WS-G-06 WS-G-07	Prevent falling objects from falling into the sampling system components	<p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> • Seismic restraints on the sampling/weld station gantry crane • Sample hood/sample hood exhaust system • Sample line HEPA filter • Sample hood exhaust flow indicating device <p><u>TSRs:</u></p> <ul style="list-style-type: none"> • Perform a pressure-test of the port valve operator/MCO shield plug seal and of the sampling system pressure boundary within the sample hood up to and including the sampling line HEPA filter • Verify the air flow rate through the sampling hood • Double verification of pressure test of the sampling system pressure boundary integrity • Double verification that the MCO port valve is properly closed prior to removal of the port valve operator from the MCO shield plug • HEPA filter operating efficiency <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> • The MHM collision avoidance including guard rails. • Personnel are trained to facility-specific procedures in the proper handling of the transportation cask, MCO, receiving crane, gantry, and MHM. • The sampling/weld station gantry crane bumper activates the MHM anticollision system to prevent collisions with the sample hood and sample lines. • Lifting devices used at the CSB are designed to handle the loads they will carry. 	NA NA NA NA

Table 3-4. Summary of Safety Features Required to Mitigate the Consequences of a Gaseous Release Design Basis Accident. (4 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
5. Gas cylinder missile impacts	WS-F-06	Prevent high-pressure gas cylinders from becoming dangerous missiles in the CSB	<u>Design feature:</u> <ul style="list-style-type: none"> Maximum hole diameter in the butt of the valve on all gas cylinders <u>TSR:</u> <ul style="list-style-type: none"> A TSR is not required. <u>Defense in depth:</u> <ul style="list-style-type: none"> Operators are trained in the proper handling of compressed gas cylinders according to established procedures Gas cylinders have flow restrictors to limit forces from gas exiting the cylinder Gas cylinders supplying the inert gas system are located outside of the CSB 	NA
Possible release from cask-MCO				
6. Drop of the cask-MCO from the receiving crane	TV-G-13	Preclude the release of particulate by proper design of the MCO and transportation cask and to handle the transportation cask within the design basis parameters	<u>Safety-significant SSCs:</u> <ul style="list-style-type: none"> Transportation cask Service station impact absorber Cask transfer safety system Receiving crane height limiting devices MCO^d <u>TSR:</u> <ul style="list-style-type: none"> Use of proper yoke to lift the cask-MCO Setting crane height limiting device setpoints to ensure crane lift height with yoke attached does not exceed 40 in. <u>Defense in depth:</u> <ul style="list-style-type: none"> Transportation cask confinement of radionuclides Qualified crane operators. Maintenance and operations manuals and details are provided by crane vendors. The hoist design includes <ul style="list-style-type: none"> Interlocks to preclude lift and horizontal motion at same time Dual brakes No free fall capacity. Lifting devices used at the CSB are designed to handle the loads they will carry. Personnel are trained to facility-specific procedures in the proper handling of the transportation cask, MCO, receiving crane, and MFIM. 	B B B NA B

Table 3-4. Summary of Safety Features Required to Mitigate the Consequences of a Gaseous Release Design Basis Accident. (4 sheets)

Accident	Checklist designator ^a	General function	Safety feature and safety classification ^b	NRC ITS category ^b
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^aChecklist designators are from HNF-SD-SNF-HIE-001, 1999, *Canister Storage Building Hazard Analysis Report*, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^bSSCs are classified per their function in mitigating or preventing specific accidents. SSCs may have other classifications based on their functions in other events.

^cDE&S, 1999, *SNF CSB Operations & Maintenance Manual*, Volume 15, "MCO Handling Machine," Rev. 0, DE&S Hanford, Incorporated, Richland, Washington.

^dSafety-class features of the MCO and not CSB facility features; however, these MCO features provide structural capability to the MCO during this event: MCO shell, locking ring, and shield plug.

CSB = Canister Storage Building.

HEPA = high-efficiency particulate air (filter).

ITS = important to safety.

MCO = multi-canister overpack.

MHM = multi-canister overpack handling machine.

NA = not applicable to ITS category classification.

NRC = U.S. Nuclear Regulatory Commission.

SSC = structure, system, and component.

TSR = technical safety requirement.

- **Safety-significant SSCs**
 - MCO shell, locking ring, and shield plug (these are a safety-class feature of the MCO and not a CSB unique design feature) — Provide structural protection and confinement of the SNF when SNF is in an open transportation cask in the MHM or being transferred from the transportation cask to the MHM
 - Service station impact absorber — Limits deceleration forces to the MCO to 35 g if the MCO is dropped from the MHM back into the transportation cask; the impact absorber must be installed and operable when the MCO is being lowered into or being raised from the service station pit
- **TSRs**
 - Impact absorber is installed in the MCO service station pit and is operable
 - Cask lid may be removed only by a crane and hoist lifting device that physically cannot lift the lid more than 5 ft above the top of the MCO.

3.6.4 Drop of Objects onto the Sampling/Weld Station

The drop of an object onto the sampling/weld station components is another cause of a leak from the sampling system. Such a drop could shear the sampling system piping or otherwise fail the confinement capability of the sampling system pressure boundary. Safety-significant confinement by the sample hood, sample hood duct, and the sample hood exhaust HEPA filter is required. The exhaust fan associated with this exhaust system must be verified to be operating before opening the MCO port valve. It is not necessary to have safety-significant electric power for the fan because the loss of sample hood exhaust flow resulting from loss of electric power or mechanical failure coincident with a sampling system leak inside the sample hood is not credible. The following are the specific safety features and controls that prevent or mitigate this event. The following SSCs and TSRs are also designed to protect against operator error in connecting the sampling system to the MCO, against failure of sampling components, and against motion of the gantry crane that could damage the sampling apparatus:

- **Safety-significant SSCs**
 - Seismic restraints on the sampling/weld station gantry crane — Prevent motion of the gantry crane when the gantry crane is in position over the MCO for sampling, the MCO is connected to the sampling system, and the MCO port valve is open
 - Sample hood and sample hood exhaust system — Provide confinement of radioactive particulate by sweeping any particulate released from the MCO into the exhaust system HEPA filter train; the HEPA filter must be rated to operate at a minimum of 99.9 % efficiency, as assumed in the safety analysis,

and be aerosol tested in accordance with ASME N510; this system must be operating when the MCO is in the sampling/weld station pit, the MCO is connected to the sampling system, and the MCO port valve is open; minimum air flow rate of 5 ft³/min is required to entrain respirable particulate and move it into the HEPA filter

- Sample line HEPA filter — Provides confinement of particulate released from the MCO during the sampling operation; must be operable when the MCO is in the sampling/weld station, the MCO is connected to the sampling system, and the MCO port valve is open; the HEPA filter must be rated to operate at a minimum of 99.9 % efficiency, as assumed in the safety analysis
- Sample hood exhaust flow indicating device — Provides positive indication that the sample hood exhaust system is operating and shows the air flow rate
- **TSRs**
 - Perform a pressure-test of the port valve operator–MCO shield plug seal and of the sampling system pressure boundary within the sample hood up to and including the sampling line HEPA filter; the pressure test should ensure the integrity of the connection
 - Verify that the air flow rate through the sampling hood is at least 100 ft³/min just before opening the MCO port valve
 - Double verification of the pressure test of the sampling system pressure boundary integrity was performed and demonstrated that the system is sufficiently leak-tight to proceed with the sampling operation
 - The HEPA filter must be rated to operate at a minimum of 99.9% efficiency and checked in accordance with ASME N510
 - Double verification that the MCO port valve is properly closed before removal of the port valve operator from the MCO shield plug.

3.6.5 Compressed Gas Cylinder Missile Impacts

A high-pressure gas cylinder is not expected to become a missile that could crash into the sample system and shear the piping because the gas cylinders used for MCO sampling and welding operations will be located outside the CSB. The only bottles available to create this hazard are those on the tube vent and purge cart and those brought into the facility for maintenance welding activities. Accidentally shearing the valve body from the cylinder, by dropping the cylinder or crashing something into the cylinder, would not result in the cylinder becoming a missile because the small orifice that remains in the neck of the bottle severely limits the flow rate of gas from the cylinder. Limiting the flow rate limits the thrust generated by the escaping gas such that the cylinder will not accelerate to a dangerous velocity. Removal of the flow-restricting orifice from

a pressurized cylinder is an extremely difficult task that could not be accomplished by one person without special equipment. The following are the specific safety features and controls that reduce the frequency of or mitigate this event:

- Design feature
 - Maximum hole diameter in the butt of the valve on all gas cylinders — Limits the thrust produced by escaping gas to an amount that cannot accelerate the cylinder to dangerous velocity; this feature provides protection against accidental breaking-off of the valve body on top of the cylinder
- TSRs
 - A TSR is not required for a design feature.

3.6.6 Drops of the Cask-Multi-Canister Overpack from the Receiving Crane

An accident that involves dropping the loaded transportation cask while moving the transportation cask from the MCO transporter to the service pit is not considered a design basis accident because the transportation cask provides a structural barrier to protect against the release of radionuclides from the MCO that would make the consequences of this accident less severe than for the gaseous release from the MCO at the sampling/weld station provided that the drop height is less than 40 in. The following are the specific safety features and controls that reduce the frequency of or mitigate this event:

- Safety-significant SSCs
 - MCO shell, locking ring, and shield plug (these are a safety-class feature of the MCO and not a CSB unique design feature) — Provide structural protection, containment, and confinement of SNF should the cask-MCO drop from the receiving crane
 - Transportation cask — Provides structural protection for the MCO
 - Receiving crane height limiting devices — Limit lift height above the floor (maximum of 40 in.) when lifting yoke is attached.
 - Service station impact absorber — Limits deceleration forces to the MCO to 35 g if the cask-MCO is dropped from the receiving crane; must be installed and operable when the cask-MCO is being lowered into or being raised from the service station pit
 - Cask transfer safety system — The impact absorber mitigates the impact of a cask-MCO drop onto the floor and its mechanical pivoting safety rails prevent the cask-MCO from falling on its side. Neither of these occurrences

leads to releases nor loss of criticality geometry. This is safety significant because it is required by NRC equivalency important-to-safety Category B for SSCs that apply to SNF

- TSRs

TSR controls are not required for the cask transfer safety system (those safety-significant SSCs resulting from only NRC equivalency requirements)

- Administrative control to verify use of the proper lifting yoke.
- Setting crane height limiting devices setpoints to ensure crane lift height with yoke attached does not exceed 40 in.

3.7 REFERENCES

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Figure 3-1. Logic Diagram for Canister Storage Building Pressurized Gaseous Release.

Figure 3-2. Gaseous Release at the Sampling/Weld Station and Mitigating Features.

4.0 CALCULATIONS FOR MULTI-CANISTER OVERPACK INTERNAL HYDROGEN EXPLOSION

4.1 PURPOSE AND OBJECTIVES

Three events have been identified that could result in formation of flammable mixtures of hydrogen and oxygen inside a multi-canister overpack (MCO) while at the Canister Storage Building (CSB). These are described in Section 4.2. The first identified event is radiolytic decomposition of oxygen-containing compounds, such as aluminum hydroxide and uranium oxide (hydrate). The second event is the charging of an MCO with a gas containing oxygen at the sampling/weld station. The third event is an ingress of air to an MCO that has been breached at the CSB.

The accident event with bounding consequences is the design basis explosion of a hydrogen-oxygen mixture at the sampling/weld station. No credit is taken for oxygen filtering. This accident could exceed the temperature limits for the MCO sample hose and lead to its rupture and release of particulate to the air. The environmental release of radioactivity in this accident gives doses to individuals located downwind that exceed guidelines. Mitigation strategies are discussed in Section 4.5. Required controls are summarized in Section 4.6.

4.2 SCENARIO DEVELOPMENT

In the postulated accidents, hydrogen accumulates because of radiolytic decomposition or corrosion of uranium in a moist environment. The general sequence of events leading to a hydrogen explosion is shown in Figure 4-1. Two conditions necessary for radiolytic production of hydrogen and oxygen in the MCO are (1) enough aluminum hydroxide, uranium oxide (hydrated), or free water and (2) a high enough radiation level, which is indicated by the thermal power of the fuel. Two conditions necessary for production of hydrogen by reaction with uranium inside the MCO are adequate amounts of exposed uranium metal and water vapor.

Radiolytic production of hydrogen and oxygen occurs slowly, and the hydrogen is produced at several times the rate of the oxygen. Thus, the mixture is not combustible until the oxygen concentration exceeds the minimum necessary. Such events will not take place until near the end of the projected storage period.

Charging the MCO with oxygen at the sampling/weld station would occur early in the storage period because sampling will take place then. Note that hydrogen accumulates rather quickly inside the MCO; the added oxygen creates a flammable mixture that then could explode. Because it takes very little energy to begin hydrogen-oxygen combustion, it has been assumed that ignition sources (e.g., static charge accumulated by moving gases, uranium hydride decomposition) are present where needed. The specific accident scenarios evaluated are described in the following subsections.

4.2.1 Hydrogen Explosion During Storage due to Radiolysis

Radiolytic decomposition of aluminum hydroxide, aluminum and iron hydrates, free water, and water bound as hydrates in the uranium oxide may lead to flammable mixtures of hydrogen and oxygen in an MCO. Hydrogen would be produced at a higher rate than the oxygen, making oxygen the limiting reactant. An explosion cannot occur until the oxygen concentration exceeds the minimum necessary.

Because oxygen gas reacts with uranium in damaged fuel elements, it is necessary to assume the active area of exposed uranium is zero. This is the minimum area assumption for safety basis calculations (HNF-SD-SNF-TI-017). With minimum exposed uranium, there is minimum hydrated water bound in the uranium oxides. Most of the oxygen comes from the aluminum hydroxide.

4.2.2 Hydrogen Explosion Following Oxygen Addition at the Sampling/Weld Station

At the sampling/weld station, the MCO is connected to the sample cart and a small gas sample is taken from the MCO. If an MCO with the bounding hydrogen concentration were depressurized at this point, it would be necessary to recharge the MCO with helium. If required, inert gas is added to the MCO to raise the internal pressure to 4.0 lb/in² gauge. Two methods for charging oxygen into the MCO have been postulated. One requires failing to purge air from the helium line so that air is forced into the MCO rather than helium. The other requires that the helium be contaminated with oxygen.

The helium line runs from the storage tank on the north side of the CSB to the sampling/weld station on the south side of the CSB. Because of its length, this pipe contains a large volume of air initially. It is possible for this line to be filled with air during a sampling sequence by omission of the helium purge steps.

Having a supply of helium contaminated with oxygen is possible because suppliers of compressed gases routinely prepare mixtures of helium and oxygen for medical use. Suppliers providing helium to the CSB will also be providing medical facilities with helium and oxygen mixtures.

By either method, oxygen is charged into an MCO with a bounding hydrogen concentration. The explosion is expected to occur shortly after the oxygen enters the MCO. Combustion temperatures and pressures are high enough that the hot gases forced from the MCO cause the sample line to melt. The compromise of the confinement boundary of the MCO leads to a release of particulate matter at the sampling/weld station. This scenario is diagramed in Figure 4-2. An event tree is provided in Appendix A.

4.2.3 Hydrogen Explosion Following an Air Ingress

It is assumed that the MCO is breached. Gases inside the MCO can escape, and gases outside the MCO can diffuse into the MCO. At some point there will be a flammable mixture in the MCO. The resulting explosion leads to a gaseous release of particulate matter.

4.3 SOURCE TERM ANALYSIS

The mathematical analysis of the postulated accidents focuses on the hydrogen and oxygen concentrations in an MCO. Mixtures of hydrogen in air are flammable in the range of 4% to 75% hydrogen by volume at atmospheric pressure. Very damaging shock waves may be produced if the hydrogen concentration is between 18 and 58 vol% in air (NUREG/CR-2726). The stoichiometric ratio (2 moles hydrogen per 1 mole of oxygen) corresponds to 29.6% hydrogen in air. The presence of helium changes the stoichiometric ratio because it displaces oxygen. For example, if there are equal volume percents of hydrogen and helium, then the stoichiometric hydrogen concentration is reduced to 22.8%. The minimum oxygen concentration needed for combustion is 4% (Bulletin 503). For a given oxygen and hydrogen concentration at higher initial gas pressures, the reaction is slowed by the increased amount of nonreacting atoms. The overall effect is to raise the minimum concentrations.

4.3.1 Basis for Hydrogen Explosion due to Radiolysis

The various assumptions used in this section are selected to show whether a combustible mixture of hydrogen and oxygen produced by radiolysis in the MCO is possible. These values should not be taken as limits.

Before leaving the Cold Vacuum Drying Facility (CVDF), the MCO is normally pressurized to about 152 kPa (1.5 atm or 7.4 lb/in²) with helium. To be conservative, the initial helium pressure is assumed to be 111.5 kPa (1.5 lb/in² gauge). The average temperature of this helium is assumed to be 25 °C (77 °F). The initial helium inventory is computed using the ideal gas law as shown below. The normal helium inventory is 30.7 moles, while the low pressure assumption gives 22.5 moles helium.

$$N(\text{He}) = (P_{\text{MCO}})(V_{\text{MCO}})/(R)(T_{\text{gas}})$$

where

- $N(\text{He})$ = number of moles of helium in the MCO initially, 30.7 moles
- P_{MCO} = pressure of the helium in the MCO, 1.5 atm
- V_{MCO} = volume of the MCO, 500 L
- R = ideal gas constant, 0.082057 L·atm/mole/K
- T_{gas} = temperature of the helium gas, 298 K (25 °C).

Oxygen and hydrogen are produced in the MCO by radiolysis of four materials: water, aluminum hydroxide, uranium oxide hydrate, and sludge hydrates. The principle reactions producing these gases are shown in Table 4-1. The oxygen is removed by reaction with exposed fuel to produce uranium oxide. This reaction is also shown in Table 4-1. The rate at which the production reactions take place depends on the radiation flux, the radiation interaction probability, and the radiolysis constants. The rate at which the removal reaction takes place depends primarily on the temperature of the fuel and its exposed area.

Table 4-1. Gas Production and Removal Reactions in the Multi-Canister Overpack.

Radiolysis reactions	
free water:	$2\text{H}_2\text{O} \longrightarrow 2\text{H}_2 + \text{O}_2$
uranium hydrate:	$2\text{UO}_3 \cdot 2\text{H}_2\text{O} \longrightarrow 2\text{UO}_3 \cdot \text{H}_2\text{O} + 2\text{H}_2 + \text{O}_2$ $2\text{UO}_3 \cdot \text{H}_2\text{O} \longrightarrow 2\text{UO}_3 + 2\text{H}_2 + \text{O}_2$
aluminum hydroxide:	$4\text{Al}(\text{OH})_3 \longrightarrow 2\text{Al}_2\text{O}_3 + 6\text{H}_2 + 3\text{O}_2$ $4\text{Fe}(\text{OH})_3 \longrightarrow 2\text{Fe}_2\text{O}_3 + 6\text{H}_2 + 3\text{O}_2$
Chemical reactions	
oxygen removal:	$\text{U} + \text{O}_2 \longrightarrow \text{UO}_2$
oxygen-free reaction with water:	$\text{U} + 2\text{H}_2\text{O} \longrightarrow \text{UO}_2 + 2\text{H}_2$
uranium hydride reaction:	$2\text{UH}_3 + 4\text{H}_2\text{O} \longrightarrow 2\text{UO}_2 + 7\text{H}_2$

The radiation flux and the fuel temperature are proportional to the power level. To simplify matters and to be conservative, all of the energy associated with a particular radiation type is assumed to be absorbed in the MCO. Because the interaction of charged particles (e.g., alpha and beta radiation) is independent of the atomic number of the material, the relative amount of energy deposited in the various materials inside the MCO depends only on the relative mass of the material. For photon radiation, the interaction probability depends on the atomic number as well as the energy of the radiation. The relative amount of energy deposited in the various materials is the ratio of the products of the mass absorption coefficient times the mass of the material. These relationships are summarized in the following equation. The equation for oxygen production has the same form, except that radiolysis constants for oxygen are substituted.

$$dN_X(\text{H}_2)/dt = (C)(M_X/M_U)(Q)\{(F_{XU})[(F_a)(G_X^a(\text{H}_2)) + (F_b)(G_X^b(\text{H}_2))] + (F_r)(G_X^r(\text{H}_2))(\mu_X/\mu_U)\}$$

where

$$dN_X(\text{H}_2)/dt = \text{rate of } \text{H}_2 \text{ generation by radiolysis of material X, mole/year}$$

$$C = \text{conversion factor} = 3.138 (\text{mole})(100 \text{ eV})/(\text{watt})/(\text{year})/(\text{molecule})$$

M_X/M_U	= ratio of mass of material X in the MCO to the mass of uranium in the MCO
Q	= radiation power level in MCO, watts
F_{XU}	= fraction of material X mass, which is uranium; it also represents a charged particle interaction fraction in material X
F_α	= fraction of MCO power caused by alpha radiation; modeled as an increasing exponential resulting from production by radioactive decay of other isotopes
$G_X^\alpha(H_2)$	= radiolysis constant for H_2 generation in material X by alpha radiation, molecules H_2 per 100 eV deposited in material X
F_β	= fraction of MCO power caused by beta radiation; modeled as a decreasing exponential
$G_X^\beta(H_2)$	= radiolysis constant for H_2 generation in material X by beta radiation, molecules H_2 per 100 eV deposited in material X
F_γ	= fraction of MCO power caused by gamma radiation; modeled as a decreasing exponential
$G_X^\gamma(H_2)$	= radiolysis constant for H_2 generation in material X by gamma radiation, molecules H_2 per 100 eV deposited in material X
μ_X/μ_U	= ratio of the mass energy absorption coefficient for material X to the coefficient for uranium.

Parameters used in the calculations are shown in Tables 4-2 and 4-3. The fractions of the total MCO thermal power for each radiation type are derived from the 1995 and 2040 power levels, and the assumed formulas are shown in Table 4-2. Note that fuel drying does not happen until the year 2000, or 2 years after the current dates for bounding power levels given in HNF-SD-SNF-TI-015, *Spent Nuclear Fuel Project Technical Databook*. These power fractions are plotted in Figure 4-3. The formulas for beta and gamma radiation shown on Table 4-2 are from HNF-SD-SNF-TI-040, *MCO Internal Gas Composition and Pressure During Interim Storage*. The formula for alpha radiation is different but represents the increase in power fraction more accurately.

The masses shown on Table 4-3 are taken from HNF-SD-SNF-TI-015. The exposed uranium fuel surface area also is assumed to determine the amount of uranium hydrate and free water present. The bounding case MCO with no scrap baskets has intact fuel. The exposed area is zero; thus, the free water inventory is zero. There is a small amount of uranium oxide associated with the sludge that does not become zero. With no scrap baskets, the uranium oxide amount is 320 g.

Table 4-2. Parameters to Model the Decreasing Multi-Canister Overpack Power Level.

Parameter	Alpha radiation	Beta radiation	Gamma radiation
Scale factor, SF	0.2447	0.4862	0.3171
Half life	14.3 y	28.8 y	28.7 y
Decay constant, L	0.0486 y^{-1}	0.0241 y^{-1}	0.0242 y^{-1}
Time offset, t_0	33.5 y	NA	NA

If "t" is the elapsed time (years since 1995), then the fractions of total power contributed by each type of radiation are listed below:

$$\text{alpha radiation: } F_{\alpha} = (SF_{\alpha})\{1.00 - \text{Exp}[-(L_{\alpha})(t+t_0)]\}$$

$$\text{beta radiation: } F_{\beta} = (SF_{\beta})\text{Exp}[-(L_{\beta})(t)]$$

$$\text{gamma radiation: } F_{\gamma} = (SF_{\gamma})\text{Exp}[-(L_{\gamma})(t)].$$

NA = not applicable.

Table 4-3. Parameters for Calculating the Rate of Hydrogen and Oxygen Generation Within a Multi-Canister Overpack.

Parameter	H ₂ O, free	UO ₃ ·2H ₂ O	UO ₃ ·H ₂ O	Al(OH) ₃	Al & Fe hydrate
M _X	200 g	320 g	0	10,650 g	1,280 g
G _X ^α (H ₂)	1.5	0.168	0.089	0.520	0.260
G _X ^β (H ₂)	0.45	0.050	0.027	0.156	0.078
G _X ^γ (H ₂)	0.45	1.2	1.2	1.2	1.2
μ _X , cm ² /g	0.03264	0.06534	0.06727	0.03015	0.02982
μ _X /μ _U	0.421	0.843	0.868	0.389	0.385
G _X ^α (O ₂)	0.75	0.084	0.044	0.260	0.130
G _X ^β (O ₂)	0.225	0.025	0.013	0.078	0.039
G _X ^γ (O ₂)	0.225	0.102	0.059	0.134	0.110
Molecular wt	18 g/mole	322 g/mole	304 g/mole	78 g/mole	92.5 g/mole
F _{XU}	1.0	0.739	0.783	0	0.011

Notes: The total mass of uranium in the MCO is taken as 6,339.6 kg. The units for "G" values are molecules per 100 eV deposited. Values for "G" are from HNF-SD-SNF-TI-015, 1998, *Spent Nuclear Fuel Project Technical Databook*, Rev. 6, Fluor Daniel Hanford, Incorporated, Richland, Washington. Mass absorption coefficient ratios are at an energy of 662 keV, which is the principle component of the gamma spectrum. The mass absorption coefficient are from ANSI/ANS-6.4.3, 1991, *Gamma-Ray Attenuation Coefficients and Buildup Factors for Engineering Materials*, American National Standards Institute, New York, New York. For uranium the value is 0.07753 cm²/g.

MCO = multi-canister overpack.

The radiolysis constants are taken from HNF-SD-SNF-TI-015. For gamma radiation the hydrogen and oxygen constants are stoichiometric (i.e., 2 to 1). However, for the other materials, the hydrogen production is more than 10 times the oxygen production. This difference is not well explained; it appears to be a combination of oxygen entrapment and hydrogen over-estimation.

The values for the mass absorption coefficients shown on Table 4-3 are taken from ANSI/ANS-6.4.3, *Gamma-Ray Attenuation Coefficients and Buildup Factors for Engineering Materials*. The values chosen are at the dominant energy of the photon spectrum, 662 keV, characteristic of Cs-137 and Ba-137m. The ratios of mass absorption coefficients are used in the calculations. The values shown were computed from a fifth-order interpolating polynomial using three table values of higher and lower energies.

Values for F_{xu} indicate the fraction of alpha and beta energy that may affect the material. For the uranium oxides, the value is the mole ratio of uranium and the compound. Water is assumed to be located in cracks and crevices, so the interaction fraction is 1.0. For aluminum hydroxide the interaction fraction is zero because the aluminum hydroxide is located on the cladding. For the canister particulate, the average interaction fraction is the mass of uranium divided by the mass of the canister particulate, that is $(236.5 \text{ g U})/(1,600 \text{ g}) = 0.148$. Because the canister particulate is 20% uranium oxide dihydrate, the interaction fraction can be computed also from the $\text{UO}_3 \cdot 2\text{H}_2\text{O}$ fraction as $(0.20)(0.739) = 0.148$.

For comparison with calculations presented in HNF-SD-SNF-TI-040, the fractions of hydrate and hydroxide removed by radiolysis were computed. These are shown on Table 4-4. The first two rows of fractions differ because of different values for radiolysis constants and mass absorption coefficients. In addition, there are slightly different power levels because the present calculations have 2 years of decay prior to the onset of radiolysis. This reduces the removal fractions as shown in Table 4-4.

Figure 4-4 shows the production of oxygen for all radiation types in each target material for no scrap baskets and intact fuel. It is assumed that the MCO is processed in the year 2000, which means that the power level has been decreasing for 2 years. Hence, the time scale begins at 2 years and ends at 42 years, corresponding to the years 2000 to 2040. The MCO is assumed to have a thermal power level of 776 W. There are no oxygen removal mechanisms in effect so that the relative importance of the various materials can be observed. The aluminum hydroxide contributes nearly all of the oxygen. The assumed effect of radiation on uranium dihydrate is to free one of the water molecules, leaving uranium monohydrate. The uranium monohydrate in turn loses its water, but at a slower rate. The contribution of free water is included for information. With intact fuel, the assumed free water is zero.

Figure 4-5 shows the production of hydrogen for all radiation types in each target material based on the same parameters used for Figure 4-4. As with the oxygen, most of the hydrogen comes from aluminum hydroxide. Both figures include the gas production from free water even though the assumption of intact fuel means no free water.

Table 4-4. Radiolysis Removal Fractions.

Conditions	Free water (%)	UO ₃ ·2H ₂ O (%)	Al(OH) ₃ (%)	Al & Fe hydrates (%)
HNF-SD-SNF-TI-040 396 W; 40 years	7.0	50	3.6	Not given
Present work 396 W; 40 years	6.9	45	3.6	4.8
Present work 776 W; 40 years	13	69	7.0	9.2
Present work 776 W; 1 years	0.39	4.2	0.28	0.36

The percentages are the fractions of the materials shown that are decomposed by radiolysis. These fractions are independent of the initial inventory of the material.

HNF-SD-SNF-TI-040, 1998, *MCO Internal Gas Composition and Pressure During Interim Storage*, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington.

Oxygen reacts readily with any exposed fuel to form uranium oxide as shown in Table 4-1. This lowers the oxygen concentration in the MCO. The reaction rate depends on the temperature of the fuel and the area of exposed fuel. The fuel temperature can be estimated using the method described in HNF-SD-SNF-TI-040. The equation for this is shown below. Values for the correlation constant are developed in Appendix A of HNF-SD-SNF-TI-040. The value recommended for fuel is $C_w = 9.5 \text{ W/K}$.

$$T_{\text{fuel}} = (W)/(C_w) + T_{\text{amb}}$$

$$T_{\text{gas}} = (0.75)(W)/(C_w) + T_{\text{amb}}$$

where

T_{fuel} = temperature of the fuel, in degrees Kelvin

T_{gas} = temperature of the MCO gas, in degrees Kelvin

W = total power of the MCO, in watts

C_w = correlation constant, 9.5 watts per degree Kelvin

T_{amb} = annual average ambient temperature, 285 K (12 °C).

The temperature of the MCO gas is assumed to be 75% of the difference with the ambient temperature. This temperature is needed to estimate the pressure of the gas in the MCO.

With large surface areas, the oxygen removal rate is large enough that the oxygen concentration is greatly reduced. When the oxygen concentration falls below 10 ppm by volume (0.001%), then the oxygen-free reaction between fuel and water vapor proceeds. The formula for

this reaction is shown in Table 4-1. To maximize the concentration of oxygen, the exposed fuel surface is reduced to the safety basis minimum, namely 0 m². The only oxygen-producing materials are aluminum hydroxide and sludge (canister particulate).

Figure 4-6 shows the total hydrogen and oxygen concentrations and the pressure inside the MCO as a function of time after leaving the CVDF. The initial MCO pressure upon leaving the CVDF is 1.1 atm. The MCO gas is entirely helium at the time it is sealed at the CVDF. Using the bounding inventories for free water and aluminum hydroxide, the oxygen concentration exceeds the minimum needed to support combustion (4.0%).

By the year 2040, the hydrogen concentration has reached 40.5% and the oxygen concentration has reached 4.7%. The MCO pressure at this time is 225 kPa (2.22 atm or 18.0 lb/in² gauge). The MCO gas temperature is 318 K (45 °C). The assumed power level is 776 W. Note that, for fuel coated in aluminum hydroxide, the maximum power level is 527 W (HNF-3035). At this lower power level, the peak oxygen concentration is 3.9% at a pressure of 186 kPa (1.83 atm or 12 lb/in²).

From the curves for hydrogen and oxygen, it is evident that these gases are not liberated in stoichiometric proportions. The ratio of hydrogen to oxygen is about 7 to 1, rather than the stoichiometric ratio of 2 to 1. It is assumed that most of the generated oxygen is held in the corrosion layer so that only hydrogen is free to accumulate. If this assumption is not true, then MCO pressures and oxygen concentrations would be higher.

4.3.2 Basis for a Hydrogen Explosion due to Oxygen in the Helium System

The composition of the gas inside the MCO shortly after it arrives at the CSB is assumed to be only helium and hydrogen. The hydrogen is generated primarily by reaction between exposed fuel and water vapor. The radiolytic decomposition of water and hydroxides adds very little and is not considered. For a reaction to occur rapidly, there must be a large, exposed fuel surface area. The MCO with two scrap baskets is bounding.

The bounding hydrogen content of an MCO with two scrap baskets will be estimated assuming the water reactions with uranium metal and uranium hydride occur at the same rate. From HNF-SD-SNF-TI-015, the enhancement factor for the metal reaction is 10 while the enhancement factor for the hydride reaction is 12. In addition, the metal reaction produces 1 mole of hydrogen gas for every mole of water reacted, but the hydride reaction produces 1.75 moles hydrogen for every mole of water reacted. The combined effect is that the hydrogen generation increases by the factor

$$\frac{(10)(1) + (12)(1.75)}{10 + 12} = 1.409$$

over the amount expected from the uranium metal reaction alone.

The hydrogen gas that could be generated from the uranium metal is limited by the amount of water available to react. The bounding free water estimate is 200 g in crevices and cracks. In addition, uranium oxide dihydrate will lose one of the water molecules at normal MCO temperatures (HNF-1523). Much of this loss may occur during drying at CVDF but, to maximize the hydrogen generation after drying, none will be assumed. The bounding hydrated water estimate for two scrap baskets is 1,190 g water (HNF-SD-SNF-TI-015). Half of this amount is available to react with uranium fuel to form hydrogen. The total water mass of 795 g is equivalent to 44 moles of water. The hydride enhancement described above leads to the bounding production of 62 moles of hydrogen in the MCO. From the ideal gas law, this hydrogen has a volume of 1,520 L at reference conditions.

The initial low helium inventory is 22.5 moles (see Section 4.3.1). Thus, the gas in the MCO is 27% helium and 73% hydrogen. Chapter 5.0 shows that the reaction producing this hydrogen can proceed rather quickly so that by the time an MCO is sampled it is reasonable to assume the above hydrogen inventory has been realized.

An MCO containing the bounding hydrogen gas inventory is vented at the sampling/weld station and assumed to be completely depressurized so that recharge with helium is necessary. However, instead of charging the MCO with helium, a gas mixture containing oxygen is added and creates a flammable mixture of hydrogen and oxygen in the MCO.

When the MCO is depressurized, the relative amounts of helium and hydrogen remain unchanged. The gas mixture is still 27% helium and 73% hydrogen. At a pressure of 1 atm and a temperature of 50 °C (122 °F), the MCO inventory is 18.9 moles total, or 13.9 moles hydrogen and 5.0 moles helium. This is below the bounding temperature to maximize the mass of hydrogen in the MCO at the time of gas recharge.

Adding a helium and oxygen mixture to the MCO increases the pressure in the MCO to 129 kPa (1.27 atm or 4.0 lb/in² gauge). The amount of gas added is calculated from the ideal gas law to be 5.1 moles. The final total in the MCO is 24.0 moles. The hydrogen concentration decreases from 73% to 58%. The oxygen concentration in the MCO depends on the oxygen concentration in the added gas. From the ideal gas law, the oxygen concentration in the MCO follows the absolute pressures. Thus, the final oxygen concentration is $0.27/1.27 = 0.213$ times the concentration of the added gas. If the added gas were 60% oxygen, then the oxygen concentration in the MCO would be 12.8%.

To achieve a flammable mixture at atmospheric pressure, the oxygen concentration must exceed 4.0% in the MCO. Thus, the oxygen concentration of the added gas must be greater than 19%. Note the oxygen concentration in air is 21%. To achieve a mixture in the MCO that will produce very damaging shock waves, the oxygen concentration in the MCO must be at least 9%. Thus, the flammable mixture in the MCO does not become very damaging until the oxygen concentration in the added gas exceeds 42%.

4.3.3 Basis for Hydrogen Explosion After an Air Ingress

As a result of an accident that breaches the MCO, the gases inside the MCO rush out. While recovery plans are being made, air diffuses into the MCO and the gas inside diffuses out. At some point, a flammable mixture is reached.

As discussed in Section 4.3.2, the low helium MCO contains a mixture of 73% hydrogen and 27% helium. When this mixes with air containing 21% oxygen and 79% nitrogen, the stoichiometric mixture of hydrogen and oxygen is reached after about 67% of the gas in the MCO has been replaced with air. The final mixture is 5% helium, 28% hydrogen, 14% oxygen, and 53% nitrogen. These determine the peak pressure during combustion.

4.3.4 Method to Estimate Peak Pressures due to Hydrogen Combustion

When the hydrogen and oxygen react, water vapor is formed and energy is released. To be conservative, it is assumed that the energy released stays in the gas and none is lost to the MCO components. The heat capacity of the gases allows the final temperature to be computed. This final temperature, together with the number of moles of gases in the MCO and the ideal gas law, is used to calculate the final pressure resulting from the combustion.

The heat of water vapor formation from hydrogen and oxygen gas is 57,800 cal/mole at a temperature of about 300 K (27 °C). The heat capacity of various gases is calculated from a quadratic formula as listed in Table 4-5.

Table 4-5. Parameters to Determine Heat Capacities.

Gas	A	B	C
H ₂	4.959	-1.96 E-04	4.76 E-07
N ₂	4.470	1.39 E-03	-6.90 E-08
O ₂	4.130	3.17 E-03	-1.01 E-06
H ₂ O	5.149	2.64 E-03	4.59 E-08
He	3.020	0	0

Notes: The heat capacity at constant volume (in cal/mole/K) is computed from the formula $C_v = A + B \cdot T + C \cdot T^2$, where T is the temperature of the gas. The heat capacities apply to the temperature range from 300 K (27 °C) to 1,500 K (1,227 °C). At higher temperatures the heat capacities are over-estimated.

The final temperature of the gas mixture is found using the following formula. The integration is between the initial temperature of the gas mixture before combustion and the final temperature of the gas mixture after combustion. The summation is over the types of gases

present in the MCO after combustion. Because the final gas temperature is unknown but determines the heat capacities, the temperature must be solved by an iterative process.

$$(H_F)(N_{H_2O}) = \int_{T_o}^{T_f} \left(\sum (C_{vi})(N_i) \right) (dT)$$

where

H_F = heat of formation of water from hydrogen and oxygen, 57,800 cal/mole formed as a vapor

N_{H_2O} = number of moles of water formed; computed as the smaller of the number of moles of hydrogen and twice the number of moles of oxygen (before combustion)

T_o = temperature of the gas mixture before combustion, in degrees Kelvin

T_f = temperature of the gas mixture after combustion, in degrees Kelvin

C_{vi} = heat capacity at constant volume of gas "i"; depends on the temperature of the gas (represented as a quadratic equation)

N_i = number of moles of gas "i" after the oxygen and hydrogen react.

For an explosion near the end of the projected storage period, the gas in the MCO is made of 22.5 moles helium, 17.3 moles hydrogen, 2.0 moles oxygen, and 0.9 mole water vapor. The MCO pressure at this time is 225 kPa (2.22 atm or 18 lb/in² gauge). The MCO gas temperature is 318 K (45 °C).

Because the oxygen concentration exceeds the minimum needed for combustion (4.0%), the combustion temperature and pressure will be computed. The combustion reaction uses all 2.0 moles of oxygen, together with 4.0 moles of hydrogen. This produces an additional 4.0 moles of water vapor. The final gas mixture in the MCO is 22.5 moles helium, 13.3 moles hydrogen, and 4.9 moles water vapor. The energy liberated by the formation of the water vapor is 233,000 calories.

By an iterative process, the final temperature of the gas mixture is calculated to be 1,640 K (1,370 °C). The corresponding pressure in the MCO is 1,110 kPa (11.0 atm or 146 lb/in² gauge). Because the welded MCO is designed to withstand internal pressures of 450 lb/in² gauge, the MCO is not damaged by this pressure. The energy liberated is absorbed in the MCO contents and walls, which increases their temperature.

The above radiolysis model was used to estimate bounding aluminum hydroxide and water inventories that would have combustion pressures greater than the MCO design pressure of 450 lb/in² gauge. The maximum thermal power level of 776 W was assumed. With a helium fill pressure of 1.1 atm, the MCO must have 48 kg of Al(OH)₃ present.

With less hydrogen in the MCO, the oxygen concentration is increased. The hydrogen might be reduced by lower radiolysis constants (values shown in Table 4-3 were bounding) or by hydrogen gettering (reaction between hydrogen and bare metal to form metal hydrides). The combustion temperatures and pressures would be affected by such a change in concentration. Several cases were run using an MCO inventory of 22.5 gmoles helium and 2.0 gmoles oxygen. Results are shown in Table 4-6. As the hydrogen inventory increases past stoichiometric (i.e., 4.0 gmoles hydrogen), the combustion energy remains constant. However, the combustion temperature declines because of the increased mass of gas in the MCO. The mass and temperature effects offset one another so that the combustion pressure in the MCO hardly changes with hydrogen inventory. Thus, if higher concentrations of oxygen are present because of decreases in hydrogen, there is no appreciable effect on the combustion pressure.

For an explosion at the sampling/weld station resulting from air in the helium line, the gas added to the MCO is 21% oxygen and 79% nitrogen. The composition of the gas before combustion is 5.0 gmoles helium, 13.9 gmoles hydrogen, 1.1 gmoles oxygen, and 4.0 gmoles nitrogen. The MCO pressure is 129 kPa (1.27 atm or 4.0 lb/in²). The MCO gas temperature is 323 K (50°C).

The combustion reaction uses 1.1 gmoles oxygen together with 2.2 gmoles hydrogen. This produces 2.2 gmoles water vapor. The final gas mixture in the MCO is 5.0 gmoles helium, 11.7 gmoles hydrogen, 2.2 gmoles water vapor, and 4.0 gmoles nitrogen. The energy liberated by the formation of the water vapor is 124,000 calories.

By an iterative process, the final temperature of the gas mixture is 1,408 K (1,134°C). The corresponding pressure in the MCO is 536 kPa (5.29 atm or 63 lb/in² gauge). This is well below the MCO design pressure of 450 lb/in². In addition, the sample line and connection are designed to withstand even greater pressure. However, the sample line is vulnerable to high temperatures. When the explosion occurs, the sample line can melt to the point that gases in the MCO rush out and carry particulate matter into the environment.

For an explosion at the sampling/weld station resulting from impure helium, if the gas added to the MCO is 60% oxygen, then the composition of the MCO gas before combustion is 7.1 moles helium, 13.9 moles hydrogen, and 3.0 moles oxygen. The MCO pressure at this time is 129 kPa (1.27 atm or 4.0 lb/in² gauge). The MCO gas temperature is 323 K (50 °C).

The combustion reaction at the sampling/weld station uses 3.0 moles of oxygen, together with 6.0 moles of hydrogen. This produces an additional 6.0 moles of water vapor. The final gas mixture in the MCO is 7.1 moles helium, 7.9 moles hydrogen, and 6.0 moles water vapor. The energy liberated by the formation of the water vapor is 355,000 calories.

Table 4-6. Effect of Hydrogen Inventory in the Multi-Canister Overpack on Combustion Pressures.

Hydrogen (gmoles)	Total (gmoles)	Gas concentration		MCO pressure (atm)	Combustion results	
		H ₂	O ₂		Temperature (K)	Pressure (atm)
2	26.5	7.55%	7.55%	1.41	1,335	7.45
3	27.5	10.91%	7.27%	1.46	1,762	9.98
4	28.5	14.04%	7.02%	1.51	2,138	12.28
5	29.5	16.95%	6.78%	1.56	2,067	12.21
6	30.5	19.67%	6.56%	1.62	2,003	12.16
8	32.5	24.62%	6.15%	1.72	1,888	12.09
10	34.5	28.99%	5.80%	1.83	1,789	12.04
12	36.5	32.88%	5.48%	1.94	1,703	12.02
16	40.5	39.51%	4.94%	2.15	1,558	12.02
20	44.5	44.94%	4.49%	2.36	1,441	12.06
24	48.5	49.48%	4.12%	2.57	1,345	12.14
28	52.5	53.33%	3.81%	2.78	1,264	12.24
32	56.5	56.64%	3.54%	3.00	1,195	12.35
36	60.5	59.50%	3.31%	3.21	1,135	12.48
40	64.5	62.02%	3.10%	3.42	1,083	12.62

Note: The MCO gases are at 50 °C. In addition to hydrogen, there are 22.5 gmoles helium and 2.0 gmoles oxygen.

MCO = multi-canister overpack.

By an iterative process, the final temperature of the gas mixture is about 3,060 K (2,790 °C). The corresponding pressure in the MCO is 1,060 kPa (10.5 atm or 140 lb/in² gauge). Because the oxygen concentration is high enough that shock waves may form, the average pressure is a factor of two higher (SFPE 1992). Before welding, the MCO design pressure is 150 lb/in²; therefore, the MCO is not expected to be damaged by the worst-case explosion. An MCO with mechanical closure is stable to an internal loading of 340 lb/in², and the after welding rated pressure is 450 lb/in². In addition, the sample line and connection are designed to withstand even greater pressure. However, the sample line is vulnerable to high temperatures. When the explosion occurs, the sample line can melt enough that gases in the MCO rush out and carry particulate matter into the environment.

The air ingress accident leads to a similar environmental release. When the gas mixture in the MCO explodes, the adiabatic flame temperature reaches 2,910 K (2,640 °C). The pressure in the MCO is 785 kPa (7.7 atm or 99 lb/in² gauge). Because the oxygen concentration is high enough that shock waves may form, the average pressure is a factor of two higher (SFPE 1992). Because the MCO is already open to the environment, the gases rush through the opening and carry particulate matter into the environment.

4.4 CONSEQUENCE ANALYSIS

The downwind doses for the contaminated helium accident are computed in the following subsections. The methodology is taken from HNF-SD-SNF-TI-059, *A Discussion on the Methodology for Calculating Radiological and Toxicological Consequences for the Spent Nuclear Fuel Project at the Hanford Site*. The particular inputs for this accident are the same as those used in the gaseous release accident. The risk guidelines are for an extremely unlikely event.

4.4.1 Downwind Dose Calculation Methodology

Inhalation doses to individuals located downwind of the CSB can be computed using the following equation (HNF-SD-SNF-TI-059). It is assumed that the individuals are not evacuated during plume passage because of the short duration of the release.

$$EDE = M_{\text{air}}(\chi/Q')(BR)(UD)$$

where

- EDE = the effective dose equivalent, Sv
- M_{air} = the respirable quantity released into the air, 60 g of uranium
- χ/Q' = the air transport factor, s/m³ (see Table 4-7)
- BR = the average inhalation rate during the release, 3.33×10^{-4} m³/s
- UD = the committed effective dose equivalent per unit gram inhaled, 4,380 Sv/g of uranium.

The air transport factors are for adverse wind conditions. These conditions are exceeded only 0.5% of the hours in a year. The approach used in U.S. Nuclear Regulatory Commission Regulatory Guide 1.145, *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants*, was used to compute the 99.5 percentile air transport factors. Plume meander and building wake effects have not been included because the release duration following the explosion is only a few minutes. The releases are assumed to take place at ground level.

Table 4-7. Comparison of Doses with Risk Guidelines for Downwind Receptors from a Bounding Internal Hydrogen Explosion at the Canister Storage Building.

Receptor location (distance and direction)	Air transport factor ^a (s/m ³)	Safety significant dose (CEDE ^b), rem (Sv)		Risk guideline ^c , rem (Sv)
		Unmitigated	Mitigated	
Onsite (100 m east)	3.41 E-02	3.0 E+02 (3.0 E+00)	Accident prevented	2.5 E+01 (2.5 E-01)
Highway 240 (9,280 m west)	2.36 E-05	2.1 E-01 (2.1 E-03)	Accident prevented	NA
Hanford Site boundary (17,390 m east)	1.30 E-05	1.1 E-01 (1.1 E-03)	Accident prevented	5.0 E+00 (5.0 E-02)

^aRelease is at ground level; release duration is less than 1 hour; no plume rise or plume meander has been assumed.

^bFifty-year committed effective dose equivalent from inhalation.

^cBased on the extremely unlikely frequency, 1 E-04 to 1 E-06 per year.

CEDE = committed effective dose equivalent.

NA = not applicable.

Hanford Site wind data collected at the Hanford Meteorological Station for the years 1983 to 1991 were used in computing the air transport factors. The worst-case locations are used for each receptor. The onsite individuals are 100 m east and 9,280 m west of the CSB. The offsite individual is located 17,390 m east. As shown in HNF-SD-SNF-TI-059, the computed air transport factors and unit dose factor lead to the minimum release amounts required to exceed the guidelines. The first guideline exceeded for extremely unlikely probability events is for the onsite worker location 100 m east of the CSB. The minimum release amount is 5.0 g of uranium fuel.

4.4.2 Consequences of a Hydrogen Explosion Due to Radiolysis

Because an explosion at the end of storage under bounding conditions has been shown to cause no harm to the MCO, there are no consequences to discuss.

4.4.3 Consequences of a Hydrogen Explosion Following Oxygen Addition at the Sampling/Weld Station

Much like the gaseous release accident, a release of pressurized gases following an internal explosion of hydrogen within an MCO is expected to cause particulate release that is dominated by entrainment of particulate as escaping gases flow past contaminated surfaces within the MCO. For pressurized releases through a powder, a conservative release fraction of 2×10^{-3} is assessed

to be bounding (DOE-HDBK-3010-94, Section 4.4.2.3.2). Applying this to the projected bounding MCO particulate loading (HNF-SD-SNF-TI-015) of 34 kg of uranium oxide, or 30 kg of uranium, leads to a value for M_{air} of 60 g of uranium. This release fraction is considered bounding because the result is based on experiments in which a pressurized gas was explosively released through a sample of powder. The hydrogen explosion during an MCO handling accident involves a pressurized release in which the gas surrounding the powder is suddenly released. Because the MCO vent path does not travel through the particulate it contains, the assumed release fraction is conservative.

Doses resulting from the oxygen addition event are shown on Table 4-7. The unmitigated case exceeds the onsite release guideline by a considerable margin. Therefore, safety-significant features are required to mitigate this accident.

4.4.4 Consequences of a Hydrogen Explosion After an Air Ingress

The same bounding release fraction used for the oxygen addition at the sampling/weld station can be used for this pressurized release. Because the same 34 kg of uranium oxide is at risk, the same release of 60 g of uranium fuel occurs. The resulting doses are the same as those shown in Table 4-7. Because the unmitigated case exceeds the onsite dose guideline, safety-significant features are required to mitigate this accident.

4.5 COMPARISON TO GUIDELINES

The consequences of a hydrogen explosion inside an MCO are primarily radiation doses to individuals downwind of the CSB. The internal hydrogen explosion scenario initiates a gaseous release. The projected doses, listed in Table 4-7, exceed the onsite guidelines for accidents in all probability categories. By initiating a program to ensure the helium received at the CSB is of adequate purity, the frequency of this event is reduced well below 10^{-6} per year. Failures by the helium supplier and CSB quality control personnel would be required for this accident to occur. An actual helium concentration measurement must be performed by the vendor to verify helium purity. The vendor's documentation verifying the testing and purity of the helium is checked when the helium bottles are received at the CSB. Thus, the risk associated with this event is lowered by reducing the estimated annual frequency of occurrence to beyond extremely unlikely (SNF-4042). The accident is prevented by ensuring the gas added to the MCO at the sampling/weld station is not contaminated with oxygen (i.e., 99% pure helium). Another method to eliminate such an event is to ensure the MCO is only depressurized enough to collect an adequate gas sample. Normal sampling is expected to lower the MCO pressure by <3.4 kPa (0.5 lb/in² gauge). Any MCO needing a pressure recharge after normal sampling would have a pressure near what it had when packed at the CVDF. In other words, very little hydrogen gas would be generated; thus, there would be insufficient hydrogen to cause an explosion if oxygen were added instead of helium.

For the air ingress accidents, the only mitigation is preventing accidents that would breach the MCO. Once such an accident occurs, the only way to prevent a hydrogen explosion is to keep air away from the MCO. The means to surround the MCO with an inert atmosphere exists at the CSB through the helium system and materials to construct impromptu confinement as needed.

4.6 SUMMARY OF SAFETY STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

No safety-class structures, systems, and components (SSCs) are required to reduce the frequency of occurrence of the hydrogen explosion design basis accident or to mitigate its dose consequences.

4.6.1 Oxygen Used as a Purge Gas

Under normal operating conditions, there is no external accumulation of flammable mixtures of hydrogen and oxygen. Under credible or accident conditions, safety-significant controls or equipment are required to ensure flammable concentrations of oxygen internal to the MCO are precluded. The safety-significant equipment and technical safety requirement (TSR) controls designated to prevent (reduce the annual frequency to beyond extremely unlikely) the dose consequences of hydrogen explosion accidents within the MCO are as follows:

- Good operating practices during the sampling process will not significantly depressurize the MCO. As little sample gas as possible should be taken from the MCO during sampling. Using a sampling operation that minimizes the need to refill the MCO with inert gas reduces the frequency with which this accident could occur. This sampling operation should be considered defense in depth for prevention of flammable gas mixtures within the MCO at the sampling station. The following specific TSR controls reduce the frequency of occurrence of this event to beyond extremely unlikely (SNF-4042):
 - TSRs
 - Verify vendors certification of helium purity of 99% on receipt at the CSB for any inert gas cylinders used to supply the inert gas system. The vendor certification must be based on vendor sample results.
 - Inert the supply lines after they have been depressurized before using inert gas system

The SSCs and TSR controls designated to prevent the MCO internal hydrogen explosion accidents are summarized in Table 4-8. U.S. Nuclear Regulatory Commission important-to-safety category SSCs and defense-in-depth features also are included for each specific accident in Table 4-8.

The suite of safety SSCs and TSR controls necessary and sufficient to prevent the MCO internal hydrogen explosion accidents do not address some of the other accidents in the same accident category. Table 4-8 also lists the safety SSCs and TSR controls needed to prevent these accidents (SNF-4042). Because these accidents are substantially different in development and progression from the design basis accidents, each scenario and the corresponding controls are also described below.

4.6.2 Oxygen Buildup from Radiolysis

A hydrogen explosion (SA-J-06a, OA-J-06a, WS-F-06a) during cask handling follows from excessive gas buildup in the MCO caused by radiolysis. It has been shown that the bounding case MCO will not be able to generate flammable gas mixtures even after 40 years of storage. Somewhat larger inventories of aluminum hydroxide remaining in the MCO after washing at K Basins could lead to flammable mixtures after many years of storage. For short durations (i.e., prior to welding), the MCO design pressure (150 lb/in² gauge) will not be impacted by the worst-case explosion or gas buildup. The mechanical seal will not fail up to a pressure 340 lb/in² gauge (HNF-SD-SNF-SARR-005). During long-term storage, combustion of these mixtures will not exceed the 450 lb/in² design pressure of the welded MCO. To exceed this pressure limit, the key interface performance assumptions identified in Chapter 1.0, Table 1-6, must be exceeded. The following performance assumption is key to preventing this event:

- Assumption
 - The K Basins washing process and the drying process at the CVDF will ensure the key performance interface assumptions defined in Chapter 1.0, Table 1-6, are met.

4.6.3 Ingress of Air

A different hydrogen explosion scenario (OA-J-06c) could occur following an MCO handling accident that allows gases inside the MCO to diffuse out and air to enter the MCO. At some point, a flammable mixture of hydrogen and air will be present in the MCO. Combustion of this mixture leads to a gaseous release accident. Onsite dose guidelines are exceeded. Therefore, safety-significant controls are needed to prevent the handling accidents. The following are the specific safety features that reduce the frequency of occurrence of this event to beyond extremely unlikely:

Table 4-8. Summary of Safety Features Required to Mitigate the Consequences of a Multi-Canister Overpack Internal Hydrogen Explosion. (3 sheets)

Accident	Checklist designator ^a	General function	Safety features and safety classification ^b	NRC ITS category ^b
Hydrogen deflagration				
1. Oxygen used as a purge gas	WS-H-06b	Prevent oxygen from entering the inert gas system	<p><u>TSR:</u></p> <ul style="list-style-type: none"> • Verify vendor certification of helium minimum purity of 99% on receipt at the CSB for any inert gas cylinders used to supply the inert gas system. The vendor certification is to be based on vendor sample results. • Inert the supply lines after they have been depressurized before using inert gas system <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> • Minimize gas loss from the MCO during sampling to avoid repressurizing with helium 	
Deflagration				
2. Oxygen buildup from radiolysis	SA-J-06a OA-J-06a WS-J-06a		<p>General assumption is that all MCOs are within specifications, in particular for aluminum hydroxide and free water in an MCO</p> <p><u>Assumption:</u></p> <ul style="list-style-type: none"> • The K Basins washing process and the drying process at the CVDF will ensure the key interface performance assumptions are met. <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> • HVAC provides air circulation for dilution. • Cask head seals prevent hydrogen leakage from the cask. • Smoking not allowed within the facility. 	

Table 4-8. Summary of Safety Features Required to Mitigate the Consequences of a Multi-Canister Overpack Internal Hydrogen Explosion. (3 sheets)

Accident	Checklist designator ^a	General function	Safety features and safety classification ^b	NRC ITS category ^b
3. Ingress of air	OA-J-06c	Prevent MCO drops, shears, impacts, and collisions by gas cylinders of MCOs Ensure MCOs are within seal-leak rate criteria	<p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> • Transportation cask • MCO (structural) • Receiving crane structure and hoist • Receiving crane positioning/interlock control system • Receiving crane height limiting devices • Service station impact absorber • MHM drop into the maintenance pit interlocks (P3, P8), sensors • MHM drop into the maintenance pit interlocks (P26, P80, P85), sensors • MHM interlocks for translational shear (P21), sensors • MHM interlocks for translational shear (P3, P6, P8, P26, P80), sensors • MHM seismic restraints for translational shear • Seismic detection and MHM power-disconnect system for translational shear • MHM interlock (P9), sensors • MHM interlocks (P6, P80), sensors • Cask servicing system <p><u>Design feature:</u></p> <ul style="list-style-type: none"> • Maximum hole diameter in the butt of the valve on all gas cylinders <p><u>TSR:</u></p> <ul style="list-style-type: none"> • Operability of MHM interlocks (P3, P6, P8, P21, P26, P80), seismic detection and MHM power-disconnect system; MHM interlock • Operability of MHM interlocks (P6, P9, P80), seismic detection and MHM power-disconnect system, and interlock circuitry • Operability of MHM interlocks (P26, P80, P85) to prevent inadvertent rotation of the MHM • Use of proper yoke (length) to lift the cask-MCO • Impact absorber installed in the MCO service station pit and functional • Administrative use of supervisor-controlled fortress key for movement of receiving crane over or east of the FFTF pit when there is no cask-MCO load • Operability of receiving crane resolver and interlock • Bottom impact absorber is installed in each storage tube prior to placing an MCO in the storage tube • Setting receiving crane height limiting devices setpoints to less than or equal to 40 in. 	B B B B B B B B B B B B B NA

Table 4-8. Summary of Safety Features Required to Mitigate the Consequences of a Multi-Canister Overpack Internal Hydrogen Explosion. (3 sheets)

Accident	Checklist designator ^a	General function	Safety features and safety classification ^b	NRC ITS category ^b
3. Ingress of air (cont.)			<u>Defense in depth:</u> <ul style="list-style-type: none"> • Personnel are trained in sitewide and facility-specific emergency response procedures that include steps to place the facility in the safest possible condition. • The MHM provides active, filtered ventilation at its open interface with both the service station and the sampling/weld station. • The MHM has an auditory indication of its movement (i.e., alarms). • The MHM is limited to relatively slow movement. • The MHM is provided with a backup grapple disengagement capability. • Personnel are trained to procedures detailing the safe sequence of operations; these procedures prohibit interferences between the receiving crane and the MHM 	

^aChecklist designators are from HNF-SD-SNF-HIE-001, 1999, *Canister Storage Building Hazard Analysis Report*, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^b SSCs are classified per their function in mitigating or preventing specific accidents. SSCs may have other classifications based on their functions in other events.

CSB = Canister Storage Building.

CVDF = Cold Vacuum Drying Facility.

FFTF = Fast Flux Test Facility.

HVAC = heating, ventilation, and air conditioning.

ITS = important to safety.

MCO = multi-canister overpack.

MHM = multi-canister overpack handling machine.

NA = not applicable to ITS category classification.

NRC = U.S. Nuclear Regulatory Commission.

SSC = structure, system, and component.

TSR = technical safety requirement.

- Safety-significant SSCs³
 - Transportation cask — Provides structural protection to an MCO, when the MCO is inside a cask, from drops from the receiving crane
 - Receiving crane and hoist—Required by Letter 97-SFD-172, *Risk Evaluation Guidelines (REGs) to Ensure Inherently Safer Designs* (Sellers 1997), and U.S. Nuclear Regulatory Commission equivalency important-to-safety Category B for SSCs that handle spent nuclear fuel
 - Receiving crane positioning/interlock control system — Prevents the receiving crane from traveling over the Fast Flux Test Facility or maintenance pit when the receiving crane is carrying an MCO
 - MCO (structural) – Maintain a gaseous seal to prevent oxygen ingress
 - Cask transfer safety system — Prevents a potential radiological release by purging cask annular gases with helium gas to within design limits (i.e., 150 lb/in² gauge). Pressure safety valve PSV-102 prevents exceedance of the design limit
 - Receiving crane height limiting devices — Limit lift height above the floor (maximum of 40 in.) when lifting yoke is attached
 - Service station impact absorber — Limits deceleration forces* to the MCO if the cask–MCO is dropped from the receiving crane into the MCO service station pit
 - MCO handling machine (MHM) interlocks (P3, P8) drop into the maintenance pit, sensors, and switches — Ensures that the MHM turret is rotated to the navigate (TV camera) position before allowing power to the bridge or trolley drive motors when an MCO is in the MHM; the interlock circuitry includes relays, contactors, and sensors (resolvers, limit switches)
 - MHM drop into the maintenance pit interlocks (P26, P80, P85), sensors, and switches — Prevents the MHM from rotating to the MCO position while over the maintenance pit when an MCO is in the MHM; the interlock circuitry includes relays, contactors, and sensors (limit switches, photoelectric switches)

³MCO (structural) – Maintain a gaseous seal to prevent oxygen ingress. MCO structure capability is not a CSB unique feature, but performs a safety-significant function in the prevention of the ingress of air into the MCO at the CSB.

- MHM interlock (P21) for translational shear, sensors, and switches — Ensures that the MCO hoist cannot operate unless the bridge and trolley seismic restraints are applied when an MCO is in the MHM; the interlock circuitry includes relays, contactors, and sensors (limit switches)
- MHM interlocks (P3, P6, P8, P26, P80) for translational shear, sensors, and switches — Prevent the seismic restraints from disengaging and power being applied to the bridge and trolley drive motors unless the MCO hoist is fully raised when an MCO is in the MHM; the interlock circuitry includes contactors, relays, and sensors (resolvers, limit switches, photoelectric switches)
- MHM seismic restraints for translational shear — Prevent translational movement of the MHM whenever engaged when an MCO is in the MHM (restraints must be engaged before MCO hoist operation)
- Seismic detection and MHM power-disconnect system for translational shear — Detects seismic event (magnitude 0.74/3 g horizontal, 0.49/3 g vertical) and removes all power to the MHM; removal of power to prevent operation of the MCO hoist, disengagement of seismic restraints (MHM interlocks are not seismically qualified)
- MHM interlock (P9), sensors, and switches — Ensure that the MCO hoist cannot operate unless the turret seismic restraints are applied when an MCO is in the MHM; the interlock circuitry includes contactors, relays, and proximity sensors
- MHM interlocks (P6, P80), sensors, and switches — Prevent the seismic restraints from disengaging and power being applied to the turret rotational drive motors unless the MCO hoist is fully raised when an MCO is in the MHM; the interlock circuitry includes contactors, relays, and sensors (resolvers, limit switches, photoelectric switches).
- Design feature
 - Maximum hole diameter in the butt of the valve in the neck of all gas cylinders — Limits the thrust produced by escaping gas to an amount that cannot accelerate the cylinder to dangerous velocity; this feature provides protection against accidental breaking-off of the valve body on top of the cylinder.
- TSR
 - Operability of MHM interlocks (P3, P6, P8, P21, P26, P80) and seismic detection and MHM power-disconnect system; the interlock circuitry includes

relays, contactors, and sensors (resolvers, limit switches, photoelectric switches)

- Operability of MHM interlocks (P6, P9, P80) and seismic detection and MHM power-disconnect system; the interlock circuitry includes power contactors, MHM relays, mechanical switches, and sensors (resolvers, limit switches, photoelectric switches)
- Operability of interlocks and sensors (P26, P80, P85); the interlock circuitry includes contactors, relays, and sensors (resolvers, limit switches, photoelectric switches)
- Use of proper yoke (length) to lift the cask-MCO
- Setting receiving crane height limiting devices setpoints to ensure crane lift height with yoke attached does not exceed 40 in.
- Impact absorber is installed in the MCO service station pit and is functional
- Administrative use of the supervisor-controlled fortress key for movement of receiving crane over or east of the Fast Flux Test Facility pit when there is no cask-MCO loaded with spent nuclear fuel suspended from the crane
- Operability of receiving crane positioning/interlock control system
- Bottom impact absorber is installed in each storage tube before placing an MCO in the storage tube.

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Figure 4-1. General Sequence for Internal Hydrogen Explosions.

Figure 4-2. Event Diagram of a Hydrogen Explosion
Caused by Oxygen in the Helium System.

MCO = multi-canister overpack

Figure 4-3. Fractions of Total Multi-Canister Overpack Power by Radiation Type.

Figure 4-4. Oxygen Production (no scrap baskets; intact fuel).

Figure 4-5. Hydrogen Production (no scrap baskets; intact fuel).

Figure 4-6. Bounding Gas Concentration and Multi-Canister Overpack Pressure.

MCO = multi-canister overpack

5.0 CALCULATIONS FOR MULTI-CANISTER OVERPACK EXTERNAL HYDROGEN EXPLOSION

5.1 PURPOSE AND OBJECTIVES

The evaluation of potential consequences of hydrogen explosions outside the multi-canister overpack (MCO) is summarized in this chapter. There could be occasions during the handling of a cask-MCO in the Canister Storage Building (CSB) in which significant concentrations of hydrogen could be found outside an MCO. Two event scenarios occur during venting of a cask-MCO shortly after it arrives at the CSB. In these scenarios, significant hydrogen buildup in the cask void space is vented into the containment tent exhausters and explodes. A third event scenario occurs during MCO handling when a major delay leads to excessive hydrogen concentration in the MCO handling machine (MHM). In a fourth scenario, an explosion occurs during interim storage when an off-normal leak rate leads to burnable concentrations of hydrogen in a storage tube. These latter two scenarios are identified in the CSB hazards analysis as OA-J-066. The fifth scenario occurs at the MCO sampling/weld station when a line leak into the sampling hood provides high enough hydrogen concentrations that an explosion in the hood could injure personnel at the hood. This latter accident is identified in the CSB hazard analysis (HNF-SD-SNF-HIE-001) as WS-L-11 and is considered the design basis external hydrogen event. While WS-L-11 and OA-J-066 have the same risk ranking value in the CSB hazards analysis, WS-L-11 is considered the design basis accident because it has a bigger potential of impact on collocated worker safety.

This design basis accident with bounding consequences is the explosion of a hydrogen-air mixture at the sampling/weld station. This bounding accident could cause serious injury to nearby personnel. The environmental release of radioactivity to individuals located downwind is within guidelines. Mitigation strategies are discussed in Section 5.5. Required controls for each accident are summarized in Section 5.6.

Beyond those identified in Chapter 7.0, there are no identified thermal constraints on extended duration storage at the CSB (HNF-SD-SNF-SARR-005). HNF-SD-SNF-SARR-005, *Multi-Canister Overpack Topical Report*, identifies a 234-hour window for shipping from the Cold Vacuum Drying Facility (CVDF) to the CSB. The length of the shipping window is based on the potential for a flammable gas mixture to build up inside the cask from extraordinary leakage of hydrogen from an MCO into the cask void space. This section identifies this as an external cask-MCO hazard when the internal atmosphere of the cask is vented at the CSB. Analysis concluded that the hazards of this event are prevented by slow venting of the cask after positive pressure is detected within the cask.

5.2 SCENARIO DEVELOPMENT

In all postulated accident scenarios, hydrogen accumulates in an MCO because of processing delays, equipment malfunctions, or catastrophic events. The general sequence of

events leading to a hydrogen explosion is shown in Figure 5-1. The accident sequence begins with the presence of enough hydrogen inside an MCO to form a flammable mixture with air outside the MCO. Three conditions necessary for hydrogen accumulation inside an MCO within a reasonable time frame are uranium metal and hydrides, water, and high temperatures. The uranium and water are reactants, and the elevated temperature speeds the reaction.

In this accident sequence, the accumulated hydrogen escapes the MCO and mixes with air to form a combustible mixture of hydrogen and oxygen. The mixture is then ignited. Because it takes very little energy to begin the hydrogen-oxygen combustion, it is assumed that ignition sources are present where needed. The combustion could be initiated by static electricity in ventilation ducting, a small particle of uranium hydride, static electricity in the spray nozzles in the water storage tanks, and other sources. The specific accident scenarios are described in the following subsections.

5.2.1 Hydrogen Explosion During Multi-Canister Overpack Cask Venting

MCOs are transported from the CVDF to the CSB in sealed and slightly pressurized transportation casks. When a cask-MCO first arrives at the CSB, it contains helium and hydrogen in the void space. Helium is introduced at the CVDF to displace air from the void space. The hydrogen is liberated primarily by the reaction of water vapor with uranium and uranium hydrides and also by the radiolytic decomposition of water-containing compounds in the MCO.

Hydrogen produced inside the MCO will increase the MCO pressure and could leak into the space between the MCO and the transportation cask. One method for producing an explosive mixture is shown in the Figure 5-2 block diagram.

Rough handling or some other failure at the CVDF is assumed to cause a mechanically sealed MCO to leak much faster than the maximum allowed rate. Within a shipping window of four days, enough hydrogen forms and leaks from the MCO and into the cask void volume to raise the gas pressure in the transportation cask. When the initial pressure check at the CSB discloses excessive pressure, the mobile service station tent is placed over the cask for contamination control. The hydrogen-gas mixture is vented to a high-efficiency particulate air (HEPA)-filtered exhaust unit. The helium purge is assumed to fail and produce a flammable mixture in the exhaust.

A spark would lead to an explosion in the ductwork near the operator and could result in serious injury. If the hydrogen-air mixture does not explode in the duct within the confinement tent, it could still explode in the ductwork near the HEPA filter and lead to significant environmental release of the radioactivity accumulated on the HEPA filter. However, the projected dose to an individual 100 m downwind does not exceed the dose criteria.

The hydrogen explosion during cask-MCO venting scenario is diagrammed in Figure 5-2. An event tree is provided in Appendix A.

5.2.2 Hydrogen Explosion from Receiving a Wet Cask–Multi-Canister Overpack

A hydrogen explosion from receiving a wet cask–MCO is a variation on the explosion during cask venting in that the source of hydrogen in the cask is due to wet corrosion of the fuel. When a cask–MCO is ready to leave the CVDF and go to the CSB, it looks the same as a cask–MCO that has just arrived at the CVDF for drying operations. It has been assumed that at the CVDF one cask–MCO is dry and ready for shipment to the CSB at about the same time a water-filled cask–MCO arrives from K Basins. A process interruption causes the two casks to be mistaken, and the water-filled cask–MCO is sent to the CSB.

A small delay in processing the cask–MCO could allow for significant hydrogen accumulation. High temperature conditions during transport would reduce the time needed for significant hydrogen accumulation. The accident diagram in Figure 5-2 shows this scenario from the venting operation to the results.

5.2.3 Hydrogen Explosion During Multi-Canister Overpack Handling

The MHM transports MCOs within the CSB. The void space inside the MHM is filled with air and may be ventilated by a HEPA-filtered exhauster located on the turret. The HEPA filter units are located at the same level as the operating platform. If there were a major equipment breakdown that trapped a leaking MCO in the MHM for an extended period of time, then significant hydrogen could accumulate in the air around the MCO. This scenario is diagramed in Figure 5-3.

A mechanically sealed MCO is assumed to leak much faster than the maximum allowed rate following the MHM malfunction. A few days later, enough hydrogen has leaked from the MCO that there are flammable concentrations of hydrogen in the MHM. A flammable mixture of air and hydrogen also exists in the exhaust ducts and HEPA filter.

A spark would lead to an explosion in the ducts and HEPA filter. Any personnel nearby could be injured. An explosion also could lead to significant environmental release of the radioactivity accumulated on the HEPA filter. The projected radiation dose to any individual downwind does not exceed the dose criteria.

5.2.4 Hydrogen Explosion During Interim Storage

MCOs are expected to be in interim storage for about 40 years. Welded MCOs have a maximum allowable leak rate of 1×10^{-7} cm³/s, so two may be placed in a storage tube. Mechanically sealed MCOs have a higher maximum allowable leak rate (1×10^{-5} cm³/s) and must be stored one to a storage tube. A high leak rate could produce flammable concentrations of hydrogen and air in the storage tube. This scenario is diagramed in Figure 5-4.

Rough handling or some other failure is assumed to cause an MCO to leak much faster than the maximum allowed rate. Within a few weeks enough hydrogen has leaked from the MCO into the storage tube to create flammable concentrations. An explosion of this mixture could damage the storage tube, but it is unlikely to exceed any safety criteria.

5.2.5 Hydrogen Explosion During Multi-Canister Overpack Gas Sampling

Cover cap welding on selected MCOs will be delayed for about one year to allow for gas sampling at the CSB. An MCO that is to be sampled is moved to the sampling pit, and a sample hood is placed over the MCO. Connections are made to the MCO sample port and MCO gas is collected using the positive pressure of the MCO. If the connection to the MCO were to fail and discharge MCO gas into the sample hood, a potentially explosive mixture of hydrogen and air could be formed in the hood. Because personnel normally are near the hood during this time, it is probable that an explosion in the sample hood would cause a fatal injury to the operator opening the MCO vent valve. This scenario is diagramed in Figure 5-5.

5.3 SOURCE TERM ANALYSIS

The mathematical analysis of the identified postulated hydrogen explosion accidents focuses on hydrogen concentration in a transportation cask, the MHM, or in a CSB storage tube. Before describing the accidents in detail, some general information relevant to all the external hydrogen accidents will be presented.

5.3.1 Hydrogen Accumulation and Other Parameters

Parameters and assumptions common to all, or most, of the postulated accidents are presented here. The values presented include gas volumes, helium inventory in the MCO, air inventory in the transportation cask, hydrogen content of the MCO after all the available free and hydrated water has reacted with the uranium, the corresponding MCO pressure, the MCO leak rate, and the peak overpressures due to hydrogen combustion.

5.3.1.1 Volumes. The volumes of accumulated hydrogen are listed in Table 5-1. Because the shapes are somewhat irregular, the volumes are approximate. However, improved volume estimates will not affect the conclusions.

Table 5-1. Volumes Assumed for Hydrogen Accumulation.

Location	Volume, L	Volume, ft ³
Free volume inside MCO	500	17.7
Outer volume of MCO	1,360	48.0
Inner volume of cask	1,460	51.5
Inner volume of MHM	2,530	89.3
Storage tube volume	4,250	150.1
Free volume of cask	100	3.5
Free volume of MHM	1,170	41.3
Storage tube - one MCO	2,890	102.1
Storage tube - two MCOs	1,530	54.0
Sample hood	600	21.2

Note: These are approximate values due to the irregular shapes. More exact volumes will have no effect on the conclusions.

MCO = multi-canister overpack.

MHM = multi-canister overpack handling machine.

5.3.1.2 Helium and Air Inventory in the Multi-Canister Overpack. Before leaving the CVDF, an MCO is pressurized to 152 kPa (22.1 lb/in²) with helium. The average temperature of this helium is assumed to be 25 °C. Rather than convert gas quantities to moles, the amounts will be converted to volumes at reference conditions, namely, 25 °C and 101.3 kPa (14.7 lb/in²). The conversion is carried out using the following equation, which is easily derived from the ideal gas law.

$$V_{\text{ref}} = (V)(P/P_{\text{ref}})(T_{\text{ref}}/T)$$

where

V_{ref} = volume at the reference temperature and pressure, in L

P_{ref} = reference pressure, 101.3 kPa (14.7 lb/in²)

T_{ref} = reference temperature, 298 K (25 °C)

V, P, T = volume, pressure, and temperature of a gas.

At reference conditions, the initial volume of helium in the MCO is given by the formula

$$V_{\text{ref}} = (500 \text{ L})(152 \text{ kPa}/101.3 \text{ kPa})(298 \text{ K}/298 \text{ K})$$

$$V_{\text{ref}} = 750 \text{ L.}$$

5.3.1.3 Bounding Hydrogen Gas in the Multi-Canister Overpack. The composition of the gas inside the MCO when it is received at the CSB is based on the assumption that there is only helium and hydrogen. The hydrogen is generated primarily by corrosion of fuel and reaction with uranium hydride. The radiolytic decomposition of water and hydroxides adds very little and has not been considered.

The bounding hydrogen content of an MCO with two scrap baskets will be estimated assuming the water reactions with uranium metal and uranium hydride occur at the same rate. From HNF-SD-SNF-TI-015, *Spent Nuclear Fuel Project Technical Databook*, the enhancement factor for the metal reaction is 10, while the enhancement factor for the hydride reaction is 12. In addition, the metal reaction produces 1 mole of hydrogen gas for every mole of water reacted, but the hydride reaction produces 1.75 moles of hydrogen for every mole of water reacted. The combined effect is that the hydrogen generation increases by the factor

$$\frac{(10)(1) + (12)(1.75)}{10 + 12} = 1.409$$

over the amount expected from the uranium metal reaction alone.

The hydrogen gas that could be generated from the uranium metal is limited by the amount of water available to react. The bounding free water estimate is 200 g in crevices and cracks. In addition, uranium oxide dihydrate will lose one of the water molecules at normal MCO temperatures (HNF-1523). Much of this loss may occur during drying at CVDF, but to maximize the hydrogen generation after drying none will be assumed. The bounding hydrated water estimate for two scrap baskets is 1,190 g water (HNF-SD-SNF-TI-015). Half of this amount is available for temperatures less than 100 °C to react with uranium fuel to form hydrogen. The total water mass of 800 g is equivalent to 44 moles of water. The hydride enhancement described above leads to the bounding production of 62 moles of hydrogen in the MCO. From the ideal gas law, this hydrogen has a volume of 1,520 L at reference conditions.

$$V = (n)(R)(T)/(P)$$

$$V = (62 \text{ moles})(0.082057 \text{ L}\cdot\text{atm}/\text{mole}/\text{K})(298 \text{ K})/(1 \text{ atm})$$

$$V = 1,520 \text{ L}$$

where

V = volume of a quantity of gas at a specified temperature and pressure

n = number of moles of the gas

R = ideal gas law constant, 0.082057 L·atm/mole/K

T = temperature of the gas, in Kelvin

P = pressure of the gas, in atmospheres (1 atm = 101.3 kPa).

To calculate the actual pressure of the gas mixture in the MCO, the following formula is used; this formula is another variation on the ideal gas law. At 75 °C the pressure of the helium and hydrogen mixture in the MCO is 537 kPa (63 lb/in² gauge):

$$P = (P_{ref})(V_{ref}/V)(T/T_{ref})$$

$$P = (101.3 \text{ kPa})(750 \text{ L} + 1520 \text{ L})(348 \text{ K})/(500 \text{ L})(298 \text{ K})$$

$$P = 537 \text{ kPa.}$$

5.3.1.4 Multi-Canister Overpack Leak Rate Calculation. Due to an off-normal condition, the MCO is assumed to leak much faster than the bounding leak rate for a mechanically sealed MCO. The bounding leak rate is $1.0 \times 10^{-5} \text{ cm}^3/\text{s}$ ($8.64 \times 10^{-4} \text{ L/d}$) at reference conditions (HNF-2155). Reference conditions are defined as having an inside pressure of 101.3 kPa (14.7 lb/in²) and an outside pressure of 1.013 kPa (0.147 lb/in²), both at a temperature of 25 °C. The reference leak rate is based on volumes inside the container. A bounding formula follows to represent the leak rate at the postulated conditions outside the container. Note that no distinction is made between hydrogen and helium leak rates. The hydrogen is lighter than helium and could diffuse more rapidly through a small leak. The formula comes from the observation that the leakage rate is proportional to the pressure difference inside and outside the cask and also the density, which is represented as pressure. The temperature adjustment is included to adjust for density change and to be consistent with the method used in the derivation of the leak rate criteria (HNF-2155).

$$L_{\text{MCO,out}} = L_x \frac{(P_{\text{MCO,in}} - P_{\text{MCO,out}})(P_{\text{MCO,ave}})(T_{\text{MCO,out}})}{(P_{\text{MCO,out}})(T_{\text{MCO,in}})}$$

where

$L_{\text{MCO,out}}$ = leak rate at the postulated conditions outside the MCO, in L/d (or L/h)

L_x = proportionality constant based on the leak rate at reference conditions, in L/d (or L/h) per kPa

$P_{\text{MCO,in}}$ = pressure inside the MCO at postulated conditions, in kPa

$P_{\text{MCO,out}}$ = pressure outside the MCO at postulated conditions, in kPa

$P_{\text{MCO,ave}}$ = average pressure, $(P_{\text{MCO,in}} + P_{\text{MCO,out}})/2$, in kPa

$T_{\text{MCO,in}}$ = temperature inside the MCO at postulated conditions, in degrees Kelvin

$T_{\text{MCO,out}}$ = temperature outside the MCO at postulated conditions, in degrees Kelvin.

The constant, L_x , takes the place of more complex parameters described in HNF-2155, *Multi-Canister Overpack Combustible Gas Management Leak Test Acceptance Criteria*. These parameters mainly depend on the leak diameter and are weakly dependent on gas temperature. The value for L_x can be obtained using reference conditions inside the container. This is shown as:

$$L_x = L_{\text{ref},\text{in}} \frac{(P_{\text{ref},\text{in}})}{(P_{\text{ref},\text{in}} - P_{\text{ref},\text{out}})(P_{\text{ref},\text{ave}})} = L_{\text{ref},\text{in}}(0.01975 \text{ kPa}^{-1})$$

where

- L_x = proportionality constant, in L/d (or L/h) per kPa
- $L_{\text{ref},\text{in}}$ = leak rate at reference conditions inside, in L/d (or L/h)
- $P_{\text{ref},\text{in}}$ = pressure inside the MCO at reference conditions, 101.3 kPa
- $P_{\text{ref},\text{out}}$ = pressure outside the MCO at reference conditions, 1.013 kPa
- $P_{\text{ref},\text{ave}}$ = average pressure, $(P_{\text{ref},\text{in}} + P_{\text{ref},\text{out}})/2 = 51.16 \text{ kPa}$.

The actual MCO leak rate changes with time according to the pressure difference between the MCO and its containment. These changes have been modeled using small time steps in spreadsheets. Specific cases are discussed below.

The leak rates modeled with the described formulas are very low. For example, a leak rate 10,000 times the criteria for a mechanically sealed MCO is 0.1 cm³/s, or 8.64 L/d at reference conditions. Such small leak rates are associated with very small holes or cracks. Thus, the associated matter released due to suspended or entrained particulate is very small and will be ignored in the analysis of external hydrogen accidents.

Hydrogen accumulation in a wet MCO, from the time it leaves the K Basins to the time it mistakenly arrives at the CSB, is based on the uranium corrosion equation used in the CVDF external hydrogen explosion analysis (SNF-2770). Because the values presented in that report were determined adequate to produce flammable mixtures of hydrogen and oxygen, it has been assumed that the same hydrogen accumulation takes place by the time the MCO is vented at the CSB.

5.3.1.5 Pressures Due to Hydrogen Deflagration. Mixtures of hydrogen in air are flammable in the range of 4% to 75% hydrogen by volume at atmospheric pressure and room temperature. Higher pressures and temperatures change the flammable concentration range, but these limits will be assumed for simplicity. Very damaging shock waves may be produced if the hydrogen concentration is between 18 and 58 vol% in air (NUREG/CR-2726). The stoichiometric ratio (2 moles hydrogen per 1 mole of oxygen) corresponds to 29.6% hydrogen in dry air. The presence of helium changes the stoichiometric ratio because it displaces oxygen.

For example, if there are equal volume percents of hydrogen and helium, then the stoichiometric hydrogen concentration is reduced to 22.8%.

When the hydrogen and oxygen react, water vapor is formed and energy is released. To be conservative, it is assumed that the energy released stays in the gas and none is lost to the MCO components. The heat capacity of the gases allows the final temperature to be computed. This final temperature, together with the number of moles of gases in the MCO and the ideal gas law, is used to calculate the final pressure due to the combustion.

The heat of formation of water vapor from hydrogen and oxygen gas is 57,800 cal/mole at a temperature of about 27 °C. The heat capacity of various gases is calculated from a quadratic formula as listed in Table 5-2. The final temperature of the gas mixture is found using the following formula. The integration is between the initial temperature of the gas mixture before combustion and the final temperature of the gas mixture after combustion. The summation is over the types of gases present in the MCO after combustion. Because the final gas temperature is unknown but determines the heat capacities, it must be solved by an iterative process.

$$(H_F)(N_{H_2O}) = \int_{T_o}^{T_f} \left(\sum (C_{vi})(N_i) \right) (dT)$$

where

H_F = heat of formation of water from hydrogen and oxygen, 57,800 cal/mole formed as a vapor

N_{H_2O} = number of moles of water formed; computed as the smaller of the number of moles of hydrogen and twice the number of moles of oxygen (before combustion)

T_o = temperature of the gas mixture before combustion, in Kelvin

T_f = temperature of the gas mixture after combustion, in Kelvin

C_{vi} = heat capacity at constant volume of gas "i"; depends on the temperature of the gas (represented as a quadratic equation)

N_i = number of moles of gas "i" after the oxygen and hydrogen react.

Table 5-2. Parameters to Determine Heat Capacities.

Gas	A	B	C
H ₂	4.959	-1.96 E-04	4.76 E-07
N ₂	4.470	1.39 E-03	-6.90 E-08
O ₂	4.130	3.17 E-03	-1.01 E-06
H ₂ O	5.149	2.64 E-03	4.59 E-08
He	3.020	0	0

Values for the heat capacity at constant volume (in cal/mole/K) are computed from the formula $C_v = A + B \cdot T + C \cdot T^2$, where T is the temperature of the gas. This method and parameter values are given in Whitwell and Toner, 1969, *Conservation of Mass and Energy*, Blaisdell Publishing Company, Waltham, Massachusetts.

The heat capacity parameters shown on this table apply to the temperature range of 300 K (27 °C) to 1,500 K (1,230 °C). At higher temperatures, the heat capacities are over-estimated.

The pressure pulse from a hydrogen explosion exists for only a fraction of a second, but may do considerable damage to the vessel containing it. An estimate of how long this pressure exists can be obtained from the following formula for the rate of pressure increase (SFPE 1992).

$$(dP/dt)_{\max} = (K_G)/(V^{1/3})$$

where

$(dP/dt)_{\max}$ = maximum rate of pressure increase, kPa/s

K_G = parameter measured for explosions in spherical containers; for hydrogen this is 66,000 kPa·m/s (SFPE 1992)

V = volume of the container with the burning gases, m³.

Dividing the final pressure rise by the maximum rate of pressure rise leads to a bound on the shortest possible time in which the pressure could reach the peak. This minimum time is useful for estimating the motion of objects affected by the pressure pulse. As an example, an explosion in a storage tube could lift the storage tube plug.

The momentum imparted to an object affected by the pressure pulse is computed as the time-integral of the force acting on the object. As a simple approximation, the pressure is assumed to rise linearly to the peak and then fall linearly back to where it started. The total time is twice the value for $t_{\min}$ given above. The force on the object is the product of the affected surface area and the pressure. Therefore, the momentum imparted to an object is the product of

the peak pressure increase ($P_x - P_o$), the affected surface area, and the time for the pressure to rise to the peak (t_{min}). The final speed of the object is this momentum divided by its mass:

$$U = (P_x - P_o)(A)(t_{min})/(M)$$

where

U = speed of object affected by the pressure pulse, in m/s

P_x = maximum pressure after completion of combustion of M_H , in kPa

P_o = starting pressure before combustion, 101.3 kPa is used

A = surface area affected by the pressure pulse, in m^2

t_{min} = minimum time for the pressure to rise to the peak value (P_x), in units of milli-seconds

M = mass of object affected by the pressure pulse, in kg.

In the case of storage tube explosions, the speed of the object can be used to estimate how high the storage tube plug could rise following a hydrogen explosion (see Section 5.3.4). In the case of an explosion in the weld/sampling hood, this speed could indicate how fast the face of the hood moves toward the operator due to the explosion (see Section 5.3.5).

5.3.2 Basis for Hydrogen Explosion During Multi-Canister Overpack Cask Venting

The assumptions used in this section are selected to show that an explosive mixture of hydrogen and air is reasonably possible. These values should not be taken as limits.

Oxidation of the uranium metal by residual water vapor in the MCO pressurizes the MCO. The cask becomes pressurized due to the assumed leakage path from the MCO to the cask. No delay in shipping is required to generate the necessary hydrogen. The bounding shipping window of 4 days is enough time if the relative humidity within the MCO exceeds 5%. After the cask arrives at the CSB it must be vented. If the pressure is relieved quickly, there could be flammable concentrations in the exhaust. An important issue is whether enough hydrogen can form and leak to the cask during shipment so that an extraordinary delay is not needed to have flammable mixtures during venting. A delay of four days is bounding, but a delay of one year is incredible.

The basis for the hydrogen explosion during venting uses a simple time-dependent pressurization model for an MCO. It is assumed that hydrogen forms at the high rate found in the oxygen-free reaction equation. The presence of oxygen reduces the reaction rate by more than a factor of 10. If the oxygen-free equation is not appropriate, then this accident would likely not be

attributable to the need for a shipping period well beyond the bounding four days. The required shipping delay would become too long to be credible.

As an MCO is transported from the CVDF to the CSB, hydrogen is formed by oxidation of uranium. The oxygen-free formula from HNF-SD-SNF-TI-015 will be used to represent this. The weight gain due to oxygen-free water vapor reacting with uranium is

$$\text{Log } K = 4.33 - 2144/T_{\text{fuel}} + 0.5 \cdot \text{Log}(H \cdot P_{\text{sat}})$$

$$\text{Log } P_{\text{sat}} = 7.0739 - 1657.46/(T_{\text{gas}} - 46.11)$$

where

- K = the weight gain, in milligrams of oxygen per square centimeter per hour
- T_{fuel} = temperature of the uranium metal, in degrees Kelvin
- T_{gas} = average temperature of the gases in the MCO, in degrees Kelvin
- H = the relative humidity of the water vapor
- P_{sat} = the saturated pressure of water vapor, in kPa.

The method shown to approximate the saturation pressure of water (P_{sat}) was taken from *Chemical Process Safety Fundamentals with Applications* (Crowl and Louvar 1990). The presence of water vapor also affects the pressure in the MCO. The formula for calculating the volume at reference conditions of water vapor in the MCO follows:

$$V_{\text{MCO,H}_2\text{O}} = (H)(V_{\text{MCO}})(P_{\text{sat}}/P_{\text{ref}})(T_{\text{ref}}/T_{\text{gas}})$$

where

- $V_{\text{MCO,H}_2\text{O}}$ = the volume of water vapor in the MCO at reference conditions, in L
- H = the relative humidity of the water vapor
- V_{MCO} = volume of the MCO, assumed to be 500 L
- P_{sat} = the saturated pressure of water vapor, in kPa
- P_{ref} = reference pressure, 101.3 kPa (1 atm)
- T_{ref} = reference temperature, 298 K (25 K)
- T_{gas} = average temperature of the gases in the MCO, in degrees Kelvin.

The weight gain formula represents a hydrogen generation rate in the MCO. It has been assumed that each mole of oxygen weight gain also produces 2 moles of hydrogen gas. A small amount of metal hydride may also be formed, but this reaction is assumed to be minor. Because the bounding MCO with two scrap baskets has 120,000 cm² of exposed surface area (HNF-SD-SNF-TI-015), the production rate of hydrogen can be calculated. In addition, a fuel reaction area enhancement factor of 10 is applied to account for radiation and surface roughness (HNF-SD-SNF-TI-015). The hydrogen generation rate (grams H₂ per hour) follows. For every

mole of oxygen (16 g oxygen) added to the metal, 2 moles of hydrogen (2 g H₂) are produced. In addition, the hydride enhancement factor (1.409) is also used.

$$\text{Rate}(\text{H}_2) = (K)(120,000 \text{ cm}^2)(10) \frac{2 \text{ g hydrogen}}{16 \text{ g oxygen}} (1.409) .$$

The hydrogen generation rate depends on the number of scrap baskets. An MCO with two scrap baskets has a safety basis fuel area of 120,000 cm² together with a hydrate water inventory of 1,190 g (HNF-SD-SNF-TI-015). An MCO with a single scrap basket has a safety basis fuel area of 80,000 cm² together with a hydrate inventory of 777 g. Both cases lead to flammable mixtures while venting the cask. The two scrap basket case produces a more severe explosion.

The hydrogen generation rate also depends on the assumed fuel temperature. After leaving the CVDF, the average fuel temperature in the MCO under bounding conditions is assumed to increase from 30 °C to 65 °C. The bounding conditions involve hot weather as indicated in the shipping thermal analysis for the safety analysis report for packaging (HNF-SD-TP-SARP-017). To represent the temperature history, the following formula is used. The parameters were selected so that half of the temperature increase occurs during the first 12 hours. A graph of the assumed temperatures during transfer to the CSB is shown in Figure 5-6.

$$T_{\text{MCO,fuel}} = (338 \text{ K}) - (35 \text{ K}) \cdot \text{Exp}(-(0.05776 \text{ h}^{-1}) \cdot t)$$

where

$T_{\text{MCO,fuel}}$ = the average fuel temperature, in degrees Kelvin
 t = the elapsed time since leaving CVDF, in hours.

The average temperature of the gas in the MCO is assumed to be several degrees lower than the fuel temperature but follows the same time dependence. While the fuel temperature is assumed to increase from 30 °C to 65 °C, the MCO gas temperature is assumed to increase from 25 °C to 50 °C. Similarly, the temperature in the cask is assumed to increase from 25 °C to 30 °C. Simple linear interpolation is used to construct the gas temperatures:

$$T_{x,t} = T_{x,i} + (T_{m,t} - T_{m,i})(T_{x,f} - T_{x,i}) / (T_{m,f} - T_{m,i})$$

where

$T_{x,t}$ = gas temperature in the MCO or cask at some intermediate time
 $T_{x,i}$ = gas temperature in the MCO or cask initially (leaving CVDF)
 $T_{x,f}$ = gas temperature in the MCO or cask finally (arriving at CSB)
 $T_{m,t}$ = fuel temperature in the MCO at some intermediate time
 $T_{m,i}$ = fuel temperature in the MCO initially (leaving CVDF)
 $T_{m,f}$ = fuel temperature in the MCO finally (arriving at CSB).

The number of grams of water in the MCO that can contribute to the generation of hydrogen is limited. The bounding mass of free water after drying is 200 g. In addition, the bounding mass of hydrated oxides of uranium (two scrap basket case) is 1,190 g (HNF-SD-SNF-TI-015). Of this mass of hydrate water, about half may be freed by thermal decomposition and thus contribute to hydrogen generation (HNF-1523). The rate at which this water becomes available increases with temperature. This water is assumed available from the start. The actual temperature dependence of the release of hydrate would slow the hydrogen buildup. Because temperatures are assumed to rise rapidly during shipment from the CVDF, this additional delay should be less than one day.

The representation of pressures and gas concentrations in the MCO and transportation cask uses the following equations. A spreadsheet was prepared to implement this model. Note that all volumes have been converted to reference temperature and pressure conditions.

Approximation for the MCO:

$$V_{\text{MCO,H}_2,J+1} = V_{\text{MCO,H}_2,J} + dV_{\text{ox,H}_2,J} - dV_{\text{MCO,tot},J}(V_{\text{MCO,H}_2,J})/(V_{\text{MCO,tot},J})$$

$$V_{\text{MCO,tot},J} = V_{\text{MCO,H}_2,J} + V_{\text{MCO,He},J} + V_{\text{MCO,H}_2\text{O},J}$$

$$V_{\text{MCO,He},J+1} = V_{\text{MCO,He},J} - dV_{\text{MCO,tot},J}(V_{\text{MCO,He},J})/(V_{\text{MCO,tot},J})$$

$$dV_{\text{ox,H}_2,J}/dt = \text{Rate}(\text{H}_2)_J \cdot (1 \text{ mole H}_2)/(2 \text{ g H}_2) \cdot R \cdot (T_{\text{ref}}/P_{\text{ref}})$$

$$dV_{\text{MCO,tot},J}/dt = (L_x)(P_{\text{MCO},J} - P_{\text{cask},J})(P_{\text{cask},J} + P_{\text{MCO},J})(T_{\text{ref}}/P_{\text{ref}})/2$$

$$P_{\text{MCO},J} = (P_{\text{ref}})(T_{\text{MCO},J}/T_{\text{ref}})(V_{\text{MCO,tot},J})/(V_{\text{MCO}})$$

Approximation for the Cask:

$$V_{\text{cask,H}_2,J+1} = V_{\text{cask,H}_2,J} + dV_{\text{MCO,tot},J}(V_{\text{MCO,H}_2,J})/(V_{\text{MCO,tot},J})$$

$$V_{\text{cask,He},J+1} = V_{\text{cask,He},J} + dV_{\text{MCO,tot},J}(V_{\text{MCO,He},J})/(V_{\text{MCO,tot},J})$$

$$V_{\text{cask,H}_2\text{O},J+1} = V_{\text{cask,H}_2\text{O},J} + dV_{\text{MCO,tot},J}(V_{\text{MCO,H}_2\text{O},J})/(V_{\text{MCO,tot},J})$$

$$P_{\text{cask},J} = (P_{\text{ref}})(T_{\text{cask},J}/T_{\text{ref}})(V_{\text{cask,H}_2,J} + V_{\text{cask,He},J} + V_{\text{cask,air},J})/(V_{\text{cask}})$$

where

$V_{\text{MCO,H}_2,J+1}$ = volume of hydrogen in the MCO at time step J+1, in liters at reference temperature and pressure

$V_{\text{MCO,H}_2,J}$ = volume of hydrogen in the MCO at time step J, in liters at reference temperature and pressure

- $V_{\text{MCO,He},J+1}$ = volume of helium in the MCO at time step J+1, in liters at reference temperature and pressure
- $V_{\text{MCO,He},J}$ = volume of helium in the MCO at time step J, in liters at reference temperature and pressure
- $V_{\text{MCO,H}_2\text{O},J}$ = volume of water vapor in the MCO at time step J, in liters at reference temperature and pressure
- $V_{\text{MCO,tot},J}$ = total volume of gas in the MCO at time step J, in liters at reference temperature and pressure
- $V_{\text{cask,air}}$ = volume of air in the cask, in liters at reference temperature and pressure
- $V_{\text{cask,H}_2,J+1}$ = volume of hydrogen in the cask at time step J+1, in liters at reference temperature and pressure
- $V_{\text{cask,H}_2,J}$ = volume of hydrogen in the cask at time step J, in liters at reference temperature and pressure
- $V_{\text{cask,He},J+1}$ = volume of helium in the cask at time step J+1, in liters at reference temperature and pressure
- $V_{\text{cask,He},J}$ = volume of helium in the cask at time step J, in liters at reference temperature and pressure
- $V_{\text{cask,H}_2\text{O},J+1}$ = volume of water vapor in the cask at time step J+1, in liters at reference temperature and pressure
- $V_{\text{cask,H}_2\text{O},J}$ = volume of water vapor in the cask at time step J, in liters at reference temperature and pressure
- $dV_{\text{ox,H}_2,J}/dt$ = rate of change in volume of hydrogen gas in the MCO due to oxidation of uranium fuel at time step J, in liters per hour at reference temperature and pressure
- $dV_{\text{MCO,tot},J}/dt$ = rate of change in volume of gas in the MCO due to leakage to the cask at time step J, in liters per hour at reference temperature and pressure
- $\text{Rate}(\text{H}_2)_J$ = rate at which hydrogen is produced in the MCO at time step J, in grams per hour
- R = ideal gas law constant, 0.082057 L·atm/gmole/K
- L_x = leak rate proportionality constant, L/h per kPa

P_{ref}	= reference pressure, 101.3 kPa (1 atm)
T_{ref}	= reference temperature, 298 K (25 °C)
$P_{MCO,J}$	= pressure inside the MCO at time step J, in kPa
V_{MCO}	= volume of the MCO, assumed to be 500 L
$T_{MCO,J}$	= temperature of gas in the MCO at time step J, in degrees Kelvin
$P_{cask,J}$	= pressure inside the cask at time step J, in kPa
V_{cask}	= free volume of the cask with an MCO, assumed to be 100 L
$T_{cask,J}$	= temperature inside the cask at time step J, in degrees Kelvin.

The pressures in the MCO and cask are shown in Figure 5-7 for two relative humidities, 2% and 50%. It can be seen that this model has the MCO pressure rising until all the water is used up. After the available water is used the pressure begins to decrease due to leakage to the cask. The slope of the pressure curve for the cask begins to decrease at this point because gas is entering the cask at a decreasing rate. Relative humidity affects how long it takes to reach the transition. Higher humidities use the water more quickly and reach the transition sooner. The corresponding hydrogen concentration curves are shown in Figure 5-8 for three relative humidities (2%, 10%, and 50%).

Because the humidity in the MCO primarily affects the time required to pressurize the cask, it will be assumed that the relative humidity is 10%. Higher or lower humidities will not affect the conclusion.

According to the above model, the cask temperature and pressure are 30 °C and 284 kPa (26.6 lb/in² gauge) after 4 days at a leak rate 10,000 times greater than allowed for a mechanically sealed MCO. The gas concentrations in the cask are 32% hydrogen, 32% helium, 7.6% oxygen, 29% nitrogen, and 0.1% water vapor as shown on Table 5-3. The corresponding volumes (at 25 °C and 1 atm) are 88 L hydrogen, 88 L helium, 21 L oxygen, 79 L nitrogen, and 0.3 L water vapor for a total of 276 L.

Note that the mixture of gases in the cask is combustible. If it were ignited, at most 3.5 g hydrogen would burn, assuming all the available oxygen was combusted. The maximum pressure during combustion uses the starting pressure of 284 kPa and reaches 1,820 kPa (249 lb/in² gauge). This exceeds the design pressure for the cask and would cause it to rupture. The contamination available for resuspension is minimal because the MCO is sealed. In addition, personnel are not normally near the cask; therefore, the explosion of the cask will not be evaluated in further detail. However, because the MCO is leaking and the cask is breached by the hydrogen explosion, there is a loss of confinement.

Table 5-3. Hydrogen and Oxygen Volumes at the Time of Venting.

Identifier	Hydrogen	Oxygen	Total
MCO free space (500 L at 362 kPa and 323 K)	980 L (60%)	0 L (0%)	1,650 L
Cask free space (100 L at 279 kPa and 303 K)	88 L 32%	21 L 7.6%	276 L
Vented at CSB	56 L 32%	13 L 7.6%	176 L
1-second flow from exhauster	0	99 L 21%	472 L
Exhauster mixture	56 L 8.7%	112 L 17%	648 L

Volumes have been converted to reference temperature and pressure. Reference temperature is 25 °C, and reference pressure is 101.3 kPa (14.7 lb/in² absolute). Gas concentrations are shown below the respective volumes. The "Total" column includes the helium and nitrogen and any water vapor.

CSB = Canister Storage Building.

MCO = multi-canister overpack.

Because the cask is pressurized, the mobile service station tent is placed over it before venting and purging the cask free space. The tent provides contamination control. The confinement tent is ventilated by a portable exhauster located outside the tent. It will be assumed that this exhauster operates at 1,000 ft³/min. If the gases in the cask are vented suddenly, then the lower explosive limit could be exceeded in the exhauster ductwork. If, in this example the cask is vented in one second, (276 - 100) L = 176 L vents into the exhaust system. In that one second, the cask gases would mix with 472 L of air. The total volume of the mixture is thus 648 L. The resulting hydrogen concentration is (32%)(176 L)/(648 L) = 8.7%, which exceeds the lower explosive limit. The hydrogen and oxygen volumes calculated above are summarized in Table 5-3 for clarity.

The total volume of hydrogen introduced to the exhaust system is 56 L at 25 °C and atmospheric pressure. This corresponds to 4.6 g of hydrogen undergoing complete combustion. Because the combustion of 1 g of hydrogen releases the same thermal energy as 28.65 g of TNT (NUREG-1320), the 4.6 g of hydrogen is comparable to 133 g of TNT. The damage created by the hydrogen is less than that from TNT because the hydrogen is spread over a large volume and burns slower. Nevertheless, some damage to the duct and HEPA filter can be expected. The adiabatic flame temperature is 1,250 K; thus, the bounding pressure in the duct is 407 kPa (44 lb/in² gauge).

If a wet MCO were brought to the CSB due to a mixup at the CVDF, the venting operation would not detect the presence of water because the upper cask port is used for the pressure measurement connection. The venting operation would also exceed 4% hydrogen in the exhauster if the bounding case hydrogen accumulation were to occur. The external hydrogen explosion analysis for the CVDF (SNF-2770) shows that after 24 hours the bounding pressure in the cask-MCO is 1,135 kPa (165 lb/in² absolute) at 25 °C. The void space in the wet cask is about 38 L. Thus, the gas volume at reference temperature and pressure is given by:

$$V_{ref} = (38 \text{ L})(1,135 \text{ kPa}/101.3 \text{ kPa})(298 \text{ K}/298 \text{ K})$$

$$V_{ref} = 428 \text{ L.}$$

From the molar concentrations given in SNF-2770, *Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation*, the hydrogen concentration is 89%. It is assumed that no oxygen is present because the cask was filled with helium at the K Basins. The volume of hydrogen to be vented is therefore $(89\%)(428 \text{ L} - 38 \text{ L}) = 348 \text{ L}$. This is a larger volume of hydrogen than before, and it could produce high enough concentrations in the exhauster to form shock waves as it burns.

If the hydrogen in the exhaust duct were ignited near the exhauster HEPA filter, the resulting pressure wave could damage the HEPA filter and its housing, allowing radioactive contamination on the filter to enter the process bay or the environment.

The amount of radioactivity released to the environment by a hydrogen explosion near the exhauster HEPA filter has been estimated using bounding assumptions. For example, it is assumed that the HEPA filter housing reads 50 mR/h at the time of the explosion. HEPA filters normally are changed when the differential pressure becomes too large, indicating that the filter is becoming plugged. An additional administrative criterion is the dose rate on the filter housing at a point nearest the filters. Because the filters must be changed by hand, the exposure to personnel working nearby and especially during filter changeout would be excessive if a dose rate limit were not in place.

Using the safety/regulatory basis spent fuel composition (HNF-SD-SNF-TI-059), the dose rates to the side of a single HEPA filter has been estimated using the ISO-PC software (WHC-SD-WM-UM-030). The filter is assumed to be 61 cm by 61 cm by 30 cm. The filter medium is homogenized throughout this volume at a density of 0.16 g/cm³, corresponding to a filter weight of 18.1 kg. Assuming an administrative dose rate limit of 50 mR/h to the side of the HEPA filter, then 1.5 g of spent fuel is present on the filter. Additional details and the program output are included in Appendix B.

5.3.3 Hydrogen Explosion During Multi-Canister Overpack Handling

Soon after arrival at the CSB, the pressure in the bounding MCO reaches about 537 kPa (63 lb/in² gauge) if the MCO vapor space is oxygen free. The gas in the MCO is 67% hydrogen

and 33% helium. It has been assumed that some accident occurs while an MCO is being transported from one location to another inside the CSB. The MHM is immobilized with the MHM ventilation system out of service. In addition, the MCO begins to leak much faster than the leak rate criteria.

As gas slowly leaves the MCO, the pressure decreases. It is assumed that the gases leave the MCO at a rate proportional to their concentration. Diffusion effects are considered minimal compared to convective flow effects. The air space around the MCO is ventilated by natural circulation only. Thus, clean air continually enters the MHM air space while a mixture of air, hydrogen, and helium continually leaves. The representation of gas concentrations in the MHM uses the equations below. Note that all volumes have been converted to reference temperature and pressure conditions.

Approximation for the MCO:

$$V_{MCO,tot,J+1} = V_{MCO,tot,J} - dV_{MCO,tot,J}$$

$$dV_{MCO,tot,J}/dt = (L_x)(P_{MCO,J} - P_{MHM})(P_{MHM} + P_{MCO,J})(T_{ref}/P_{ref})/2$$

$$P_{MCO,J} = (P_{ref})(T_{MCO,J})/(T_{ref})(V_{MCO,tot,J})/(V_{MCO})$$

Approximation for the MHM:

$$C_{MHM,Hx,J+1} = (C_{MHM,Hx,J})[1 - (dV_{MCO,tot,J} + dV_{air})/(V_{MHM})] + (C_{MCO,Hx})(dV_{MCO,tot,J})/(V_{MHM})$$

$$C_{MHM,air,J+1} = (C_{MHM,air,J})[1 - (dV_{MCO,tot,J} + dV_{air})/(V_{MHM})] + (C_{CSB,air})(dV_{air})/(V_{MHM})$$

where

$V_{MCO,tot,J+1}$ = volume of gas in the MCO at time step J+1, in liters at reference temperature and pressure

$V_{MCO,tot,J}$ = volume of gas in the MCO at time step J, in liters at reference temperature and pressure

$dV_{MCO,tot,J}/dt$ = rate of change in volume of gas in the MCO due to leakage to the MHM at time step J, in liters per day at reference temperature and pressure

L_x = leak rate proportionality constant, L/d per kPa

$P_{MCO,J}$ = pressure inside the MCO at time step J, in kPa

V_{MCO} = volume of the MCO, assumed to be 500 L

$T_{MCO,J}$ = temperature of gas in the MCO at time step J, in degrees Kelvin

P_{ref}	= reference pressure, 101.3 kPa (1 atm)
T_{ref}	= reference temperature, 298 K (25 °C)
$C_{MHM,Hx,J+1}$	= concentration of hydrogen or helium in the MHM at time step J+1, in percent
$C_{MHM,Hx,J}$	= concentration of hydrogen or helium in the MHM at time step J, in percent
$C_{MHM,air,J+1}$	= concentration of air in the MHM at time step J+1, in percent
$C_{MHM,air,J}$	= concentration of air in the MHM at time step J, in percent
V_{MHM}	= free volume of the MHM with an MCO inside, assumed to be 1,170 L
$C_{MCO,Hx}$	= concentration of hydrogen or helium in the MCO, in percent. Note that this does not change with time because there is no gas production during the event and the gas leakage is not enhanced by diffusion effects.
$C_{CSB,air}$	= concentration of air at the CSB, assumed to be 100% (21% oxygen and 79% nitrogen)
dV_{air}/dt	= rate at which air enters and leaves the MHM due to natural circulation, in liters per day at reference temperature and pressure
P_{MHM}	= pressure inside the MHM, assumed to be 101.3 kPa
T_{MHM}	= temperature inside the MHM, assumed to be 303 K (30 °C).

The hydrogen concentration in the MHM rises to a peak value determined by the relationship between hydrogen addition and hydrogen removal. Hydrogen addition is characterized by the assumed leak rate from the MCO to the MHM. Hydrogen removal is characterized by the assumed natural circulation rate from the MHM to the environment. Table 5-4 summarizes reasonable combinations that were used with the above model.

Higher leak rates and lower natural circulation rates are needed to reach flammable concentrations in the MHM. The case with a leakage factor of 10,000 and a natural circulation rate of 30% per day is shown in Figure 5-9. The MCO leakage corresponds to 0.1 cm³/s (8.64 L/d) at reference conditions. It is assumed that the MHM is filled with air initially to provide the oxygen. Figure 5-9 shows the concentrations of oxygen and hydrogen in the MHM following the start of the leak from the MCO. From the graph, the hydrogen concentration exceeds the lower flammability limit after 0.4 days. The peak hydrogen concentration is 15.38%, but this is not reached until 4.2 days after the start of the leak.

Table 5-4. Peak Hydrogen Concentration for Various Add/Removal Factors.*

MHM natural circulation per day	MCO leakage factor		
	1,000	3,000	10,000
100%	1.07% in 4.0 d	2.86% in 3.0 d	7.33% in 2.0 d (4% in 11 h)
30%	3.12% in 9.8 d	7.33% in 6.8 d (4% in 37 h)	15.38% in 4.2 d (4% in 10 h)
10%	7.33% in 20.5 d (4% in 4.6 d)	14.54% in 13.3 d (4% in 31 h)	24.81% in 7.6 d (4% in 9 h)

*The MHM natural circulation rate is the fraction of air replaced per day. The MCO leakage factor times $1 \text{ E-05 cm}^3/\text{s}$ is the leak rate at reference conditions. The percents shown are the peak hydrogen concentration at the time indicated. Where the peak is greater than 4%, the time needed to exceed 4% is shown in parentheses.

MCO = multi-canister overpack.

MHM = multi-canister overpack handling machine.

Thirty hours after the start of the leak, the hydrogen concentration in the MHM would be 10%. Thus, the mass of hydrogen present would be 9.6 g, which is equivalent to 274 g of TNT. Again, the damage from hydrogen is lower due to the greater volume affected and the slower rate of combustion. The adiabatic flame temperature is 1,370 K (1,100 °C), which leads to a maximum pressure of 436 kPa (48 lb/in² gauge).

A hydrogen explosion in the MHM would damage the MHM due to the transitory high pressures. Because the MCO would not be damaged, the only available source of radioactivity is the HEPA filter units on the MHM turret. These could fill with the hydrogen-air mixture and be affected by the deflagration. For personnel protection reasons, the pair would read less than 50 mR/h on contact. Thus, the worst-case explosion near them would have consequences no worse than the rupture of the containment tent exhausters during MCO venting. The potential for personnel injury exists because personnel normally are located near the MHM turret to operate the MHM.

5.3.4 Hydrogen Explosion During Interim Storage

While an MCO is inside a storage tube at the CSB, an abnormal leakage rate could lead to flammable concentrations of hydrogen and air in the storage tube. The same equations derived to model the hydrogen accumulation in the MHM apply to the storage tube with the exception of differences in three of the input parameters. First, the storage tube with a single, mechanically sealed MCO has a free volume of about 2,890 L. Second, the temperature of the air in the storage tube is assumed to be 35 °C. Third, the natural ventilation rate for the storage tube comes from the value for volumetric changes due to barometric pressure variations during the year (WHC-EP-0651). WHC-EP-0651, *Barometric Pressure Variations*, gives the following

value for this rate. Note that the MHM subscript is used to be consistent with the formulas in the previous section.

$$dV_{\text{air}}/dt/V_{\text{MHM}} = 1.69 \text{ per year} = 0.463\% \text{ per day}$$

As with the MHM, it will be assumed that the storage tube is initially filled with air so that oxygen is present to react with the hydrogen leaking from the MCO. Because the ventilation rate is fixed, higher leak rates lead to higher peak concentrations of hydrogen in the storage tube. A summary of peak concentrations and times to reach those concentrations are shown in Table 5-5.

Table 5-5. Peak Storage Tube Concentrations for Various Multi-Canister Overpack Leak Rates.*

MCO leakage factor	Peak hydrogen concentration (%)	Time to reach peak hydrogen (days)	Time to exceed 4% hydrogen (days)
1,000	16.1	124	9.6
3,000	21.2	71	3.1
10,000	25.9	37	0.9

*The MCO leakage factor times $1 \text{ E-}05 \text{ cm}^3/\text{s}$ is the leak rate at reference conditions.

MCO = multi-canister overpack.

The case with a leakage factor of 10,000 is shown in Figure 5-10. The MCO leakage corresponds to $0.1 \text{ cm}^3/\text{s}$ (8.64 L/d) at reference conditions. Figure 5-10 shows the concentrations of oxygen and hydrogen in the storage tube following the start of the leak from the MCO. From the graph, the hydrogen concentration exceeds the lower flammability limit after about 23 hours. The peak hydrogen concentration is 25.9%, but this is not reached until 37 days.

If the hydrogen concentration in the storage tube were 20% at the time of the explosion, then the mass of hydrogen present would be 47 g, which is equivalent to 1,350 g of TNT. Again, the damage from hydrogen would be lower due to the greater volume affected and the slower rate of combustion. The adiabatic flame temperature is 2,320 K, which leads to a maximum pressure of 690 kPa (85 lb/in² gauge). The peak pressure is reached in about 13 milliseconds. Because the storage tube plug has a surface area of 0.37 m^2 and a mass of 2,406 kg, the speed of the plug after the explosion is 1.1 m/s. Under the influence of earth's gravity the plug would rise about 6.6 cm. Thus, a hydrogen explosion in the storage tube could barely lift the storage tube plug. Note that the hydrogen concentrations are high enough that shock waves can be formed. The effect of this phenomenon is to possibly double the peak pressures (SFPE 1992). No radioactive releases are expected from this accident because the MCO pressure boundary should remain intact, and the storage tubes are assumed to have very little surface contamination.

With two MCOs in a storage tube, the volume of air is reduced to 1,530 L. The reduced air volume means that less hydrogen needs to leak from an MCO to reach flammable concentrations. However, the MCOs placed in the tube are sealed by welding on a cover cap. The leak rate criterion for these MCOs is $1 \times 10^{-7} \text{ cm}^3/\text{s}$. If one bounding case MCO has a leak rate 30,000 times this criteria, then the hydrogen concentration reaches a flammable concentration of 4% in 16 days. The assumed MCO leak rate corresponds to $0.003 \text{ cm}^3/\text{s}$ at reference conditions.

5.3.5 Hydrogen Explosion During Multi-Canister Overpack Sampling

To determine the composition of gases in an MCO, selected MCOs are moved from the storage tubes to the sampling/weld station for analysis. A sampling hood is placed over the MCO. The hood is connected to the HEPA-filtered exhaust system, and the flow rate through the hood is between 47 L/s and 118 L/s. Gas is vented from the MCO via a sampling line attached to the MCO. If this connection were to fail, hydrogen and helium in the MCO would be vented to the hood and the exhauster.

The mathematical representation of the composition of the gas in the sample hood follows. It is assumed that the flow rate from the MCO is proportional to the pressure of the MCO, as discussed in Section 5.3.1.4. The initial flow rate from the leak is an input to control hydrogen accumulation in the hood. A spreadsheet was prepared to implement this model. Note that all volumes have been converted to reference temperature and pressure conditions.

Approximation for the MCO:

$$V_{\text{MCO,tot},J+1} = V_{\text{MCO,tot},J} - dV_{\text{MCO,tot},J}$$

$$dV_{\text{MCO,tot},J}/dt = (F_0)(V_{\text{MCO,tot},J})/(V_{\text{MCO,tot},0})$$

Approximation for the Sample Hood:

$$C_{\text{Hood,Hx},J+1} = (C_{\text{Hood,Hx},J})[1 - (dV_{\text{MCO,tot},J} + dV_{\text{air}})/(V_{\text{Hood}})] + (C_{\text{MCO,Hx}})(dV_{\text{MCO,tot}})/(V_{\text{Hood}})$$

$$C_{\text{Hood,air},J+1} = (C_{\text{Hood,air},J})[1 - (dV_{\text{MCO,tot},J} + dV_{\text{air}})/(V_{\text{Hood}})] + (C_{\text{CSB,air}})(dV_{\text{air}})/(V_{\text{Hood}})$$

where

$V_{\text{MCO,tot},J+1}$ = volume of gas in the MCO at time step J+1, in liters at reference temperature and pressure

$V_{\text{MCO,tot},J}$ = volume of gas in the MCO at time step J, in liters at reference temperature and pressure

- $dV_{MCO,toJ}/dt$ = rate of change in volume of both hydrogen and helium in the MCO as it vents to the hood at time step J, in L/s at reference temperature and pressure
- F_0 = initial flow rate from the MCO to the hood, in L/s
- $C_{Hood,Hx,J+1}$ = concentration of hydrogen or helium in the hood at time step J+1, in percent
- $C_{Hood,Hx,J}$ = concentration of hydrogen or helium in the hood at time step J, in percent
- $C_{Hood,air,J+1}$ = concentration of air in the hood at time step J+1, in percent
- $C_{Hood,air,J}$ = concentration of air in the hood at time step J, in percent
- V_{hood} = volume of air in the hood, assumed to be 600 L, based on approximate dimensions of 30 in. by 37.5 in. by 32.5 in.
- $C_{MCO,Hx}$ = concentration of hydrogen or helium in the MCO, in percent. Note that this does not change with time because there is no gas production during the event and the gas leakage is not enhanced by diffusion effects.
- $C_{CSB,air}$ = concentration of air at the CSB, assumed to be 100% (21% oxygen and 79% nitrogen)
- dV_{air}/dt = rate at which air enters and leaves the hood due to operation of the hood exhaust, in L/s at reference temperature and pressure.

To simplify calculations, the temperature of the gas in the hood is 25 °C, which is also the reference temperature. The ventilation rate for the hood is assumed to be 47 L/s (100 ft³/min) to minimize the hydrogen removal rate. The initial flow rate from the MCO into the hood is assumed to be 20 L/s (42 ft³/min). From the equation for choked flow through an orifice that follows, there must be a hole with a cross-sectional area of 6.05 mm² (0.0094 in²) to produce this flow rate. Of course, higher flow rates will lead to greater hydrogen concentrations. Note that when the MCO flow rate exceeds 71 L/s (150 ft³/min) then the hood exhaust capacity is exceeded and the above equations do not apply. The excess gas (air, hydrogen, and helium) is being forced out of the hood. Flow rates that are lower than the assumed value lead to lower hydrogen concentrations. The value chosen simply illustrates a flow rate that produces flammable mixtures in the hood.

$$\dot{Q}_{choke} = C_{dis} A P_{MCO} \sqrt{\frac{\gamma g M}{R T_{MCO}} \left(\frac{2}{\gamma + 1} \right)^{(\gamma + 1)/(\gamma - 1)}}$$

where

Q_{choke} = mass flow rate out the hole, in lbm/s

C_{dis} = discharge coefficient, which is assumed to be 1.0

A = cross-sectional area of the hole, in in.²

g = conversion factor, 32.17 lbm-ft/s²/lbf

M = average molecular weight of the escaping gas, 2.67 lbm/lb-mole

R = ideal gas constant, 1,545 ft-lbf/lb-mole/°R

T_{MCO} = absolute temperature of the gas in the MCO, 627 °R (75 °C)

P_{MCO} = absolute pressure of the gas in the MCO, 78 lbf/in²

γ = the ratio of the heat capacities at constant pressure and volume for the hydrogen-helium mixture. For monatomic gases like helium, γ is 1.67; while for diatomic gases like hydrogen and air, γ is 1.40. The weighted average γ was computed for the hydrogen-helium mixture using the number of moles of each as the weighting factor, giving a value of 1.49.

Under the above conditions, the peak hydrogen concentration in the hood is 16.7%, which is reached in 27 seconds. The lower flammability limit (4% hydrogen) is reached in 2.0 seconds. Notice the time scale is now in seconds rather than days. Figure 5-11 shows the concentrations of oxygen and hydrogen in the weld/sampling hood following the start of the release from the MCO. Note that the time scale on this graph is seconds.

If the hydrogen concentration in the weld/sampling hood was 10% at the time of the explosion then the hood would contain 4.9 g of hydrogen, which releases a thermal energy equivalent to 140 g of TNT. Again, the damage from hydrogen is lower due to the greater volume affected and the slower rate of combustion. The adiabatic flame temperature is 1,370 K, which leads to a maximum pressure of 442 kPa (49 lb/in² gauge). Based on conservative assumptions, this pressure is high enough to damage the hood and injure any personnel nearby. The potential for personnel injury exists because personnel normally are located near the sample hood during sampling operations.

To quantify the potential hazard to personnel, consider the effect of the explosion on the viewing window in front of the operator. Using the viewing window dimensions of 30 in. wide by 18 in. tall, the peak pressure increase of 49 lb/in² applies a force of 26,700 lb to the viewing window. Assuming the window is 0.5 in. thick and has a density of 1,100 kg/m³, then its mass is 4.87 kg (10.7 lb). The peak pressure is reached in 4.4 milliseconds using the method presented in Section 5.3.1.5. If no energy is lost to breaking the window free of its mounts, then the speed of

the window is 106 m/s (237 mi/h). If the hood window were to strike a nearby operator, the impact could possibly cause a fatality. If half the energy were needed to free the window, the speed would still be 71% of the maximum. Thus, there is a real possibility of serious injury or death from an explosion in the sample hood.

In addition to personnel injury, the hydrogen explosion in the sample hood may break the sample line, resulting in a rapid depressurizing of the MCO. Radioactive contamination in the MCO and sample hood HEPA filter can be released to the environment. The primary sources of radioactivity are (1) the HEPA filter near the sample hood, (2) the dry particulate matter suspended inside the MCO by the explosion, and (3) the entrained particulate matter resuspended and carried out with the gases leaving the MCO. Of these three, the third is estimated to provide nearly all of the activity released. Estimates of the amounts released are provided in Section 5.4.

5.4 CONSEQUENCE ANALYSIS

The downwind doses for each accident are computed in the following subsections. During cask venting, the containment tent HEPA filter is ruptured and releases a portion of its activity into the air. The hydrogen explosion in a storage tube is not expected to produce meaningful offsite consequences because there is no radioactive contamination nearby. The hydrogen explosion in the MHM will produce offsite doses no worse than the cask venting accident because the material at risk in the HEPA filters will be limited by the same criteria to minimize occupational exposure to personnel. The hydrogen explosion in the weld/sampling hood leads to much larger releases due to the depressurization of the MCO.

5.4.1 Downwind Dose Calculation Methodology

Inhalation doses to individuals located downwind of the CSB can be computed using the following equation (HNF-SD-SNF-TI-059). It is assumed that the individuals are not evacuated during plume passage because of the short duration of the release.

$$EDE = M_{\text{air}}(\chi/Q')(BR)(UD)$$

where

EDE = the effective dose equivalent, in Sv

M_{air} = the respirable quantity released into the air, in grams of uranium fuel

χ/Q' = the air transport factor, s/m^3 (see Table 5-6)

BR = the average inhalation rate during the release, $3.33 \times 10^{-4} \text{ m}^3/\text{s}$

UD = the committed effective dose equivalent per unit gram inhaled, 4,380 Sv/g.

Table 5-6. Comparison of Doses with Risk Guidelines for Downwind Receptors from a Bounding Hydrogen Explosion During Cask Venting.

Receptor location (distance and direction)	Air transport factor ^a (s/m ³)	Safety significant dose (CEDE ^b), rem (Sv)		Risk guideline ^c , rem (Sv)
		Unmitigated	Mitigated	
Onsite (100 m east)	3.41 E-02	7.5 E-02 (7.5 E-04)	Accident prevented	1.0 E+00 (1.0 E-02)
Highway 240 (9,280 m west)	2.36 E-05	5.2 E-05 (5.2 E-07)	Accident prevented	NA
Hanford Site boundary (17,390 m east)	1.30 E-05	2.8 E-05 (2.8 E-07)	NA	5.0 E-01 (5.0 E-03)

^aRelease is at ground level; release duration is less than 1 hour; no plume rise or plume meander has been assumed.

^bFifty-year CEDE from inhalation.

^cBased on the anticipated frequency, 0.1 to 0.01 per year.

CEDE = committed effective dose equivalent.

NA = not applicable.

The air transport factors are for adverse wind conditions. These conditions are exceeded only 0.5% of the hours in a year. The approach used in U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.145, *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants*, was used to compute the 99.5 percentile air transport factors. Plume meander and building wake effects have not been included because the release duration following the explosion is only a few minutes. The releases are assumed to take place at ground level.

Hanford Site wind data collected at the Hanford Meteorological Station for the years 1983 to 1991 was used in computing the air transport factors. The worst-case locations are used for each receptor. The onsite individuals are 100 m east and 9,280 m west of the CSB. The offsite individual is located 17,390 m east. As shown in HNF-SD-SNF-TI-059, *A Discussion on the Methodology for Calculating Radiological and Toxicological Consequences for the Spent Nuclear Fuel Project at the Hanford Site*, the computed air transport factors and unit dose factor lead to the minimum release amounts required to exceed the guidelines. The first guideline exceeded is for anticipated probability events at the onsite worker location 100 m east of the CSB. The minimum release amount needed to exceed the onsite guideline is 0.20 g of uranium fuel.

For hydrogen explosions near a HEPA filter, the bounding release fraction is 0.01 with a respirable fraction of 1.0 (DOE-HDBK-3010-94, Section 5.4.2.2). Applying this to the limiting release amount of 0.20 g uranium means the HEPA filter loading must not exceed 20 g of uranium fuel. For the 2 ft by 2 ft by 1 ft filter, the contact reading at the side with a 1.5 g loading is about 50 mR/h. Therefore, with 20 g of uranium the contact reading would be about

670 mR/h. As long as each HEPA filter array has less than 20 g of uranium on it, any hydrogen explosions impacting the filter face will not exceed the downwind dose guidelines.

5.4.2 Consequences of a Hydrogen Explosion After Venting the Cask

During venting of the cask-MCO, the hydrogen concentration in the portable exhaust ductwork could be high enough to explode if ignited. Such an explosion would damage the ductwork and could injure personnel nearby. If the bounding case hydrogen were to explode in the exhaust HEPA filter instead, it would damage the housing and filter and lead to an environmental release of radioactivity.

For HEPA filter blasts, the bounding release fraction is 0.01 with a respirable fraction of 1.0 (DOE-HDBK-3010-94, Section 5.4.2.2). Assuming the filter is loaded with the amount of fuel (1.5 g) needed to give a reading of 50 mR/h, then the airborne release would be 0.015 g fuel. Downwind dose results are shown in Table 5-6. The assumed release duration is less than one hour. The onsite and offsite dose guidelines are not exceeded. However, the potential for personnel injury may require safety-significant features to mitigate this accident.

5.4.3 Consequences of a Hydrogen Explosion During Multi-Canister Overpack Handling

A hydrogen explosion in the MHM could damage the MHM due to high pressures. No environmental releases of radioactivity from the MCO are expected because the MCO would not be damaged. The only other sources of radioactivity are the HEPA filter units on the MHM turret. These filter units could fill with hydrogen air mixture and be part of the deflagration. For personnel protection reasons, each filter would be expected to read less than 50 mR/h on contact. Thus, the worst-case explosion near them would have consequences no worse than the rupture of the containment tent exhaust during MCO venting, shown in Table 5-6. The onsite and offsite dose guidelines would not be exceeded. The potential for personnel injury exists because personnel will be located near the MHM turret to operate it. Therefore, safety-significant features may be required to mitigate this accident.

5.4.4 Consequences of a Hydrogen Explosion During Interim Storage

The worst-case event in the storage tubes is when a tube containing a single MCO develops an explosive mixture of hydrogen and air. If this mixture were to detonate, it could seriously damage the storage tube and possibly lead to a misalignment that would prevent future removal of the MCO by normal means. Any environmental release of radioactivity due to resuspension of surface contamination would be very small and would lead to onsite and offsite doses well below the guidelines for anticipated events.

5.4.5 Consequences of a Hydrogen Explosion During Multi-Canister Overpack Sampling

A hydrogen explosion in the sample hood could damage the sample hood due to high pressures. Significant environmental releases of radioactivity from the MCO are expected because the sample line could also be damaged and allow the MCO to rapidly release its gaseous contents. Particulate matter contained in the MCO could be resuspended by the explosion and entrained in the exiting gases.

The bounding particulate inventory at the end of the CSB storage period is 66 kg (HNF-1527). For an MCO with two scrap baskets and three fuel baskets, the bounding releasable particulate is 34 kg. Dose calculations for downwind receptors are based on the uranium fuel released. Assuming the particulate is all UO_2 , then the uranium fuel is 88% of the particulate mass, or 30 kg.

The explosion in the sample hood could liberate particulate from the canister HEPA filter attached to the sample hood. For HEPA filter blasts, the bounding release fraction is 0.01 with a respirable fraction of 1.0 (DOE-HDBK-3010-94, Section 5.2.2.2). The sample hood canister HEPA filter is assumed to contain 20 g of fuel, the amount of fuel when released yields a safety-significant consequence. Subjecting this HEPA filter to the blast of a hydrogen explosion would lead to an airborne release of 0.2-g fuel.

The release of particulate matter suspended inside the MCO by the explosion in the sample hood is limited by the ability of gases to support particulate matter. The maximum respirable particulate loading is about 1 g/m^3 . Because the MCO internal volume is about 0.5 m^3 , the bounding mass lofted inside the MCO is 0.5 g. Because not all of this will exit the MCO and also because the mass estimated to be released by the blowdown of the MCO is much larger, this mass has been ignored as an insignificant contribution to the total release.

Both the airborne release from the damaged sample hood HEPA filter and from any particulate suspended within the MCO because of the external explosion are insignificant compared to the bounding release due to the entrainment of particulate matter by the escaping gases. The external hydrogen explosion event is essentially a pressurized gas release event followed by an external explosion that allows the particulate to bypass any filter or other containment. Therefore, the external hydrogen explosion and the gaseous release event are expected to potentially have similar dose consequences. For pressurized gases vented through a powder sample, a conservative release fraction of 2×10^{-3} is assessed to be bounding (DOE-HDBK-3010-94, Section 4.4.2.3.2). Using this release fraction, the total respirable release is:

$$\text{Fuel released (respirable)} = (2 \times 10^{-3})(30 \text{ kg U})(1,000 \text{ g/kg}) = 60 \text{ g U.}$$

The bounding total released by an unmitigated hydrogen explosion in the sample hood followed by a gaseous release from the MCO is 60 g of uranium.

Resulting doses are shown on Table 5-7. The unmitigated case exceeds the onsite guideline by a considerable margin. In addition, death of an operator performing the sample connection is likely; therefore, safety-significant features are required to mitigate this accident.

Table 5-7. Dose Calculation Summary for a Hydrogen Explosion in the Sample Hood.

Receptor location (distance, direction)	Duration (hours)	Unmitigated dose ^a , rem (Sv)	Evaluation guideline ^b / release limits, rem (Sv) anticipated ^c	Mitigated dose, rem (Sv)
Onsite (100 m east)	<1	300 (3.0)	1.0 (1.0 E-02)	Accident prevented
Highway 240 ^d (9,280 m west)	<1	2.1 E-01 (2.1 E-03)	--	Accident prevented
Hanford Site boundary (17,390 m east)	<1	1.1 E-01 (1.1 E-03)	0.5 (5.0 E-03)	Accident prevented

^aFifty-year committed effective dose equivalent.

^bEvaluation guideline for onsite (100 m) receptor only.

^cAnticipated event frequency is >0.01 to ≤ 0.1 per year. This frequency is based on estimates from HNF-SD-SNF-HIE-001, 1999, *Canister Storage Building Hazard Analysis Report*, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington. Where controls involve operator actions and the occurrence of the event is attributed to human error, see Chapter 7.0.

^dProvided for information only.

5.5 COMPARISON TO GUIDELINES

Mitigation of these hydrogen explosions is discussed in the following subsections. For each scenario, mitigation reduces the likelihood that an explosive hydrogen mixture can be formed. If an explosive mixture of hydrogen and oxygen is not formed, then there are no dose or personal injury consequences for the scenario.

5.5.1 Mitigation of Hydrogen Explosions During Cask Venting

Mitigation of a hydrogen explosion in the tent exhaust system begins with ensuring the MCO has met the leak rate requirement at CVDF before being transported to the CSB. If the leak rate meets the criteria, then the time needed to accumulate significant hydrogen in the cask is too long for a shipping delay to provide the necessary time.

Excessive hydrogen is prevented from building up in the cask before venting by ensuring there are no delays during transport between the CVDF and the CSB. Current design calls for venting within 4 days after sealing at the CVDF.

Preventing a hydrogen explosion in the tent exhaust system is based on preventing the formation of an explosive mixture of hydrogen and air in the ductwork. An explosive mixture of hydrogen and air is prevented by reducing the rate at which hydrogen enters the ductwork and ensuring that planned helium flow is present to dilute the hydrogen.

The consequences of an explosion in the HEPA filter are mitigated by ensuring the uranium fuel loading is less than 20 g. Because the single HEPA filter is unlikely to be shielded and 20 g uranium fuel leads to excessive dose rates, this limit will easily be met by ALARA (as low as reasonably achievable) program controls.

5.5.2 Mitigation of Hydrogen Explosions Inside the Multi-Canister Overpack Handling Machine

Mitigation of a hydrogen explosion during MCO handling begins with ensuring the MCO meets the leak rate requirements and protecting the MHM from catastrophic failures and delays in repairing the ventilation system.

The MHM active ventilation system precludes any significant hydrogen buildup. The periodic use of this ventilation system is recommended in the event that an MCO is trapped in the MHM for any length of time.

The consequences of an explosion in the HEPA filters are mitigated by ensuring the total uranium fuel loading on both HEPA filters is less than 20 g. Because the HEPA filters are unlikely to be shielded and 20 g uranium fuel leads to excessive dose rates on the MHM turret, this limit should easily be met by ALARA program controls.

5.5.3 Mitigation of Hydrogen Explosions Inside Storage Tubes

Mitigation of a hydrogen explosion during interim storage begins with ensuring the MCO meets the leak rate requirements before being placed in a storage tube. As long as the MCO leak rate meets the criteria, then natural barometric changes make it impossible to accumulate significant hydrogen in a storage tube.

5.5.4 Mitigation of Hydrogen Explosions During Multi-Canister Overpack Sampling

Mitigation of a hydrogen explosion during MCO sampling requires protecting the hose connection to the MCO from major leaks. The MCO leaves the CVDF with a leak rate of less than 10^{-5} cm/s, and the sample line leakage is also very low. During the opening of the MCO sample port valve, the operator should measure the hydrogen concentration in the hood. Excessive concentrations would require immediate action, such as closing the sample port valve or evacuating the sampling/weld station.

Another way to prevent the explosion is to pressure check the sample line after it is connected to the MCO. Purging the line with helium would be necessary before making the connection to ensure no oxygen is forced into the MCO during the pressure test.

An alternate approach is to modify the weld/sampling hood design to use an airtight attachment to the MCO. The hood then could be filled with helium to displace air. The exhausters still would be needed to direct MCO gases through the HEPA filter. With an inert atmosphere surrounding the sample line, any hydrogen leaks would not lead to flammable mixtures inside the sample hood. Thus, the accident frequency would be reduced to beyond extremely unlikely.

The consequences of an explosion in the HEPA filters are mitigated by ensuring the total uranium fuel loading on all HEPA filters is < 20 g. Because the HEPA filters are unlikely to be shielded and 20 g uranium fuel leads to excessive dose rates near the sample hood, this limit should easily be met by ALARA program controls.

5.6 SUMMARY OF SAFETY STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

No safety-class structures, systems, and components (SSCs) are required to prevent hydrogen explosion design basis accident (WS-L-11) outside of the MCO. Under normal operating conditions, there is no external accumulation of flammable concentrations of hydrogen.

5.6.1 Sample Line Disconnection

The MCO leaves the CVDF with a leak rate $< 10^{-5}$ cm/s, and the sample line leakage also is very low. Under abnormal or accident conditions, safety-significant equipment is required to ensure flammable concentrations of hydrogen external to the MCO and CSB systems are precluded. To prevent the bounding external hydrogen explosion in the sample hood, it is necessary to check the leak rate of the sample line before the MCO port valve is opened. The maximum allowable leak rate is based on the bounding hydrogen concentration and air flow rate in the sample hood. If the air flow rate is ≥ 5 ft³/min in the sample hood and the assuming sample line leak rate is up to 40 cm³/s, then the hydrogen concentration in the hood will not exceed 1%. The 5-ft³/min flow rate represents an easily detected minimum, and the 40 cm³/s is derived from it. The following are the specific safety SSCs and technical safety requirement (TSR) controls that reduce the frequency of occurrence of this event to beyond extremely unlikely:

- Safety-significant SSCs
 - MCO valve operator and sample line — Provide confinement of flammable hydrogen gas with the confinement boundary to

- Sampling hood exhaust system (hood; ducting; heating, ventilation, and air conditioning fan) — Provides air negative pressure and flow ($>5 \text{ ft}^3/\text{min}$) to dilute any flammable gas concentrations to below 1% (25% of the lower flammability limit)
- **TSRs**
 - Verify minimum air flow rate for hydrogen gas dilution ($5 \text{ ft}^3/\text{min}$) in the hood exhaust
 - Double verification of sampling connection assembly and performance of the pressure test of the sample assembly
 - Limit the contact dose rate on the sampling system, including the sample hood exhaust HEPA filter and the sample piping systems HEPA filters, to $<200 \text{ mR/h}$ at contact.

The SSCs and TSR controls designated to reduce the frequency of occurrence of the MCO external hydrogen explosion to beyond extremely unlikely are summarized in Table 5-8. U.S. Nuclear Regulatory Commission important-to-safety category SSCs and defense-in-depth features also are included for each specific accident in Table 5-8.

The suite of safety SSCs and TSR controls necessary and sufficient to prevent the MCO external hydrogen explosion accidents do not address some of the other accidents in the same accident category. Table 5-8 also lists the safety SSCs and TSR controls needed to prevent or control these accidents. Because these accidents are substantially different in development and progression from the design basis accidents, each scenario and the corresponding controls are also described below.

5.6.2 Hydrogen Leakage from the Multi-Canister Overpack

The hydrogen explosion in the MHM (OA-J-06b) caused by hydrogen leakage from the MCO occurs during MCO handling. This accident scenario assumes that the MHM contains an MCO with a small leak (10,000 times the criteria). If the MHM is immobilized by a power failure or some other event and the ventilation system is off, the gas mixture in the MHM will become flammable in less than a day. Combustion of this hydrogen mixture would at most release activity accumulated on the MHM HEPA filters into the environment. Using the bounding release factor for explosions on HEPA filters, the onsite dose guidelines are met if the HEPA filter loading is less than 20 g of spent nuclear fuel. Because the corresponding exposure rate near the filter exceeds 600 mR/h , ALARA considerations will ensure the filter loading is well below 20 g. The following are the specific safety features and controls that reduce the frequency of occurrence of this event to beyond extremely unlikely or mitigate this event:

Table 5-8. Summary of Safety Features Required to Mitigate the Consequences of a Multi-Canister Overpack External Hydrogen Explosion.

Accident	Checklist designator ^a	General function	Safety features and safety classification ^b	NRC ITS category ^b
Hydrogen deflagration				
1. Sample line disconnection	WS-L-11	<p>Ensure sufficient air flow in the hood to dilute quantities of hydrogen gas leaking from the sample line or connection to below <1% (25% of the lower flammability limit)</p> <p>Ensure that the sample line connection from the sample valve to the connecting hose does not leak</p>	<p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> • MCO valve operator and sample • Sampling hood exhaust system (hood, ducting, HVAC fan) <p><u>TSRs:</u></p> <ul style="list-style-type: none"> • Verify minimum air flow rate for hydrogen gas dilution (5 ft³/min) in the hood exhaust • Double verification of sampling connection assembly and performance of the pressure test of the sample assembly • Limit the contact dose rate on the sampling system, including the sample hood exhaust HEPA filter and the sample piping systems HEPA filters, to less than 200 mR/h at contact 	<p>NA</p> <p>NA</p>
2. Hydrogen leakage from the MCO	OA-J-06b (in MHM or storage tube)	Mitigate the quantity of release to below onsite consequence guidelines	<p><u>Assumption:</u></p> <ul style="list-style-type: none"> • Reliance on leak testing at the CVDF to ensure that only MCOs that meet Spent Nuclear Fuel Project criteria on MCO leakage are shipped to the CSB <p><u>TSR:</u></p> <ul style="list-style-type: none"> • Limit the contact dose rate on the sampling system, including the sample hood exhaust HEPA filter and the sample piping systems HEPA filters, to less than 200 mR/h at contact <p><u>Defense in depth:</u></p> <ul style="list-style-type: none"> • Limit flow rate of vented gases so that when mixed with air in the portable exhaust duct work, the mixture is not flammable 	

^aChecklist designators are from HNF-SD-SNF-HIE-001, 1999, *Canister Storage Building Hazard Analysis Report*, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^bSSCs are classified per their function in mitigating and/or preventing specific accidents. SSCs may have other classifications based on their functions in other events.

CSB = Canister Storage Building.
 CVDF = Cold Vacuum Drying Facility.
 HEPA = high-efficiency particulate air (filter).
 HVAC = heating, ventilation, and air conditioning.
 ITS = important to safety.
 MCO = multi-canister overpack.
 MHM = multi-canister overpack handling machine.
 NA = not applicable to ITS category classification.
 NRC = U.S. Nuclear Regulatory Commission.
 SSC = structure, system, and component.
 TSR = technical safety requirement.

- Assumption
 - Reliance on leak testing at the CVDF to ensure that only MCOs that meet Spent Nuclear Fuel Project criteria on MCO leakage are shipped to the CSB
- TSR
 - Limit the contact dose rate on the sampling system, including the sample hood exhaust HEPA filter and the sample piping systems HEPA filters, to <200 mR/h at contact.

5.7 REFERENCES

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Figure 5-1. General Sequence for External Hydrogen Explosions.

Figure 5-2. Hydrogen Explosion in the Confinement Tent Exhaust System.

CSB = Canister Storage Building
 HEPA = high-efficiency particulate air
 MCO = multi-canister overpack
 SNF = spent nuclear fuel

Figure 5-3. Hydrogen Explosion in the Multi-Canister Overpack Handling Machine and Mitigating Features.

HEPA = high-efficiency particulate air
 MCO = multi-canister overpack
 MHM = MCO handling machine
 SNF = spent nuclear fuel

Figure 5-4. Hydrogen Explosion in a Storage Tube and Mitigating Features.

Figure 5-5. Hydrogen Explosion in the Sample Hood and Mitigating Features.

Figure 5-6. Fuel, Multi-Canister Overpack, and Cask Temperatures
Enroute to Canister Storage Building.

Figure 5-7. Multi-Canister Overpack and Cask Pressures
Enroute to Canister Storage Building.

Figure 5-8. Hydrogen Concentrations in the Cask Enroute to Canister Storage Building.

Figure 5-9. Multi-Canister Overpack Handling Machine Gas Concentrations with No Ventilation.

Figure 5-10. Gas Concentrations in a Storage Tube with One Multi-Canister Overpack.

Figure 5-11. Gas Concentrations in the Sample Hood.

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6.0 CALCULATIONS FOR THERMAL RUNAWAY REACTIONS INSIDE THE MULTI-CANISTER OVERPACK

6.1 PURPOSE AND OBJECTIVES

A thermal runaway reaction is only possible at the Canister Storage Building (CSB) if fuel temperatures are extremely high in combination with excessive water or oxygen available in the multi-canister overpack (MCO). Chemical reaction rates increase and produce more gases and heat as fuel temperatures increase. Pressure inside the MCO increases as a result. If pressure inside the MCO continues to increase to the point that the MCO pressure boundary is challenged, then the MCO could fail and release radioactive particulate and hydrogen gas into the surrounding environment.

The deterministic calculations summarized in this chapter demonstrate that a thermal runaway fuel reaction accident is not physically possible at the CSB if the MCOs satisfy dryness tests (<200 g of water, HNF-SD-SNF-TI-015) at the Cold Vacuum Drying Facility (CVDF) and if the aluminum hydroxide thermal decomposition data based on an initial quantity of 9.47 kg for a two-scrap basket MCO (HNF-SD-SNF-TI-015) and decomposition rate (Figure 6-8) remain valid and representative. Because these results indicate that thermal runaway reactions will not occur, no detailed accident scenarios were documented, but the bounding conditions used in this analysis are described. For these conditions, a thermal runaway event was determined not to occur at the CSB. It should be noted that with extreme temperatures (MCO wall temperatures >115 °C) and a complete shear of an MCO that provides large quantities of air as an oxidant, a thermal fuel runaway could occur in the upper MCO scrap basket.

6.2 SCENARIO DEVELOPMENT

There are two primary chemical reactions that could lead to a thermal runaway event in an MCO at the CSB: (1) the reaction of water with uranium and uranium hydride (UH_3), and (2) the reaction of oxygen with uranium and uranium hydride.

There are two bounding scenarios for thermal runaway events involving the reaction of water with uranium and uranium hydride. The first scenario (Case 1) assumes all free water, including moisture in the MCO atmosphere, is available for reaction. The second scenario (Case 2) includes all free water plus the amount of water that is thermally freed from the aluminum hydroxide and therefore bounds the first scenario (Case 1). The analyses of Cases 1 and 2 are described in Section 6.2.1. No thermal runaways result in either case.

There are also two bounding scenarios for thermal runaway events involving the reaction of oxygen with uranium and uranium hydride: one scenario (Case 3) for an MCO being accidentally injected with oxygen and a second scenario (Case 4) for an MCO that sustains a complete shear while at a high temperature (MCO wall temperatures equal to 115 °C). The analyses of Cases 3 and 4 are described in Section 6.2.2. All oxygen scenarios are bounded by Case 4 with one

exception. The exception is the extreme case of a completely sheared MCO with wall temperatures greater than 115 °C and the air temperature greater than 102 °C, which is discussed as a beyond design basis evaluation (Section 6.2.2.3). Case 3 describes an accident that is initiated when the MCO is accidentally filled with oxygen at the sampling/weld station. The MCO was determined not to overpressurize at bounding MCO temperatures. The unmitigated consequences of this event would not violate the safety limit on MCO pressure and would not violate criticality controls. No safety-class features are required to prevent or mitigate this event. Because releases do not occur, offsite release limits and onsite evaluation guidelines are satisfied. The unmitigated scenario is brought to a stable state by ongoing MCO inerting and/or cooling at the sampling/weld station and the natural consumption of the oxygen. The off-normal MCO is handled within recovery operations under emergency response procedures, with the preferred approach being to move the off-normal MCO to the overpack storage tube for long-term observation and storage. Case 4 evaluates the impact of a hypothetical complete shear of an MCO to initiate a thermal runaway reaction. This results in a violation of criticality geometry controls and a loss of the MCO confinement safety function (a complete shear), so it is prevented by safety-class equipment (analysis of violation of criticality geometry controls is discussed in Chapter 2.0). However, Case 4 does not result in a thermal runaway, even though there is an unlimited supply of air to support the reaction.

6.2.1 Thermal Runaway Reaction from Water Reacting with Uranium and Hydride

In the following subsections, the chemical reactions from water are briefly described, the amount of water required to breach the MCO (depending on gas temperature and gas reaction) is estimated, and the amount of water available in an MCO for chemical reactions is detailed. Values show that there is not enough water to pressurize an MCO beyond its capable limits.

6.2.1.1 Chemical Reactions with Water. Depending on temperature and steam pressure, water (liquid or vapor) will react with uranium and form uranium dioxide particulate and hydrogen gas, liberating heat during the reaction:

Water will also react with uranium hydride (UH_3) to form uranium dioxide and hydrogen, liberating heat during the reaction (FAI/98-40):

6.2.1.2 Water Mass Required to Reach the Multi-Canister Overpack Pressure Rated Design Limit. The rated design pressure of an MCO before the cover cap is welded in place is 150 lb/in² (11.2 atm absolute) (HNF-SD-SNF-DR-003). This rated pressure has a large margin to failure (i.e., no leakage is expected for even larger pressures) and is stable to internal loading of 340 lb/in² gauge (HNF-SD-SNF-SARR-005). The mechanically sealed MCO design pressure after the cover cap is welded onto the MCO at the CSB sampling/weld station is 450 lb/in²

(31.6 atm absolute). It is anticipated that all MCOs will have the cover caps welded on within days of arrival at the CSB; except six. These six MCOs will be monitored and sampled and not have their cover caps welded (HNF-3312, HNF-3354). The MCOs reserved for sampling have significant time to pressurize before the MCO cover cap is welded in place, and all of the other MCOs have much less time to pressurize.

Each MCO is pressurized to approximately 1.5 atm with helium before leaving the CVDF (SNF-2356). The average temperature of this helium is conservatively assumed to be 25 °C because the MCO wall temperature is cooled to 25 °C at the CVDF before the MCO is shipped to the CSB. Using the ideal gas law, the initial helium inventory in an MCO is estimated to be about 33 gmols:

$$N_{\text{He}} = (P)(V)/(R)(T)$$

where

- N_{He} = number of gram-moles of helium in the MCO
- P = helium pressure inside the MCO, 1.5 atm
- V = gas volume of the MCO, 538 L (HNF-SD-SNF-CN-023)
- R = ideal gas law constant, 0.082057 L·atm/mole/K
- T = temperature of the gas inside the MCO, 25 °C.

The number of moles of gas required to increase the MCO pressure (before the MCO and cover cap are welded together) to 11.2 atm (150 lb/in² gauge) and 31.6 atm (450 lb/in² gauge) also can be computed from the ideal gas law, if the gas temperature is known or assumed. If the MCO gas temperature is 150 °C (423 K), which is very conservative and beyond the bounding value of 125 °C (HNF-SD-SNF-TI-015), about 173.5 moles of gas must be present in the MCO to achieve a pressure of 11.2 atm (150 lb/in² gauge). With about 33 moles of helium in an MCO at the time of arrival at the CSB, approximately 140.5 moles of other gases would need to be created at the CSB to reach 11.2 atm (150 lb/in² gauge) if the gas temperature was 150 °C.

If all of the newly created hydrogen are from the uranium–water reaction only, then 140.5 moles (2,530 g) of water are needed to reach 11.2 atm (150 lb/in² gauge) at a 150 °C gas temperature. If all of the created hydrogen are from the uranium hydride–water reaction, then only 80 moles (1,440 g) of water are needed to reach 11.2 atm (150 lb/in² gauge) at a 150 °C gas temperature, because the hydride–water reaction produces 1.75 moles of hydrogen for every mole of water instead of only 1 mole produced by the uranium–water reaction. However, only 765 g of water are needed to consume all of the hydride mass because there are only 5.13 kg of uranium hydride available (HNF-SD-SNF-TI-015) at the CSB. Hence, the hydride mass will take only 765 g of water before being depleted, producing about 74.5 moles of hydrogen. The remaining 66 moles (140.5 moles minus 74.5 moles) of gas required for 11.2 atm of pressure are supplied by 66 moles of water (a water mass of 1.19 kg) that are consumed in the uranium–water reaction. Adding the water consumed by the two reactions (1,190 g plus 765 g) yields about 1.96 kg of water, which is the amount of free water needed for gas-producing reactions to pressurize the MCO to 11.2 atm (150 lb/in² gauge) at a 150 °C gas temperature. The same simple calculation is

performed for the 31.6 atm (450 lb/in² gauge) MCO pressure rated limit and for lower gas temperatures. The results are shown in Table 6-1. After the water is consumed, hydrogen is expected to react with uranium to form uranium hydride (hydrogen gettering). For purposes of this analysis, no hydrogen gettering is assumed to conservatively bound the MCO pressure.

Table 6-1. Water Mass Required to Pressurize Multi-Canister Overpack to 11.2 Atmosphere (150 lb/in² gauge) and 31.6 Atmospheres (450 lb/in² gauge) Versus Reaction and Gas Temperature.

Chemical reaction	High best estimate gas temperature, 100 °C	Bounding gas temperature, 125 °C	Beyond design basis gas temperature, 150 °C
Water mass required to reach 11.2 atm (150 lb/in ² gauge)			
Hydride-water	1.69 kg	1.56 kg	1.45 kg
Uranium-water	2.95 kg	2.73 kg	2.53 kg
Bounding uranium-hydride mass* plus uranium	2.38 kg	2.15 kg	1.96 kg
Water mass required to reach 31.6 atm (450 lb/in ² gauge)			
Bounding uranium-hydride mass* plus uranium	8.83 kg	8.20 kg	7.65 kg

*Assumes 765 g of water are used to react with a finite bounding uranium hydride mass of 5.13 kg (HNF-SD-SNF-TI-015, 1998, *Spent Nuclear Fuel Project Technical Databook*, Rev. 6, Fluor Daniel Hanford, Richland, Washington). The mass is consumed completely by hydride-water reaction.

Table 6-1 lists the total free water required to reach gas pressures of 11.2 atm (150 lb/in² gauge) and 31.6 atm (450 lb/in² gauge) for water reactions and their combined weighted average (weighted towards the uranium-water reaction) at three different gas temperatures. The bounding uranium hydride mass is based on 0.765 kg of water is needed to consume the 5.13 kg of hydride, the bounding value for an MCO with two scrap baskets (HNF-SD-SNF-TI-015). The 125 °C gas temperature is the maximum MCO gas temperature anticipated for CSB storage (HNF-SD-SNF-TI-015).

For comparative purposes, if the newly created gas is a stoichiometric mixture of hydrogen and oxygen due to radiolysis of water and the gas temperature is 150 °C, only about 1.37 kg of water needs to be available for a pressure of 11.2 atm to be attained. The radiolysis process is very efficient in producing gas because it generates 1.5 moles of hydrogen for every mole of water. This hydrogen production rate is not as efficient as the hydride-water reaction (1.75 moles of hydrogen per 1.0 mole of water), but is more efficient than the uranium-water reaction (1.0 mole hydrogen per 1.0 mole of water). However, the radiolysis process is very slow, even for a period of 40 years (HNF-SD-SNF-TI-040). For a period of one year or less, the amount of water radiolytically decomposed has been shown to be less than 0.5% of the water available in the

free and hydroxide phases and less than 5% of the water in uranium hydrate (1.19 kg) (see Chapter 5.0). Because this analysis focuses on thermal behavior and resulting high pressures of the MCO at the CSB during the first year, the slowly occurring radiolysis process is not considered. Radiolysis is considered in Chapter 5.0 for flammability potential and high pressure concerns over the entire 40-year projected storage period of an MCO at the CSB.

6.2.1.3 Bounding Water Mass and its Availability for Reactions in Multi-Canister Overpack. Water (HNF-SD-SNF-TI-015) in the bounding MCO can be classified into four groups: (1) free water (200 g), (2) water chemically bound in uranium hydrate (1.19 kg), (3) water chemically bound in aluminum hydroxide (3.32 kg) for MCOs containing fuel stored in aluminum canisters, and (4) water chemically bound in aluminum and iron hydrates (0.13 kg).

The projected bounding inventory of free water in an MCO received at the CSB is 200 g. The bounding MCO is assumed to be dried at the CVDF, with less than 200 g of free water remaining in cracks after the dryness tests at the CVDF (HNF-1851; HNF-SD-SNF-TI-015).

In addition to the 200 g of free water, there is a bounding value of about 1.19 kg of water in the uranium hydrate that is part of the uranium oxide particulate matter (HNF-1523, HNF-SD-SNF-TI-015) for an MCO with two scrap baskets and three fuel baskets. However, this water would not be initially available for hydrogen-producing reactions, and some of the hydrate water is expected to be removed at the CVDF (HNF-SD-SNF-CN-023). Water molecules bound in the uranium hydrate ($\text{UO}_3 \cdot 2\text{H}_2\text{O}$) are freed at temperatures above about 60 °C (FAI/98-40). Half the hydrate water (the first water molecule) liberates fairly easily, while the other half (the last water molecule) requires higher temperatures. Exact decomposition temperatures are uncertain because hydrate decomposition also depends on the relative humidity in the surrounding gas, with dry gases promoting fast decomposition and saturated gases stopping decomposition (FAI/98-40). The reaction for the two stages of hydrate decomposition is shown as:

The MCO with the bounding water content is one with two scrap baskets and three fuel baskets. For this MCO, up to 3.32 kg of water are contributed by both the bounding quantity of aluminum hydroxide on the fuel cladding and by an additional 0.13 kg of water in aluminum and iron hydrates in the canister sludge (HNF-1523, HNF-SD-SNF-TI-015). This bound water, like the uranium hydrate water, would not be available initially for reactions. Very little of the hydroxide water is expected to be freed from the thermal decomposition of the aluminum hydroxide based on current data that suggests about 5% of the water is freed for fuel temperatures less than 200 °C (HNF-1523, Rev. 1, Appendix B), and essentially no water is freed for fuel temperatures less than 150 °C. However, the earlier decomposition data from *Oxides and Hydroxides of Aluminum* (ALCOA 1987) and reported earlier (HNF-1523, Rev. 0, Appendix B) show more thermal decomposition at lower temperatures. Thermal decomposition behavior of aluminum hydroxide is described in ALCOA (1987), Figure 4.4, which is the source for Figure 6-8. This figure illustrates loss of water, porosity, internal surface area history, and change in density as a function of temperature. Weight loss is plotted on the right-hand side.

About 20% of the hydroxide mass is lost (water) between 200 °C and 400 °C, and about another 10% is lost between 400 °C and 600 °C. The ALCOA thermal decomposition rates are more conservative at lower temperatures than the more recent data (HNF-1523, Rev. 1, Appendix B) and they are used for thermal decomposition. ALCOA decomposition data, expressed as water loss fraction of total hydroxide mass, which is 35% water, is converted to loss fraction of total water. At temperatures around 200 °C, the ALCOA data show the amount of water freed from decomposition is about 15% of the total water (5% of the total hydroxide mass, Figure 6-8). For normal operations at the sampling/weld station, the MCO fuel temperatures will be less than 100 °C (HNF-2256). However, it is assumed that severe off-normal conditions at the station could result in MCO fuel temperatures above 100 °C. Hence, partial thermal decomposition of aluminum hydroxide is considered in the off-normal event calculations. The reaction is shown as:

The expected bounding amounts of water in an MCO from all sources on arrival at the CSB and the availability of the water for reactions are shown in Table 6-2 as a function of fuel temperature. If the MCO fuel temperatures reach values close to 300 °C, then the thermal decomposition of aluminum hydroxide, along with hydrate decomposition and initial free water, could supply about 3.32 kg of water. This total is based on 57% thermal decomposition of the bound water from aluminum hydroxide and aluminum and iron hydrate (HNF-SD-SNF-TI-015), 100% thermal decomposition of the uranium hydrate, and 0.2 kg of free water. Because the iron and aluminum hydrate mass is small relative to aluminum hydroxide mass, both compounds are assumed to decompose at the same rate as the aluminum hydroxide.

The bounding water mass numbers in Table 6-3 are derived from the required water amounts identified in Table 6-1 and the available water amounts identified in Table 6-2. Table 6-3 shows the additional free water that would be needed at different gas temperatures for MCO pressures to increase to 11.2 and 31.6 atm (150 and 450 lb/in² gauge). It is assumed in Table 6-3 that the peak fuel temperatures will not be more than 50 °C higher than the gas temperatures, which has been shown to be true for most conditions (HNF-SD-SNF-CN-023). The peak fuel temperatures occur on the innermost fuel assemblies or scrap and are less than 50 °C higher than the average gas temperature; whereas, the peripheral fuel elements or scrap are cooler than the average gas temperature. It is shown in Section 6.2.1.4 that if no fuel reactions are occurring (lack of oxidants), then the maximum fuel temperature is only 15 °C higher than the wall temperature.

Table 6-3 shows that, under normal conditions, at least 7.83 kg of additional free water are needed in an MCO at the CSB for the MCO pressure to reach the 31.6 atm (450 lb/in² gauge) design pressure after the cover cap is welded in place. Even under conditions that are beyond the bounding temperature causing more bound water to be liberated, at least 5.74 kg of additional free water would need to be available, which is more than the 4.84 kg total water that could be available in an MCO (HNF-SD-SNF-TI-015). Hence, if all the water (4.84 kg, Table 6-2) in the free, hydrate, and hydroxide phases were available for chemical reactions, the MCO pressure still would stay below the 450 lb/in² gauge design pressure after the cover cap is welded in place.

Table 6-2. Bounding Water Mass and Availability for Reactions in Multi-Canister Overpack for Thermal Runaway Reactions from Water.

Source of water	Total possible water mass (maximum free water is in an MCO with 2 scrap baskets and 3 fuel baskets)	Availability of water for reactions (Thermal decomposition, percent of total water mass)		
		Fuel T $\leq 100^{\circ}\text{C}$	Fuel T = 200°C	Fuel T = 300°C
Free water in cracks	0.20 kg	0.20 kg	0.20 kg	0.20 kg
Water in uranium hydrate	1.19 kg	0.60 kg (50 %)	1.19 kg (100 %)	1.19 kg (100 %)
Water in aluminum hydroxide (ALCOA 1987)*	3.32 kg	0.20 kg (6%)	0.50 kg (15 %)	1.90 kg (57 %)
Water in Al+Fe hydrates	0.13 kg	0.0 kg	0.02 kg (15 %)	0.07 kg (57 %)
TOTAL	4.84 kg	1.0 kg	1.91 kg	3.36 kg

*ALCOA, 1987, *Oxides and Hydroxides of Aluminum*, ALCOA Technical Paper No. 19, Revised, ALCOA Laboratories.

Table 6-3. Additional Water Mass Needed to Pressurize Multi-Canister Overpack to 11.2 Atmosphere (150 lb/in² gauge) and 31.6 Atmospheres (450 lb/in² gauge) for Different Gas Temperatures for Thermal Runaway Reactions from Water.

Water balance description	High best estimate gas temperature, 100 °C	Bounding MCO gas temperature, 125 °C (HNF-SD-SNF-TI-015) ^a	Beyond design basis gas temperature, 150 °C
11.2 atm (150 lb/in ² gauge)			
Total water required to reach 150 lb/in ² gauge (Table 6-1)	2.38 kg	2.15 kg	1.96 kg
Total free water available (Table 6-2)	1.0 kg ^b	<1.91 kg ^c	1.91 kg ^c
Additional water needed to reach 150 lb/in ² gauge (water shortage at the CSB)	1.38 kg	>0.24 kg	0.05 kg
Safety margin	138%	>13%	3%
31.6 atm (450 lb/in ² gauge)			
Total water required to reach 450 lb/in ² gauge (Table 6-1)	8.83 kg	8.20 kg	7.65 kg
Free water available (Table 6-2)	1.0 kg ^b	1.91 kg ^c	1.91 kg ^c
Additional water needed to reach 450 lb/in ² gauge (water shortage at the CSB)	7.83 kg	6.29 kg	5.74 kg
Safety margin	780%	329%	301%

^aHNF-SD-SNF-TI-015, 1998, *Spent Nuclear Fuel Project Technical Databook*, Rev. 6, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^bFuel T ≤ 100 °C.

^cFuel T ≤ 200 °C.

CSB = Canister Storage Building.

For thermal runaway reactions from water, Table 6-3 shows there is insufficient water in the MCO to exceed the MCO rated pressure of 11.2 atm (150 lb/in² gauge) before the cover cap is welded in place. The additional water needed is 0.24 kg to pressurize the MCO to 11.2 atm at the CSB under bounding conditions. This indicates that activating the cooling system of the shield wall or removing the MCO from the sampling/weld station when the MCO temperature exceed 100 °C is prudent. There is additional margin in the MCO rated pressure of 11.2 atm, because no release is expected for pressures below 340 lb/in² gauge (HNF-SD-SNF-SARR-005).

6.2.1.4 Analysis Results of High-Temperature Scenarios. The HANSF code, Version 1.2 was used to simulate bounding events with high temperature boundary conditions (FAI/98-40; HNF-SD-SNF-CN-023). The HANSF code has been used extensively for analyses of CVDF processes, and its quality assurance has been documented (HNF-SD-SNF-CN-023). The models developed for the code include the inner and outer fuel elements in each fuel assembly and 54 fuel assemblies per fuel basket. The models also include the scrap basket, which is physically modeled like a porous bed of gravel.

The high-temperature scenario analysis was motivated by the high-temperature calculations documented in CSB-HV-0014, *Long Term MCO Temperature Without Cooling in the Sampling Station*. Those calculations analyzed an MCO in the sampling/weld station without active cooling for about two months. The MCO handling machine (MHM) also was assumed to be unable to remove the MCO from the sampling/weld station. For this unmitigated scenario, a 132 °C MCO wall temperature (design limit) was calculated to occur in about 40 days (CSB-HV-0014).

There were two high-internal MCO gas temperature cases with water-based reactions analyzed with Version 1.2 of the HANSF code (FAI/98-40). The key input parameters are given in Appendix C. The simulations used a bounding MCO with one scrap basket and four fuel baskets. However, to maximize the water content and available reactant for the thermal runaway reactor, the simulated water content of this MCO was equivalent to that of an MCO with two scrap baskets and three fuel baskets. An MCO with two scrap baskets has the maximum hydrate water (1.19 kg) and total water (4.84 kg) in the free, hydrate, and hydroxide phases (see Table 6-2). The MCO with one scrap basket has more decay heat than the MCO with two scrap baskets because a fuel basket has more heat (or mass) than a scrap basket. To maximize the results and minimize the number of simulations, a hypothetical MCO was modeled with decay heat of an MCO with one scrap basket and the water content of an MCO with two scrap baskets. The temperature results of the single scrap basket represent the behavior of a second scrap basket. Five fuel baskets would have about 35 W of decay power more than four fuel baskets and one scrap basket. However, 35 W of decay is insignificant when compared to the potential chemical heat rate in one scrap basket.

The total reaction surface area is not maximized for the entire MCO. The total reaction surface area is not important at the CSB because the reaction is limited by oxidants (water or oxygen), not by reaction rate or reaction area. After the CVDF, water is very limited and air is not present in an MCO. For air ingress scenarios, a single scrap basket with a 4.5 m² bounding surface area will determine the bounding temperature results for a second scrap basket, if present. The second scrap basket would compete with the first basket for oxidants such that the first

basket would not heat as much, which is less conservative. All of the following results are obtained with this bounding, hypothetical MCO, except for the first two cases which use a lower decay power associated with aluminum hydroxide coated fuel.

6.2.1.4.1 Case 1 (CHOTSCEN). The MCO with the maximum water is one with aluminum hydroxide on the fuel cladding, which provides a potential water source. The bounding decay heat for aluminum hydroxide fuel is 528 W (HNF-3035). A bounding temperature MCO is in the sampling/weld station for at least 40 days without active cooling. The calculated fuel temperatures are consistent with the 132 °C MCO wall temperature. Simulations for this case assumed initial fuel temperatures of 125 °C and calculated the temperatures for two days. It was assumed that the 1.5 atm of helium injected at the CVDF included water. The water was assumed to be 2% (saturated steam at 25 °C) of the injected helium, which amounts to about 9 g of water mass. Steady-state temperatures for this case were attained in less than a day of simulated time (see Figures 6-1 and 6-2).

The fuel temperatures for Case 1 are shown in Figures 6-1 and 6-2 as a function of time. The hottest fuel temperature for Case 1 occurs on the inner fuel element nearest the center post of the MCO. This maximum temperature is about 145 °C for the fuel baskets and is steady. The hottest temperature for the scrap fuel is about 140 °C with a steady-state value of 135 °C. The scrap fuel is cooler than the fuel elements because the scrap basket copper fins effectively conduct heat toward the MCO wall and because some heat escapes from the scrap to the shield plug.

The MCO gas temperature reaches about 140 °C in the fuel baskets and about 132 °C in the scrap basket. The time in Figures 6-1 and 6-2 starts after the MCO wall temperature reaches 132 °C, which would be at least 40 days after the bounding MCO is placed in the sampling/weld station (CSB-HV-0014) with no active cooling for the shield wall. The initial helium temperature is 25 °C when it is injected into the MCO at a pressure of about 1.5 atm at the CVDF. In the simulation the gas heats up in about two or three minutes, due to the low heat capacity of the gas, and causes a rapid pressure increase. The MCO gas pressure reaches 7.0 atm in two days and is remaining steady. It is not expected that the fuel temperatures will heat up to these temperatures because the MCO wall temperatures were expected to be made cooler than 132 °C.

6.2.1.4.2 Case 2 (CHOTSCR2). Case 2 investigates the effects of aluminum hydroxide water on MCO fuel reactions as a continuation of Case 1. Case 2 uses the final results of Case 1 for all initial conditions (e.g., the hottest fuel element is about 146 °C initially, the time starts at two days). This simulation adds 0.52 kg of water, which is about 15% of the water contained in aluminum hydroxide and the aluminum and iron hydrates in the canister sludge (HNF-SD-SNF-TI-015, HNF-1523, Rev. 0). ALCOA data (ALCOA 1987) indicate that as much as 15% of the hydroxide water can be freed by thermal decomposition for temperatures up to 200 °C, and about 57% can be freed for temperatures up to 300 °C (HNF-1523, Rev. 0). In Case 1, the maximum fuel temperature was 146 °C, at which temperature less than 6% of the water in aluminum hydroxide is expected to be freed by thermal decomposition. Because thermal decomposition of aluminum hydroxide is not part of the HANSF code, additional water vapor (steam) was added as a source to simulate the water from aluminum hydroxide on temperatures and pressure. To be conservative, 15% or 0.52 kg of hydroxide water was added to the MCO

fuel baskets over a 10,000 second interval. The kinetic disposition rate was not modeled explicitly because of the conservatism and the assumed rapid source rate.

In the simulation, the freed hydroxide water was added only to the fuel baskets, which is more conservative than evenly distributing the water to all the baskets. The added water from hydroxide causes the maximum fuel temperature to increase from 146 °C to about 155 °C in less than three hours (shown in Figure 6-3). All of the temperature and pressure results for this case are shown in Figures 6-3 and 6-4. The fuel and gas temperatures decrease after three hours because no more water is available to continue the chemical reactions. In less than two days, the maximum fuel temperature reaches a lower steady-state value of 145 °C. The hydroxide water-fuel reaction creates hydrogen gas, which has a very high thermal conductivity, and heat is removed from the MCO faster. The scrap fuel does not heat up, indicating that no steam enters the scrap basket from the top fuel basket. The MCO pressure rises to about 10.0 atm (133 lb/in² gauge), which is below the MCO design pressure of 11.2 atm (150 lb/in² gauge). The maximum fuel temperature does not rise above 155 °C and the gas temperature does not rise above 140 °C, indicating that the helium cover gas provides good thermal conductivity, thereby keeping the temperatures stable in the MCO at the CSB.

6.2.1.5 Conclusions and Conservatisms (Thermal Runaway Reactions from Water). The simulations show that MCO temperatures will remain stable even under very severe external thermal conditions, and the maximum gas pressure will stay below 11.2 atm. This controlled behavior was shown even with many conservatisms included in the evaluation. The main conservatisms and/or margins over bounding parameter values used in the computer simulations are itemized in the following list.

- No hydrate water is removed at the CVDF, leaving all hydrate water available for thermal decomposition and reaction at the CSB.
- No hydride mass is consumed at the CVDF and the CSB, as the hydride reaction rate multiplier was kept at 12 (HNF-SD-SNF-TI-015) for all simulations at all times.
- MCO wall temperature is conservatively chosen to be 132 °C as the result of being in the sampling/weld station pit without active cooling for 40 days; whereas the wall temperature is only 126 °C at 40 days (CSB-HV-0014).
- Steam mass of 9 g is added to the MCO to account for the CVDF helium supply, possibly being contaminated with 2% steam.
- Fifteen percent of aluminum hydroxide water is released at fuel temperatures <150 °C instead of 200 °C (HNF-1523, Rev. 0) for Case 2, and this water is added only to the hotter fuel baskets instead of evenly distributing the water source over both scrap and fuel baskets.
- No hydrogen gettering takes place, which maximizes the gas pressure; if hydrogen gettering was allowed to take place, the hydrogen gas fraction in the MCO would be

significantly reduced, thereby lowering the MCO pressure. Hydrogen gettering is expected to occur after all of the free water has been depleted; this process could lower the MCO pressure by as much as 80%.

This summarizes the results of thermal runaway reaction rates with water and the following section provides results from reaction rates with oxygen.

6.2.2 Thermal Runaway Reaction from Oxygen Reacting with Uranium Hydride and Uranium

Heat also can be generated in an MCO when oxygen (or air) enters as the result of an off-normal event or as the result of radiolysis and reacts with the uranium metal fuel. This section examines the entrance of oxygen or air as the result of an off-normal event. Chapter 5.0 examines the long-term effects of radiolysis and flammability issues. Any oxygen that enters the MCO will react with uranium hydride and uranium to liberate heat, depending on the temperature (HNF-SD-SNF-TI-015). These reactions are as follows:

A high-pressure condition in an MCO is impossible with an air ingress event because pressure decreases when oxygen is consumed. However, as heat is liberated in these uranium-oxygen reactions, a thermal runaway or excursion may be possible with sufficient quantities of oxygen for reaction and sufficiently high fuel temperatures. Furthermore, because these reactions with oxygen liberate heat and increase the fuel and gas temperatures, additional water could decompose from the uranium hydrate and aluminum hydroxide. This would increase the pressure and temperature in the MCO. The reactions with oxygen will be followed by the reactions with water after the oxygen is consumed. Because all of these reactions are coupled and inter-related, the HANSF code (FAI/98-40) was used to simulate the air ingress case.

The HANSF code (FAI/98-40), was used to evaluate the effect of competing reactions and to determine if a thermal runaway occurs for two different bounding air entry cases. Full realistic scenarios were not developed because no thermal runaways are expected even for very conservative or extremely off-normal conditions.

6.2.2.1 Case 3 (COXY2SC4). An MCO is charged with pure oxygen instead of helium at the CSB sampling/weld station during gas sampling (i.e., helium cylinders accidentally filled with oxygen or oxygen cylinders accidentally used in place of helium). In obtaining a gas sample from one of the monitored MCOs, the helium pressure in the MCO is accidentally reduced to 1.0 atm. Hence, when oxygen, instead of helium, is accidentally injected into the MCO to 1.5 atm, 0.5 atm (about 33%) of the total pressure is due to oxygen. It is also assumed that only passive cooling is available in the sampling/weld station such that the air temperature and MCO wall temperature are both 132 °C. This maximum steady-state temperature is reached only after at least 50 days in

the sampling/weld station with no active cooling (CSB-HV-0014). In the HANSF simulation, all fuel temperatures are conservatively assumed to be 153 °C, which is the maximum fuel temperature calculated for a 132 °C MCO wall and bounding decay power of 776 W for 5 fuel baskets (HNF-SD-SNF-TI-015).

A very high fuel temperature was used to assess margin. If oxygen reactions at high temperatures do not cause thermal excursion, then no thermal excursion would result for oxygen reactions at lower temperatures. This scenario is very conservative and may not be credible, but it is expected to bound all air entry cases (except the complete shear of an MCO at elevated temperature MCO) and cases with helium bottles contaminated with air or oxygen. This case bounds all air ingress events, without complete shear, at the sampling/weld station because 100% oxygen is postulated to be injected and air has an oxygen content of only 21%. Air ingress through a single orifice (around 1 in. in diameter) cases are bounded by this scenario because very little air can flow into the MCO against the gas being generated within and flowing out of the MCO. Also, no natural circulation with air ingress is possible at the CSB because natural circulation requires two openings, one for air entry and one for gas exit, and two openings are not available in the MCO at the CSB. However, the effects of one very large opening, such as in a complete shear is different (see Section 6.2.2.2). The complete shear scenario was simulated in Case 4 because it represents a physical situation with an unlimited amount of oxidant reaching the fuel.

The temperature and pressure results for Case 3 are shown in Figures 6-5 and 6-6. The design basis accident for air ingress was chosen to be Case 3, with oxygen instead of helium injected at the gas sampling station. For Case 3, the innermost fine scrap fuel has a thermal increase up to almost 440 °C before the oxygen is depleted in the scrap basket and the fuel cools rapidly (see Figure 6-5). This temperature increase occurs because the fine scrap fuel has a high surface-area-to-volume ratio and is initially conservatively at 153 °C. This is hot enough to rapidly oxidize the uranium hydride in the scrap fuel and dramatically increase the fine scrap temperature. The oxygen-hydride reaction at this high temperature rapidly consumes the oxygen, depleting it within an hour. There is not enough water available to continue the chemical reactions. As such, a sustained thermal runaway reaction does not occur. If aluminum hydroxide is included, only a small amount of water is expected to be freed by thermal decomposition because elevated temperatures exist for less than an hour and are restricted to only part of the innermost fine scrap, which represents less than 3% of the total fuel and cladding mass.

The maximum MCO pressure of about 6.2 atm is far below the 11.2 atm (150 lb/in² gauge) MCO rated pressure before the cover cap is welded in place. This maximum pressure is lower than that found in Cases 1 and 2, as expected, because the oxygen reactions do not produce as much gas as the water reactions. The pressure is also lower because the temperatures are generally not as high and the hydrates do not completely decompose, providing less water for reaction.

6.2.2.2 Case 4 (CAIR2SC). In Case 4, the MCO is in the MHM without the MHM extract system cooling fan turned on. An analysis by the MHM manufacturer showed that the MCO wall temperature can reach a steady-state temperature of 115 °C and an MHM air temperature of

102 °C. Case 4 uses these temperatures and assumes that the MHM completely shears off the top, providing a large opening for air to enter the MCO. The scrap fuel and in-tact fuel assembly temperatures are conservatively assumed to be 125 °C. Under these hot conditions, the oxygen in the air reacts with both the uranium fuel and uranium hydride at a high enough rate to slowly increase the fuel temperatures. The scrap basket has better heat rejection than the fuel basket, especially because it is exposed to 102 °C air above it. Hence, the scrap fuel does not heat up as fast as the inner fuel elements, which reach high temperatures very rapidly after 18 hours (shown in Figure 6-7). The maximum temperature reached by the innermost fuel assemblies is about 540 °C, which is still below the uranium-iron eutectic temperature of 725 °C (HNF-SD-SNF-SARR-005).

To prevent a thermal excursion during a shear accident, the fuel temperatures must be kept below 125 °C. This can be achieved by keeping the MCO wall below 115 °C. Also, with interlocks, switches, and sensors in the MHM, shears are not credible (see Table 6-4).

6.2.2.3 Beyond Design Basis Accident. In Case 4 at the MHM without its fan on, the air temperature is 102 °C, based on a previous analysis. Calculations for a complete shear of an MCO at MHM have shown that if the air temperature in the MHM was higher than 102 °C (e.g., 115 °C), then the scrap fuel would start burning rapidly within 8 hours of a complete shear and be completely oxidized in about 10 additional hours. This 100% scrap fuel burn (oxidation) generates about 1,000 kg of UO_2 , which is the approximate material at risk in the scrap basket. This material at risk can produce an airborne source term of about 1 kg of UO_2 , given a respirable airborne release fraction of 1×10^{-3} for oxidizing uranium (DOE-HDBK-3010-94). This source term results in an offsite dose of about 1 rem over a 12-hour period. The fuel in the MCO and the air in the MHM should never be hot enough (≤ 102 °C) to cause a large fuel burn, as is demonstrated in Case 4. Hence, the conditions required for a large fuel burn are beyond the design basis accident for a complete shear providing unlimited oxidant for fuel reactions.

6.2.2.4 Conclusions and Conservatisms. Temperatures remain stable even under very severe external thermal conditions. However, the MCO pressure could get very close to the MCO pressure design limit. This could be a problem, but there are many conservatisms in the evaluation. The main conservatisms and/or margins over bounding parameter values assumed in the computer simulations are itemized as follows:

- No hydrate water is removed at the CVDF, leaving all hydrate water available for thermal decomposition at the CSB.
- No hydride mass is consumed at the CVDF and the hydride reaction rate multiplier was kept at 12 (HNF-SD-SNF-TI-015) for all times, which keeps the hydride-oxygen reaction going. In reality, much of the hydride would be consumed at the CVDF and not be available at the CSB.
- MCO wall temperature is 132 °C because the MCO is placed in the sampling/weld station for 40 days without active cooling.

Even with all of the above margins in the simulations, the calculated MCO gas pressure stays below the MCO design pressure of 11.2 atm (150 lb/in² gauge) before the cover cap is welded in place. The fuel temperatures also are stable after an increase in the innermost fine scrap fuel due to oxidization of the uranium hydride and the large area-to-volume ratio of the fine scrap. Even for a complete shear of a moderately high-temperature MCO, the fuel temperatures stay below guidelines (HNF-SD-SNF-SARR-005).

6.3 SOURCE TERM ANALYSIS

Detailed analyses show there is not enough heat, air, or water to have a credible thermal runaway reaction at the CSB.

Because there is no release expected even under severe off-normal conditions, no source term was estimated.

6.4 CONSEQUENCE ANALYSIS

Detailed analyses show there is not enough heat, air, or water to have a credible thermal runaway reaction at the CSB.

Because there is no release expected, even under severe off-normal conditions, the inhalation dose consequences are zero.

6.5 COMPARISON TO GUIDELINES

Because the dose consequences are zero for thermal runaway reaction events at the CSB, all dose guidelines are met. These results are predicated on the condition that the MCOs passed the dryness tests at the CVDF that ensure that less than 200 g of free water can be present in the MCO after leaving the CVDF. The results depend on the amount of hydrides in the MCO and the amount of aluminum hydroxide, as well as their thermal decomposition rates as a function of temperature. If the MCO design pressure were lowered to 150 lb/in² gauge, then there would still be no dose consequences or safety limit violation, but the margin of safety would be significantly reduced.

The equivalent cases involving MCOs with two scrap baskets, analyzed and presented here, maximize the amount of water and hydrides in the MCO. These cases are expected to bound the thermal and high-pressure estimates and associated consequences when compared with events involving an MCO with one scrap basket or an MCO with no scrap baskets.

6.6 SUMMARY OF SAFETY STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

No safety-class or safety-significant structures, systems, and components (SSCs) are required to prevent the consequences of this accident.

6.6.1 Thermal Runaway Reaction

The technical safety requirement (TSR) controls designated to mitigate or prevent the bounding MCO thermal runaway accident are as follows:

- Assumption
 - The K Basins washing process and the drying process at the CVDF will ensure the key performance assumptions defined in Chapter 1.0, Table 1-6, are met.

The SSCs and TSR controls designated to prevent the MCO thermal runaway accident are summarized in Table 6-4. U.S. Nuclear Regulatory Commission important-to-safety categories and defense-in-depth features also are included for each specific accident in Table 6-4.

The suite of safety SSCs and TSR controls necessary and sufficient to prevent the MCO thermal runaway accident do not address some of the other accidents in the same accident category. Table 6-4 lists the safety SSCs and TSR controls needed to prevent these accidents. Because these accidents are substantially different in development and progression from the design basis accident, each scenario and the corresponding controls are also described below.

6.6.2 Oxygen Ingress due to Shear

Complete and partial shears of the MCO are prevented to protect criticality geometry, as described in Chapter 2.0. Since the maximum allowed outer MCO wall temperatures can be higher than 115 °C, it is most important to prevent MCO shears when rapid fuel-air reactions can occur at fuel temperatures above 125 °C when oxygen could contact the fuel (equivalent to maintaining the MCO wall temperature below 115 °C). Preventing oxygen from reaching the fuel is accomplished by maintaining the MCO vessel integrity by preventing shears by the MHM.

- Safety-class SSCs
 - MHM interlock (P21) and sensors — Ensure that the MCO hoist cannot operate unless the bridge seismic clamps and trolley seismic restraints are applied when an MCO is in the MHM

Table 6-4. Summary of Safety Features Required to Prevent a Multi-Canister Overpack Thermal Runaway. (2 sheets)

Accident	Checklist designator ^a	General function	Safety features and safety classification ^b	NRC ITS category ^b
1a. Thermal runaway reaction — fuel reaction with water	SA-J-10b OA-J-10b WS-J-10b	None at the CSB required for safety	General assumption is that the MCO is received within specifications. <u>Assumption:</u> <ul style="list-style-type: none"> The K Basins washing process and the drying process at the CVDF will ensure that the key interface performance assumptions are met. 	
1b. Thermal runaway reaction — use of contaminated or wrong gas for inerting	WS-H-06b	None at the CSB required for safety	<u>Defense in depth:</u> <ul style="list-style-type: none"> Personnel are trained to facility-specific procedures regarding maintenance, handling and receipt inspection of gas cylinders. Verification of vendor certification of helium purity on receipt of gas cylinders at CSB. 	
2. Oxygen ingress due to shear	<u>Rotational</u> WS-E-07 SA-E-07 OA-E-07 <u>Translational</u> WS-F-07 SA-F-07b OA-F-07 SA-F-05	Prevent shear of the MCO	<u>Safety-class SSCs:</u> <ul style="list-style-type: none"> MHM interlock (P21) and sensors MHM interlocks (P3, P6, P8, P26, P80) and sensors MHM seismic restraint system Seismic detection and MHM power-disconnect system MHM interlock (P9), sensors and switches MHM interlocks (P6, P80), sensors and switches <u>TSRs:</u> <ul style="list-style-type: none"> Operability of MHM interlocks (P3, P6, P8, P21, P26, P80), seismic detection and MHM power-disconnect system; MHM interlock Operability of MHM interlocks (P6, P9, P80), seismic detection and MHM power-disconnect system, and interlock circuitry <u>Defense in depth:</u> <ul style="list-style-type: none"> The MHM-service pit interface provides active, HEPA-filtered ventilation. The MHM-sampling/weld station interface provides active ventilation. The MHM is designed to ASME NOG-1^e to preclude tipping. The MHM has an auditory indication of its movement (i.e., alarms). The MHM is limited to relatively slow movement. The MHM is provided with a backup grapple disengagement capability. Personnel are trained to procedures detailing the safe sequence of operations. 	NA NA NA NA NA NA

Table 6-4. Summary of Safety Features Required to Prevent a Multi-Canister Overpack Thermal Runaway. (2 sheets)

Accident	Checklist designator ^a	General function	Safety features and safety classification ^b	NRC ITS category ^b
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^aChecklist designators are from HNF-SD-SNF-HIE-001, 1999, *Canister Storage Building Hazard Analysis Report*, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^bSSCs are classified per their function in mitigating or preventing specific accidents. SSCs may have other classifications based on their functions in other events.

^cASME NOG-1, 1995, *Rules for Construction of Overhead and Gantry Cranes (Top Running Bridge, Multiple Girder)*, American Society of Mechanical Engineers, New York, New York.

CSB = Canister Storage Building.

CVDF = Cold Vacuum Drying Facility.

HEPA = high-efficiency particulate air (filter)

ITS = important to safety.

MCO = multi-canister overpack.

MHM = multi-canister overpack handling machine.

NA = not applicable to ITS category classification.

NRC = U.S. Nuclear Regulatory Commission.

- MHM interlocks (P3, P6, P8, P26, P80) and sensors — Prevent the seismic restraints and clamps from disengaging and power being applied to the bridge and trolley drive motors unless the MCO hoist is fully raised when in the MCO or impact absorber mode or at the tube plug exchange limit when in the tube plug exchange mode; the interlock circuitry includes relays, contactors, and sensors (resolvers, limit switches, photoelectric switches)
- MHM seismic clamps and restraints — Prevent translational or rotational movement of MHM whenever engaged when an MCO is in the MHM (restraints must be engaged before MCO hoist operation)
- Seismic detection and MHM power-disconnect system — Detects seismic event (magnitude 0.74/3 *g* horizontal, 0.49/3 *g* vertical) and removes all power to the MHM; removal of power prevents operation of the MCO hoist, disengagement of seismic restraints, and MHM translational or rotational movement (MHM interlocks are not seismically qualified)
- MHM interlock (P9), sensors, and switches — Ensure that the MCO hoist cannot operate unless the turret and base locking pins are applied when an MCO is in the MHM; the interlock circuitry includes relays, contactors, and sensors (proximity)
- MHM interlocks (P6, P80), sensors, and switches — Prevent the turret and base locking pins from disengaging and power being applied to the turret rotational drive motors unless the MCO hoist is fully raised when in the MCO or impact absorber mode or at the tube plug exchange limit when in the tube plug exchange mode; the interlock circuitry includes relays, contactors, and sensors (resolver, limit switches, photoelectric switches).
- **TSRs**
 - Operability of MHM interlocks (P3, P6, P8, P21, P26, P80) and seismic detection and MHM power-disconnect system; the interlock circuitry includes relays, contactors, and sensors (resolvers, limit switches, photoelectric switches)
 - Operability of MHM interlocks (P6, P9, P80) and seismic detection and MHM power-disconnect system; the interlock circuitry includes power contactors, MHM relays, mechanical switches, and sensors (resolvers, limit switches, photoelectric switches)

6.7 REFERENCES

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Figure 6-1. Temperature Versus Time for Multi-Canister Overpack Components for Case 1, CHOTSCEN.

CHOTSCEN: HE FILLED MCO @ 1.5 atm, 25 C, 2% steam, UH3=12, U=10, 132 C Wall

Figure 6-2. Temperature Versus Time for Multi-Canister Overpack Components in Bottom Fuel Basket and Pressure Versus Time for Case 1, CHOTSCEN.

CHOTSCEN: HB FILLED MCO @ 1.5 atm, 25 C, 2% steam, UH3=12, U=10, 132 C Wall

Figure 6-3. Temperature Versus Time for Multi-Canister Overpack Components for Case 2, CHOTSCR2.

Figure 6-4. Temperature Versus Time for Multi-Canister Overpack Components in Bottom Fuel Basket and Pressure Versus Time for Case 2, CHOTSCR2.

Figure 6-5. Temperature Versus Time for Multi-Canister Overpack
for Case 3, COXY2SC4.

COXY2SC4: O₂, He FILLED MCO @ 1.5 atm, UH3 Rate=12, U=10, 132 C Wall

Figure 6-6. Temperature Versus Time for Multi-Canister Overpack Components in Bottom Fuel Basket and Pressure Versus Time for Case 3, COXY2SC4.

COXY2SC4: O₂, He FILLED MCO @ 1.5 atm, UH₃ Rate=12, U=10, 132 C Wall

Figure 6-7. Pressure Versus Time for Multi-Canister Overpack
for Case 4, CAIR2SC.

CAIR2SC: MCO With AIR INGRESS-OPEN TOP(100%) UH3=12, U=10, 115 C Wall

Figure 6-8. Thermal Decomposition of Aluminum Hydroxide
(ALCOA 1987, Figure 4.4).

7.0 CALCULATIONS FOR VIOLATION OF DESIGN TEMPERATURE CRITERIA

7.1 PURPOSE AND OBJECTIVES

Heat is produced in the multi-canister overpack (MCO) from radioactive decay energy release and energy released from chemical reactions that occur between the fuel and water or gases. The MCO and Canister Storage Building (CSB) have been designed to provide for ample heat transfer away from the MCO so that an unacceptably high temperature will not be reached during normal handling and storage of the MCO at the CSB. This analysis investigates possible situations where normal heat conduction may be reduced in such a way or for such a length of time as to result in potential overheating of the MCO and/or surrounding structures. Preventive measures are required to preclude such overheating because it could compromise the safety function of safety components such as the MCO. Required controls to prevent the potential consequences of each overheating condition are summarized in Section 7.6.

7.2 SCENARIO DEVELOPMENT

Both radioactive decay and chemical reactions within the MCO generate heat. The bounding situation in which the heat transfer from the MCO to the outside environment could be reduced enough to lead to violation of temperature criteria have been identified by the CSB hazard analysis (HNF-SD-SNF-HIE-001). In this case, the natural convective cooling air flow to the vault is disrupted. This case bounds extended storage of an MCO and MCO effects due to convective heat transfer at other locations in the CSB. This hazard is VL-B-07 and involves exceeding the design temperature for the concrete vault structure. It should be noted that the loss of active cooling of an MCO at the weld station is not considered a serious hazard because there are no impacts for loss of cooling for 40 days.

7.2.1 Multi-Canister Overpack and Vault Concrete Temperatures During Vault Passive Cooling Disruption

This situation in which unacceptable wall temperatures may be reached is one in which the passive cooling of the CSB vault is significantly reduced such that the MCOs in interim storage and vault structure overheat (VL-B-07). If the vault intake and/or exhaust stacks are partially or fully blocked, then the natural convection of air through the vault will be reduced. Significant blockage of the flow could result from many different, unlikely causes, including debris being trapped in the inlet or frost forming over the inlet. Without the vault convective air cooling, temperatures within the vault could rise above design temperature criteria for the vault walls and ceiling and for the MCO centerline. High temperatures could cause the concrete operating deck and vault walls to suffer structural damage, thereby compromising their safety functions. The MCO temperature could exceed design temperature criteria, which could cause loss of MCO safety functions to confine and control the geometry of the spent nuclear fuel.

ACI-349, *Code Requirements for Nuclear Safety Related Concrete Structures*, provides limitations for concrete temperatures during normal operation or any long-term period. The temperatures shall not exceed 150 °F (66 °C) except for local areas, such as around penetrations, which are allowed to have increased temperatures not to exceed 200 °F (93 °C). For an accident duration or any short-term period, the concrete surface temperature shall not exceed 350 °F (177 °C).

Bounding calculations have been performed that assess the effect of loss or partial loss of vault convective cooling flow upon MCO and vault temperatures (CSB-HV-0003). These calculations assume that the vault is full of MCOs and that the corresponding total heat load is 191.6 kW (HNF-SD-SNF-TI-015). The outside air temperature available to cool the vault is assumed to be 115 °F (46 °C), and the surrounding ground temperature is assumed to be 60 °F (16 °C). Given these conditions, the maximum initial temperature of the MCO wall (with no blockage of vault air flow) is expected to be about 252 °F (122 °C) and the maximum vault concrete ceiling surface temperature is expected to be 132 °F (56 °C). CSB-HV-0003, *Spent Nuclear Fuel Vault Loss of Cooling Analysis*, calculations indicate that if the intake stack cross-sectional area is instantly reduced to 25% of normal (i.e., is 75% blocked), then the MCO wall temperature would reach 268 °F (131 °C) and the ceiling temperature would reach 151 °F (66 °C) in 72 hours. Both temperatures are continuing to rise. If the vault inlet stack were somehow completely blocked, the MCO wall temperature would reach the 270 °F (132 °C) CSB limit in about 15 hours and would continue to rise in temperature at a rate of about 1 degree per hour. If 50% or less of the inlet area were blocked, then it is expected that the vault air flow rate and MCO and ceiling temperatures would be nearly equal to those expected for zero blockage.

The bottom of the inlet area of the vault intake structure is more than 19 m above the surrounding grade (H-2-119294, H-2-119280). A vertical grating surrounds the opening to the intake stack on four sides. This grating consists of a heavy gauge (0.13-in. wire diameter) interwoven stainless steel screen with 0.75-in. square openings supported by more widely spaced steel cross members (H-2-119298). The overall dimensions of this grating are about 15.5 ft by 17 ft on two sides and 15.5 ft by 18 ft on two sides, giving a total flow area for all four vertical inlet grates of about 1,080 ft² (H-2-119294). Inlet air flows through this grating and down the inlet stack to a second horizontal grate (H-2-119282) inside the inlet stack that serves a safeguards and security function. This horizontal grating is composed of a metal lattice with perpendicular members spaced 6 in. apart. While it is possible for objects to partially block the intake by accumulating on either of these gratings, objects will not easily be able to reach and accumulate on them. Blowing debris, such as tumbleweeds or garbage, will occasionally be lifted to the height of the upper vertical grating and become lodged.

The intake stack horizontal cross-section is rectangular, with minimum interior dimensions of 16 ft by 10 ft, 8 in. producing a flow area of 172 ft² (H-2-119280). Because the intake outer grating is open on all sides and the opening is quite large, it is improbable that a significant portion (> 50% blockage) of the intake could become blocked. Both the intake and exhaust are significantly above grade. Over a long period of time, it is conceivable that some debris could accumulate over the opening or pass through the outer grating and accumulate on the inner

horizontal grating. Because the openings in the vertical inlet grate are significantly smaller than those of the horizontal grate, it is not considered possible for significant debris to accumulate on the horizontal grate. Because the vertical inlet grating has a total flow area that is more than 6 times that of the horizontal cross-section of the inlet, about 92% of the vertical grating area must become fully blocked before more than 50% of the inlet cross-section area will be blocked. Given that such a large percentage of the four-sided vertical inlet must become fully blocked and that this inlet is located at such a great height above the existing grade, it is judged incredible for the inlet to block such that an unacceptable passive cooling condition will exist. While it would be prudent to have an infrequent but regular program to visually inspect the inlet for blockage caused by accumulated debris, no such inspection is relied upon. Such an inspection would also ensure that the vertical screen was still intact so that large debris could not pass into the stack.

7.2.2 Multi-Canister Overpack Temperature at the Sampling/Weld Station without Active Cooling

Another possible situation in which unacceptable temperatures may be reached is one in which the MCO is located at the sampling/weld station for an extended period of time without active cooling (WS-B-07). Because the MCO is tightly confined at the sampling/weld station, the surrounding steel and concrete could act to insulate it from adequate heat transfer once the thermal heat flux through the immediately surrounding materials has reached equilibrium. If the initial maximum temperature of the sampling/weld station pit shielding wall is 29 °C (85 °F), then calculations show that for a maximum heat generation MCO, the design criteria temperature for either the MCO shell or the concrete is exceeded in about 50 days (MCO shell) and 40 days (concrete) without active cooling (CSB-HV-0014 and CSB-S-0043C).

It should be noted that if a bounding decay heat MCO is indefinitely left in the pit the maximum resulting wall temperature is not expected to exceed 138 °C (280 °F). No adverse effects to the MCO are expected from temperatures slightly above the MCO design temperature. From a safety perspective, wall temperatures above the MCO design temperature do not necessarily damage the safety function of the MCO outer wall or cause damage to MCO internals. See HNF-SD-SNF-SARR-005, *Multi-Canister Overpack Topical Report*, Chapter 4.0, for thermal limitations.

Calculation CSB-S-0043C, *HCSA Deck Design — Confirmation*, evaluates the thermal effects on a concrete structure of an MCO left in the sampling/weld pit for 40 days. Using the thermal gradients shown in CSB-HV-014, *Long Term MCO Temperature Without Cooling in the Sampling Station*, the deck and the pit meet all design criteria (worst-case demand-capacity ratio is 0.99 [vertical reinforcing on inside face of the tubular portion of the pit]). The calculation considered concrete strength degradation from thermal exposure by reducing the concrete strength from 4,000 lb/in² to 3,000 lb/in². This approach is conservative and has been used in other CSB structural calculations to account for concrete degradation.

Since the bounding decay heat MCO can remain in the weld station for more than 40 days without impact to the concrete or the MCO shell, this hazard has been evaluated as being bounded by the loss of vault cooling event.

7.3 SOURCE TERM ANALYSIS

The scenario described above could lead to the damage of safety-class equipment or structures such that their safety function could be compromised. DOE Order 6430.1A, *General Design Criteria*, indicates that safety-class controls are required to prevent conditions that would lead to the damage of safety-class equipment or structures that would impede their ability to perform their safety function. Because the development of radiological source term and dose consequences could not lead to more restrictive safety classification and controls, no source term is developed.

7.4 CONSEQUENCE ANALYSIS

Loss of the vault convective cooling could lead to temperature increases over a long period of time, resulting in potential gradual damage to the vault and operating deck concrete. Heat damage to the concrete would continue slowly once it began. A damaged operating deck may not survive the design basis earthquake, resulting in a possible violation of criticality geometry control of the array of MCOs stored in the vault if the vault were to structurally fail. Ample time would be available to identify and correct any loss of air flow condition in the vault. Because the outer vertical inlet screens are so large and are located so far above the existing grade, it is not considered credible for sufficient blockage of the inlet to occur and result in a temperature violation. These temperature criteria violation scenarios will be prevented so that no safety-class structures or equipment will be damaged.

7.5 COMPARISON TO GUIDELINES

Safety-class features are needed to prevent the scenario; therefore, no comparison to dose consequence guidelines is made.

7.6 SUMMARY OF SAFETY STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

7.6.1 Loss of Vault Cooling

The safety-class structural components that are required to ensure that passive cooling is sufficient to prevent the MCOs or safety-class facility concrete structures from being exposed to temperatures in excess of design criteria are as follows:

- Safety-class structures, systems, and components (SSCs)
 - Vault (concrete) — Maintains geometry to provide for passive convective cooling air flow past the storage tubes and for criticality geometry control of the MCOs stored in the tubes
 - Vault intake structure — Provides inlet for passive cooling air to the vault, is above grade, and has screened entrances that provide assurance that the inlet will not become significantly obstructed
 - Vault exhaust structure — Provides exit for passive cooling of vault, is above grade, and is designed such that it will not become significantly obstructed
 - Storage tubes, tube base assemblies, and carbon steel base slab embeds — Provide spacing of MCOs within the vault to ensure that each will be cooled by passive air flow and that the array will be maintained in a critically safe geometry.

The SSCs designated to prevent violation of the design temperature criteria are summarized in Table 7-1. U.S. Nuclear Regulatory Commission important-to-safety category SSCs and defense-in-depth features also are included for each specific accident in Table 7-1.

Table 7-1. Summary of Safety Features Required to Prevent Violation of Design Temperature Criteria Design Basis Accidents.

Accident	Checklist designator ^a	General function	Safety features and safety classification ^b	NRC ITS category ^b
1. Loss of vault cooling	VL-B-07 VL-B-10 VL-B-11	Maintain structures and configuration required to maintain adequate passive convective cooling flow through the vault	<u>Safety-class SSCs:</u> <ul style="list-style-type: none"> • Vault, vault intake structure (including screen), vault exhaust structure, carbon steel basemat embeds, tube base assemblies, and storage tubes <u>Defense in depth:</u> <ul style="list-style-type: none"> • Differential temperature monitors are located on outlet stack and give indication of undesired trends • Various screens on the inlet and outlet stack reduce the likelihood of accumulation of debris in the vault 	A

^aChecklist designators are from HNF-SD-SNF-HIE-001, 1999, *Canister Storage Building Hazard Analysis Report*, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^bSSCs are classified per their function in mitigating or preventing specific accidents. SSCs may have other classifications based on their functions in other events.

ITS = important to safety.

NRC = U.S. Nuclear Regulatory Commission.

SSC = structure, system, and component.

7.7 REFERENCES

- ACI-349, 1985, *Code Requirements for Nuclear Safety Related Concrete Structures*, American Concrete Institute, Farmington Hills, Michigan.
- CSB-HV-0003, 1996, *Spent Nuclear Fuel Vault Loss of Cooling Analysis*, Fluor Daniel Hanford, Incorporated, Richland, Washington.
- CSB-HV-0014, 1998, *Long Term MCO Temperature Without Cooling in the Sample Station*, Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, Washington.
- CSB-S-0043, 1996, *HCSA Deck Design - Confirmation*, Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, Washington.
- DOE Order 6430.1A, *General Design Criteria*, U.S. Department of Energy, Washington, D.C.
- H-2-119280, 1997, *Structural Canister Storage Building Operation Floor Reinforcement Details and Intake Structure Details*, Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, Washington.
- H-2-119282, 1997, *Structural Canister Storage Building Intake/Exhaust Security Barrier*, Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, Washington.
- H-2-119294, 1996, *Structural Canister Storage Building Air Intake Steel Structure*, Rev. 3, Fluor Daniel Hanford, Incorporated, Richland, Washington.
- H-2-119298, 1996, *Structural Canister Storage Building Air Intake Steel Details*, Rev. 3, Fluor Daniel Hanford, Incorporated, Richland, Washington.
- HNF-SD-SNF-HIE-001, 1999, *Canister Storage Building Hazard Analysis Report*, Rev. 2, Draft, Fluor Daniel Hanford, Incorporated, Richland, Washington.
- HNF-SD-SNF-SARR-005, 1999, *Multi-Canister Overpack Topical Report*, Rev. 1, Fluor Daniel Hanford, Incorporated, Richland, Washington.
- HNF-SD-SNF-TI-015, 1998, *Spent Nuclear Fuel Project Technical Databook*, Rev. 6, Fluor Daniel Hanford, Incorporated, Richland, Washington.

8.0 CALCULATIONS FOR RECOVERY ACTIONS RELATED TO GASEOUS RELEASES AND EXPLOSIONS FROM OVERPACK STORAGE TUBES

8.1 PURPOSE AND OBJECTIVE

The use of the overpack storage tube assembly (OSTA) and the tube vent and purge cart are related to recovery actions of off-normal multi-canister overpacks (MCOs). Potential uses include the possibility of receiving an MCO that is out of specification (see Table 1-6) or an MCO with uncertain confinement capabilities. Analyses were performed for these uses to identify safety functions and classify structures, systems, and components. These functions and classifications are intended to achieve an appropriate level of defense in depth (to prevent or mitigate the radiological consequences of postulated hazards and accident events to the collocated onsite worker) and worker safety (to reduce exposure to radiation) for the OSTAs and tube vent and purge cart. The results of the hazard evaluation for an off-normal MCO in an overpack storage tube, with support by the tube vent and purge cart, are summarized below. Further, details are in the Canister Storage Building (CSB) Hazards Analysis, Chapter 4.0 (HNF-SD-SNF-HIE-001).

This analysis assumes that the OSTAs will be used for two types of recovery situations. The first is an off-normal MCO in a cask coming from the Cold Vacuum Drying Facility (CVDF) to the CSB. The second is an off-normal occurrence at the CSB where a normal MCO has sustained an impact, drop, or collision during handling operations. In the former case, an MCO shipped from the CVDF in its transportation cask is received at the CSB and undergoes normal load-in and load-out MCO operations, which include checking the internal pressure of the transportation cask in the service station pit before removing the cask lid. An off-normal MCO in the cask would be discovered during this check if the cask pressure is measured to be off-normal. In the latter case, the MCO suffers an impact, drop, or collision after the lid is removed from the cask and during subsequent MCO handling operations in the CSB.

Based on hazard evaluations (HNF-SD-SNF-HIE-001) for storage of an off-normal MCO in the overpack storage tubes, unmitigated design basis accidents within the overpack storage tubes involve gas releases from an MCO in the overpack tube; flammable gas explosions; and gas releases from the overpack tube to the operating area (see Table 8-1). Hydrogen gas can be generated and accumulate within the MCO. MCO gas pressures are not expected to exceed 5.2 atm during the interim storage time period at the CSB (HNF-SD-SNF-TI-015). If the MCO is dropped or otherwise damaged in a way that could lead one to suspect the loss of integrity of the MCO confinement safety function, the MCO could be placed into an overpack storage tube. This chapter evaluates the potential consequences of these unique representative and bounding design basis accidents for the overpack storage tubes.

Table 8-1. Binned Listing of Candidate Accidents for Off-normal Multi-Canister Overpack Storage (HNF-SD-SNF-HIE-001^a).

Candidate accident	Risk ranking ^b	Release or change energy	Reference designator
Gaseous releases and explosions from overpack storage tubes			
Gaseous release in the overpack storage tube	FRxF2/SRxS2 FRxF2/SRxS2	Medium Low	OA-B-07 OA-F-02
Hydrogen explosions in the overpack storage tube	FRxF3/SRxS2 FRxF2/SRxS2 FRxF2/SRxS2 FRxF2/SRxS2	Medium High Medium Low	OA-J-06d OU-R-01 VL-J-06 OA-F-02
Gaseous release from the overpack storage tube to the operating area	FRxF3/SRxS2	Medium	OA-H-06c

^aHNF-SD-SNF-HIE-001, 1999, *Canister Storage Building Hazard Analysis Report*, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^bFR Frequency of recovery event, which describes the undetermined likelihood of the "off-normal hazardous condition" developing following termination and recovery of the initial event; therefore, the off-normal frequency ranking is a product of FR and the frequency of the initial event (e.g., F3, F2, F1).

SR Severity of the recovery event, which describes the undetermined magnitude of release due to the unanalyzed condition of the damaged multi-canister overpack; therefore, the off-normal consequence ranking is a product of SR and the consequence of the initial event (e.g., S3, S2, or S1).

8.2 SCENARIO DEVELOPMENT

Once an off-normal occurrence has been confirmed and a safe and stable condition has been established, it is assumed that CSB operations will initiate recovery actions that begin with a recovery team meeting to assess the occurrence and determine the path forward. The recovery team will be responsible for ensuring worker and public health and safety during the handling, stabilization, and final disposition of the off-normal MCO. For this analysis, it is assumed that the preferred planned approach is to move the off-normal MCO for storage in an overpack storage tube. It is assumed that recovery operations will continue until the MCO has been placed in an overpack storage tube and the tube gas space has been filled with inert gas. Once the tube has been inerted, an MCO is considered to have been placed in a stable configuration so that normal operations can resume elsewhere in the facility. In the present design, the capabilities of the tube vent and purge cart, plug assembly, and other available equipment are to be used to monitor the physical characteristics of an off-normal MCO while outside and inside the OSTA. If an off-normal MCO's characteristics are outside of the bounding parameters identified in HNF-2256, *Simulation of Normal and Off-Normal Multi-Canister Overpack Behavior*, this MCO is to be considered to pose an unreviewed safety question situation.

Hazards have been identified for the overpack storage tubes (HNF-SD-SNF-HIE-001) that rely on mitigation or prevention related to overpack storage tube or overpack storage tube plug safety functions. The condition of the off-normal MCO is assumed to be as follows:

- Off-normal MCO is mechanically sealed or weld sealed but may have releases due to lost confinement function of the MCO
- The maximum pressure developed in an MCO (during 40-year storage) will be less than 5.2 atm (before any gas explosion)
- Limited hydrogen gas generation rate and total generation quantity due to maximum of 200 g of water from cold vacuum drying processing and 1,190 g of uranium hydrate water (MCO with two scrap baskets)
- Long-term hydrogen generation rate and release limited to radiolysis of aluminum hydroxide (48 kg maximum)
- Analysis indicates that a flammable mixture within the OSTA is improbable with inerted tubes
- Inert atmosphere and pressure is periodically monitored.

The hazards associated with the overpack storage tubes are dominated by energy and release mechanisms resulting from hydrogen explosions in the tube (OA-J-06d), gas releases from the OSTA to the operations area (OA-B-07), and pressurized releases into the tubes from the MCO (OA-H-06c) (HNF-SD-SNF-HIE-001). These analyses evaluate these hazards by using scenarios that have initiating events of pressurized releases from the MCO into the tube and hydrogen explosions in the tubes. Releases from the tube into the operating area result from the physical mechanics of these initiating events. The specific accident scenarios will be described and justified in the following section. Calculated unmitigated dose consequences are compared to guidelines, and preventive or mitigative features and controls are discussed. The consequences of each of these accidents is bounded by the bounding risk gaseous release accident described in Chapter 3.0.

8.2.1 Gaseous Release Accident

Three gaseous release accident variations are considered: (1) a pressurized release from the MCO into an inerted overpack storage tube without the tube plug mechanically locked; (2) a pressurized release from the MCO into an inerted overpack storage tube with the tube plug mechanically locked, followed by a failed connection between the tube plug and the tube vent and purge cart; and (3) a pressurized release from the MCO into an air-filled overpack storage tube with the tube plug mechanically locked, followed by an immediate detonation of the flammable gas mixture formed in the overpack storage tube.

It is possible that an MCO accident (e.g., a drop) could damage or weaken a seal on the MCO without leading to an immediate leak. A leak could begin due to handling or increased internal pressure while or shortly after the MCO is placed into the overpack storage tube. The scenario considered will not begin until the MCO has been placed in the overpack storage tube and the tube plug has been placed in the tube. The overpack storage tube will be filled with helium at a pressure of about 7 lb/in² after the MCO has been placed in the tube. If the pressurized release occurs after this inerting, no explosion can result and any particulate release will only be due to motive forces from the pressurized gas. The maximum pressure possible inside the MCO before this venting is 5.2 atm (HNF-SD-SNF-TI-015). If the pressurized release occurs somewhat rapidly, significant radiological particulate could be entrained and released. The resultant pressure in the overpack storage tube is sufficient to lead to the lifting of the tube plug and a venting of gas and entrained particulate to the operating area. This release and the resultant dose consequence will be considered. Distribution of this particulate could be further enhanced by a subsequent explosion in the tube, if the tube has not yet been inerted. The dose consequences of the release due to both the pressurized gas (with entrained particulate) release into the overpack storage tube and its subsequent ignition will also be considered.

If the gaseous release is contained by the closed, inert gas-filled OSTA, there is still an opportunity for particulate released into the tube to be released into the operating area, if an accident occurs when inerting the tube with the tube vent and purge cart. If the connection between the tube plug and the cart high-efficiency particulate air (HEPA) filter was not properly installed or failed, an unfiltered pressurized release could occur from the overpack storage tube. This release would contain resuspended particulate and any particulate that had not yet settled since the original MCO pressurized release into the tube. This scenario will be considered a unique accident whose unmitigated dose consequences and controls are discussed below.

8.2.2 Flammable Gas Explosion

While the MCO is designed to maintain confinement during all credible CSB drop accidents, it is conceivable that an MCO drop accident could cause an immediate breach in the MCO confinement. An MCO whose confinement is breached will possibly be placed into an overpack storage tube. To demonstrate the need for inerting the overpack storage tube, the unmitigated accident assumes that the tube is not filled with inert gas. Hydrogen can continue to be produced within the MCO and leak into the tube, mix with air, and form a flammable gas in the overpack storage tube. A worse scenario could result if air entered the MCO through its breach and mixed with hydrogen in the MCO to produce a flammable atmosphere within the MCO. The explosion of this mixture in the MCO could cause greater damage to the MCO confinement and lead to radioactive particulate releases from the MCO. The blast effect would dislodge particulate from the fuel, and the particulate would be carried out of the MCO as it depressurizes. The pressure generated as a result of such an explosion, P_F , may be calculated using the equations below (SFPE 1992). The first equation is solved for the final temperature, T_F , and then this value is used in the ideal gas law to solve for the final pressure.

$$H * N_{H_2O} = \int_{T_0}^{T_F} (\sum_i C_{v_i} * N_i) dT$$

and

$$P_F = \frac{nRT_F}{V}$$

where

- H = heat of formation of water from hydrogen and oxygen
- N_{H_2O} = the number of moles of water formed
- T_0 = the initial temperature of the gas
- T_F = the final temperature of the gas
- Cv_i = the specific heat capacity at constant volume of gas I [obtained using a quadratic fit as a function of temperature to data from Whitwell and Toner (1969)]
- N_i = number of moles of gas I after the reaction
- P_F = final pressure
- n = total number of moles of gas after the reaction
- R = the universal gas constant
- V = the MCO gas volume.

A stoichiometric ratio of hydrogen and oxygen from air is not expected within the MCO because the MCO is filled with helium at the CVDF, and the production of hydrogen is greatly reduced if oxygen enters the MCO. A leak could develop in the MCO, allowing the helium-hydrogen mixture to escape while hydrogen continues to be produced. After the MCO has depressurized to equilibrium pressure with the tube, air can diffuse into the MCO. If a stoichiometric mixture of oxygen in air with hydrogen is conservatively used to calculate the pressure immediately after ignition, then pressure within the MCO is calculated to be about 8 atm. If a detonation occurs, it may lead to an instantaneous overpressure of about 16 atm because of the reflected pressure pulse within the essentially confined MCO. The MCO might sustain additional damage from this explosion but is expected to substantially withstand this instantaneous overpressure. The blast effect would dislodge particulate from the fuel and the particulate would be carried out of the MCO as it depressurizes. The particulate release from this accident is calculated and, as expected, is similar to that calculated for the bounding unmitigated gaseous release accident.

The gaseous release accident could also lead to the formation and subsequent explosion of a flammable gas mixture in the overpack storage tube outside of the MCO. The mechanical consequences of and the controls to prevent such an explosion are discussed below.

In summary, scenarios for these events describe a pressurized release of gases from an MCO into an overpack storage tube because of either internal MCO pressure or a flammable gas explosion within the MCO. The unmitigated scenario is brought to a stable state by allowing the MCO inside the OSTA and the OSTA to be vented and purged of any additional gas generated. The tube vent and purge cart are used until the MCO in the OSTA and the OSTA are brought to a stable inert atmosphere. Any contamination is cleaned consistent with radiation control procedures. The off-normal MCO is handled within recovery operations under emergency response procedures, with the preferred approach being to move the off-normal MCO to another available overpack storage tube for long-term observation and storage.

8.3 SOURCE TERM DEVELOPMENT AND CONSEQUENCE ANALYSIS

8.3.1 Gaseous Release Accident

The relatively quick venting of a potentially pressurized MCO in an overpack storage tube would result in radioactive releases comparable to those predicted for the bounding gaseous release accident at the sampling/weld station. The unmitigated radioactive particulate release can be estimated using bounding release fractions derived from experiments in which pressurized gases are vented through powders. The radioactive particulate available for release would be generated by reactions within the MCO that occur after the fuel is washed. Flowing gas exiting the MCO would sweep past the fuel surfaces and entrain uranium oxide particulate. This particulate must then escape through a tortuous path and out a small opening in the MCO or one of its seals to be released to the overpack storage tube.

The bounding airborne release fraction and limiting respirable fraction for this release is based on data reported in DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions/Rates for Nonreactor Nuclear Facilities*, Section 4.4.2.3.2. For pressurized gases less than 0.17 MPa gauge, the release fraction is bounded by 2×10^{-3} . The bounding mass of particulate formed in the MCO is about 34 kg of uranium oxide, comprised of 30 kg of uranium (HNF-SD-SNF-TI-015).

The mass of respirable radioactive particulate released (Q) during this venting is calculated using (HNF-SD-SNF-TI-059):

$$Q = (MAR)(RF)(LPF)$$

where

MAR = material at risk (30 kg)
 RF = release fraction (2.0×10^{-3})
 LPF = leak path factor (conservatively set to 1).

The amount released into the overpack storage tube during MCO venting is calculated to be:

$$Q = (30 \text{ kg})(2.0 \times 10^{-3})(1) = 0.060 \text{ kg} = 60 \text{ g.}$$

The overpack storage tube and tube plug provide passive confinement for gases escaping the MCO; however, the pressure reached in the overpack storage tube would cause the tube plug to momentarily lift so that some portion of the tube gases escapes to the operating area. As the pressurized gas is released from the MCO, it will expand into the overpack storage tube. The overpack storage tube is expected to be at about 7 lb/in² pressure before this event occurs, if it is backfilled with helium. Given the combined gaseous volume (V_3) in the MCO ($V_1 = 500 \text{ L}$) and the free space in the overpack storage tube ($V_2 \approx 2,600 \text{ L}$), the equilibrium pressure in both after the gaseous release can be calculated as follows using the ideal gas law.

The total number of moles of gas is:

$$n_3 = n_1 + n_2 = (5.2 \text{ atm})(500 \text{ L})/(RT) + (1.48 \text{ atm})(2600 \text{ L})/(RT) = (6,440 \text{ atm-L})/(RT)$$

where

n_i = is the number of moles of gas in the MCO (n_1), overpack storage tube (n_2), or combined total (n_3)

RT = the molar gas constant multiplied by the gas temperature in the MCO and overpack storage tube (assumed to be about the same temperature).

The equilibrium pressure, assuming that no temperature change takes place during venting, is:

$$P_{\text{equil}} = (n_3)(RT)/(500 \text{ L} + 2,600 \text{ L}) = (6,440 \text{ atm-L})/(3,100 \text{ L}) = 2.1 \text{ atm.}$$

For the unmitigated accident, the tube plug is not mechanically locked into place. The tube plug has a weight of about 5,300 lb and a surface area exposed to the tube gas space of about 573 in²; therefore, the minimum internal tube pressure required to lift the plug is about 9.3 lb/in² (1.6 atm). The overpack storage tube internal pressure must exceed about 1.6 atm to lift the tube plug so that the seal is broken. The fraction of the overpack storage tube gas released to the operating deck will be calculated:

$$\text{Gas fraction released} = (2.1 \text{ atm} - 1.6 \text{ atm})/2.1 \text{ atm} = 0.24.$$

If the 60 g of particulate released from the MCO is spread uniformly in the overpack storage tube gas, then about 24% of the particulate, or 14 g, is released outside the tube into the building and environment.

If the overpack storage tube were not filled with inert gas, then the gas released from the MCO to the overpack storage tube could form a flammable mixture. If this mixture were to detonate, there would be sufficient force to lift the tube plug, permanently breaking the seal (see Section 8.3.2). In this case, all 60 g of particulate could be released to the environment.

The radiological dose (effective dose equivalent [EDE]) to a downwind receptor may be calculated using (HNF-SD-SNF-TI-059):

$$EDE = (M)(\chi/Q')(BR)(UD)$$

where

- EDE = the effective dose equivalent (rem)
- M = the respirable radioactive particulate released (g)
- χ/Q' = the air transport factor (s/m^3)
- BR = the average inhalation rate during the release (m^3/s)
- UD = the committed effective dose equivalent per unit gram (rem/g).

For this release the appropriate values for the air transport factor (χ/Q') are given in Table 3-2 for release durations from the CSB that are less than one hour. For the onsite receptor 100 m from the CSB, the maximum value for χ/Q' is $3.41 \times 10^{-2} \text{ s/m}^3$; or the receptor at the Hanford Site boundary, the value is $1.30 \times 10^{-5} \text{ s/m}^3$; and for the receptor at Highway 240, the value is $2.36 \times 10^{-5} \text{ s/m}^3$ (HNF-SD-SNF-TI-059). The breathing rate (BR) for a short duration release is $3.33 \times 10^{-4} \text{ m}^3/\text{s}$, that of an individual performing light activity (HNF-SD-SNF-TI-059). The unit dose (UD) equivalent for the spent nuclear fuel is $4.38 \times 10^5 \text{ rem/g}$ (HNF-SD-SNF-TI-059).

For the onsite worker (100 m), the calculated dose from this gaseous release accident without a subsequent explosion in the tube is:

$$\begin{aligned} EDE_{\text{onsite}} &= (14 \text{ g}) (3.41 \times 10^{-2} \text{ s/m}^3) (3.33 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g}) \\ &= 70 \text{ rem.} \end{aligned}$$

The offsite (17,390 m east) and Highway 240 (9,280 m west) receptor doses from this gaseous release accident without a subsequent explosion in the tube are calculated to be:

$$\begin{aligned} EDE_{\text{offsite}} &= (14 \text{ g}) (1.30 \times 10^{-5} \text{ s/m}^3) (3.33 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g}) \\ &= 0.027 \text{ rem.} \end{aligned}$$

$$\begin{aligned} EDE_{240c} &= (14 \text{ g}) (2.36 \times 10^{-5} \text{ s/m}^3) (3.33 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g}) \\ &= 0.048 \text{ rem.} \end{aligned}$$

If the release is enhanced by an immediate detonation in the overpack storage tube, then both the onsite and offsite releases would increase by about a factor of 6 to 420 rem onsite and 0.16 rem offsite. Such a detonation cannot occur after the tube has been filled with inert gas. The operation of placing the MCO into the overpack storage tube and initially inerting the tube will be considered part of the recovery actions and not part of normal operations as allowed under the CSB Authorization Basis.

If the particulate were fully contained by a sealed OSTA, then the mitigated doses would be zero. There is still a potential for release of a portion of this particulate when the tube vent and purge cart is connected to the tube plug. The tube vent and purge cart would be used to relieve the pressure from the overpack storage tube through HEPA filters so that the potential for pressurized unfiltered relief of the overpack storage tube is reduced. If the filters are specified to operate at a particulate removal efficiency (below 10 microns) of at least 99.9%, then the resultant mitigated doses are reduced by a factor of 1,000. The onsite (100 m) mitigated dose from the gaseous release accident (without subsequent flammable gas explosion) is therefore reduced from 70 rem to 0.07 rem, which is well below the onsite guideline of 10 rem.

If the connection between the tube vent and purge cart and the overpack storage tube plug were to fail during pressure purging, then a release could occur that bypasses the HEPA filters. This failure could occur due to operator error, such as the operator moving the cart with the flexible hose connected to the tube plug. If particulate in the overpack storage tube had settled out of the gas and was distributed on surfaces within the tube, then the pressurized release or particulate from the overpack storage tube would be described by the same bounding release fractions used during the initial release from the MCO. Applying the release fraction of 2×10^{-3} to the maximum particulate in the tube (60 g) gives a mass of respirable radioactive particulate released to the environment of 0.12 g. This release will lead to a dose of 0.6 rem to the onsite (100 m) receptor and to a dose of less than 1 mrem to the offsite receptor. If the particulate in the overpack storage tube has not settled out of the gas before the connection between the tube plug and cart fails, then the release to the operating area could be up to the total particulate (60 g).

The approximate time needed for the particulate to settle can not be determined using a Stokes settling equation for a tranquil gas. For the gas and particulate in the CSB scenario, the terminal settling velocity of the particulate and then the time required to settle may be described by (Hinds 1982, Eq. 3.13):

$$V_{TS} = \frac{\rho_p d^2 g}{18 \eta}$$

where

$$\begin{aligned} V_{TS} &= \text{terminal settling velocity (cm/s)} \\ \rho_p &= \text{particle density (g/cm}^3\text{)} \\ d &= \text{particle diameter (cm)} \end{aligned}$$

g = gravitational constant (cm/s^2)
 η = viscosity of air ($\text{dyn}\cdot\text{s/cm}^2$)

and

$$T_{\text{settle}} = \frac{H}{V_{\text{TS}}}$$

where

T_{settle} = time required to settle (s)
 H = settling height (cm).

For 1-micron-diameter particulate of density 5 g/cm^3 , the terminal settling velocity is given by:

$$V_{\text{TS}} = (5 \text{ g/cm}^3) (1 \times 10^{-4} \text{ cm})^2 (980 \text{ cm/s}^2) / (18 * 1.81 \times 10^{-4} \text{ P}) = 0.015 \text{ cm/s}$$

and the corresponding time to settle to the bottom of a 40 ft tall storage tube is:

$$T_{\text{settle}} = (40 \text{ ft}) (30.48 \text{ cm/ft}) / (0.015 \text{ cm/s}) = 81280 \text{ s} \approx 23 \text{ h.}$$

For particulate larger than 1 micron in diameter, the settling time will be less than that calculated for 1 micron. After more than 23 hours after a release into the tube, the particulate will have settled so that it must be resuspended before it could be released.

To determine a reasonable pressure increase that could be expected without a pressurized release during a 24-hour time period, one must consider both the maximum hydrogen generation rate from the MCO and the pressure increase that might be expected from tube temperature changes. After about the first four days that the MCO is sealed at the CVDF, the hydrogen generation gas rate is expected to fall. During the first 3×10^5 seconds, the MCO temperature could be expected to rise to 360 K, while the hydrogen concentration climbs to as high as 32%, resulting in a pressure of up to 2.6 atm (HNF-2256, Appendix T5). The average hydrogen generation rate during this time interval will be higher than the rate at subsequent times under normal conditions. The maximum sustained hydrogen gas generation rate from an MCO at the CSB is about 4.8×10^{-5} moles/s (HNF-2256). During 24 hours, about 4.15 moles of hydrogen gas may be generated. If the tube contained gas from an MCO that had blown down from 3 atm internal pressure and the tube was initially pressurized to 4 lb/in², then at a gas temperature of 313 K the total number of moles of gas in the storage tube and MCO would be about 190. Adding about 4 moles of gas to this system would raise the pressure by about 2%, from about 8.1 lb/in² gauge to 8.2 lb/in² gauge. If the temperature of the gas in the tube were to rise about 25 K during this time period, then the pressure would rise about an additional 8% to about 8.9 lb/in² gauge. These changes are calculated to represent typical tube pressure changes that could occur from large temperature changes and large normal hydrogen gas generation rates. Given that one might reasonably expect the tube pressure to rise up to about 1 lb/in² gauge during

a nearly worst-case 24-hour time period, a pressure rise much greater than 1 lb/in² gauge could indicate a pressurized release that could suspend significant particulate. If the temperature of the tube gas were to drop during the 24-hour time period, then a gaseous release from the MCO would be partially masked by the competing temperature induced pressure drop. Any significant pressurized release from the MCO would still produce a final pressure more than 1 lb/in² gauge above that measured about 24 hours previously.

8.3.2 Flammable Gas Explosion

Without mitigation, a flammable hydrogen gas mixture can form within the MCO and/or the overpack storage tube. If a detonation occurs within the MCO, it can lead to an instantaneous overpressure of about 16 atm due to the reflected pressure pulse wave within the essentially confined MCO. The blast effect would dislodge particulate from the fuel, and the particulate would be carried out of the MCO as it depressurized. The airborne release fraction and the respirable fraction recommended as bounding for this accident in Section 5.3.2.2 of DOE-HDBK-3010-94 are identical to those used in the gaseous release accident. The amount of particulate released to the inside of the overpack storage tube will be 60 g. The difference in the calculated release will be due to the increase in the fraction of gas that escapes the overpack storage tube after the explosion. The tube initial pressure (before the explosion) will be assumed to be atmospheric because the tube is assumed to be filled with air so that an explosion is possible. Although a detonation could occur within the MCO, the actual overpressure within the MCO just after the explosion will be 8 atm with an internal gas temperature of 2,700 K. Assuming that no gas temperature change takes place during MCO venting to the tube following the explosion, the resultant equilibrium pressure in the tube and MCO may be calculated.

If the MCO pressure after the explosion is 8 atm, then the total number of moles of gas is:

$$n_3 = n_1 + n_2 = (8 \text{ atm})(500 \text{ L})/(R \cdot 2700 \text{ K}) + (1.0 \text{ atm})(2,600 \text{ L})/(R \cdot 370 \text{ K}) = (8.5 \text{ atm-L/K})/R.$$

Gas temperature, ignoring heat loss and differences in gas heat capacities, will be about 800 K. The maximum tube pressure is:

$$P = (n_3)(R \cdot 800 \text{ K})/(500 \text{ L} + 2,600 \text{ L}) = (8.5 \text{ atm-L/K})(800 \text{ K})/(3,100 \text{ L}) = 2.2 \text{ atm}.$$

The overpack storage tube internal pressure must exceed about 1.6 atm to lift the tube plug so that the seal is broken. The fraction of the overpack storage tube gas released to the operating deck is calculated:

$$\text{Gas fraction released} = (2.2 \text{ atm} - 1.6 \text{ atm})/2.2 \text{ atm} = 0.27.$$

If the 60 g of particulate released from the MCO is spread uniformly in the overpack storage tube gas, then about 27% of the particulate, or 16 g, is released outside the tube into the building and environment.

For the onsite worker (100 m), the calculated dose from this accident is:

$$\begin{aligned} \text{EDE}_{\text{onsite}} &= (16 \text{ g}) (3.41 \times 10^{-2} \text{ s/m}^3) (3.33 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g}) \\ &= 81 \text{ rem.} \end{aligned}$$

The offsite (17, 390 m east) and the Highway 240 (9,280 m west) receptor doses are calculated to be:

$$\begin{aligned} \text{EDE}_{\text{offsite}} &= (16 \text{ g}) (1.30 \times 10^{-5} \text{ s/m}^3) (3.33 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g}) \\ &= 0.031 \text{ rem.} \end{aligned}$$

$$\begin{aligned} \text{EDE}_{240} &= (16 \text{ g}) (2.36 \times 10^{-5} \text{ s/m}^3) (3.33 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g}) \\ &= 0.055 \text{ rem.} \end{aligned}$$

8.4 CONSEQUENCE ANALYSIS

8.4.1 Gaseous Release Accident

The overpack storage tube and tube plug provide passive confinement for gases escaping the MCO; however, the pressure reached in the overpack storage tube would cause the tube plug to momentarily lift so that some portion of the tube gases escapes to the operating area. As the pressurized gas is released from the MCO, it will expand into the overpack storage tube. The overpack storage tube is backfilled with helium; it is expected to be at a minimum of 4 lb/in² gauge pressure before this event occurs. Given the combined gaseous volume (V_3) in the MCO ($V_1 = 500 \text{ L}$) and the free space in the overpack storage tube ($V_2 \approx 2,600 \text{ L}$), the equilibrium pressure in both after the gaseous release, using the ideal gas law, is about 2.1 atm.

The overpack storage tube internal pressure must exceed about 1.6 atm to lift the tube plug so that the seal is broken. The fraction of the overpack storage tube gas released to the operating deck is 0.24. If the 60 g of particulate released from the MCO is spread uniformly in the overpack storage tube gas, about 24% of the particulate, or 14 g, is released outside the tube into the building and environment.

If the overpack storage tube is not filled with inert gas, the gas released from the MCO to the overpack storage tube could form a flammable mixture. If this mixture detonates, there would be sufficient force to lift the tube plug, permanently breaking the seal (see flammable gas explosion discussion that follows). In this case, all 60 g of particulate could be released to the environment.

The radiological dose (effective dose equivalent) to a downwind receptor can be calculated using (HNF-SD-SNF-TI-059):

$$EDE = (M)(\chi/Q')(BR)(UD)$$

where

- EDE = the effective dose equivalent (rem)
- M = the respirable radioactive particulate released (g)
- χ/Q' = the air transport factor (s/m^3)
- BR = the average inhalation rate during the release (m^3/s)
- UD = the committed effective dose equivalent per unit gram (rem/g).

For this release, the appropriate values for the air transport factor (χ/Q') are given for release durations from the CSB that are less than one hour. For the onsite receptor 100 m from the CSB, the maximum value for χ/Q' is $3.41 \times 10^{-2} \text{ s/m}^3$. The value for the receptor at the Hanford Site is $1.30 \times 10^{-5} \text{ s/m}^3$ (HNF-SD-SNF-TI-059). The breathing rate (BR) for a short duration release is $3.33 \times 10^{-4} \text{ m}^3/\text{s}$, that of an individual performing light activity (HNF-SD-SNF-TI-059). The unit dose (UD) equivalent for the spent nuclear fuel is $4.38 \times 10^5 \text{ rem/g}$ (HNF-SD-SNF-TI-059).

For the onsite worker (100 m), the calculated dose from this gaseous release accident without a subsequent explosion in the tube is:

$$\begin{aligned} EDE_{\text{onsite}} &= (14 \text{ g}) (3.41 \times 10^{-2} \text{ s/m}^3) (3.33 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g}) \\ &= 70 \text{ rem.} \end{aligned}$$

This detonation could not occur after the tube has been filled with inert gas. The operation of placing the MCO into the overpack storage tube and initially inerting the tube will be considered part of the recovery actions and not part of normal operations. If the particulate is fully contained by a sealed OSTA, the mitigated doses would be zero. There is still a potential for release of a portion of this particulate when the tube vent and purge cart is connected to the tube plug. The tube vent and purge cart would be used to relieve the pressure from the overpack storage tube through HEPA filters, so that the potential for pressurized unfiltered relief of the overpack storage tube is reduced. If the filters are specified to operate at a particulate removal efficiency (below $10 \mu\text{m}$) of at least 99.9%, the resultant mitigated doses are reduced by a factor of 1,000. The onsite (100 m) mitigated dose from the gaseous release accident (without subsequent flammable gas explosion) is therefore reduced from 70 rem to 0.07 rem, which is well below the onsite guideline of 10 rem.

If the connection between the tube vent and purge cart and the overpack storage tube plug fails during pressure purging, a release could occur that bypasses the HEPA filters. This failure could occur due to operator error (e.g., the operator moving the cart with the flexible hose connected to the tube plug). If particulate in the overpack storage tube had settled out of the gas and was distributed on surfaces within the tube, the pressurized release of particulate from the

overpack storage tube would be described by the same bounding release fractions used during the initial release from the MCO. Applying the release fraction of 2×10^{-3} to the maximum particulate in the tube (60 g) gives a 0.12 g mass of respirable radioactive particulate released to the environment. This release will lead to a dose of 0.6 rem to the onsite (100 m) receptor and to a dose of <1 mrem to the offsite receptor. If the particulate in the overpack storage tube has not settled out of the gas before the connection between the tube plug and cart fails, the release to the operating area could be up to the total particulate (60 g). In this case, the quick-disconnect valve, flexible connection hose, cart piping from the connecting hose to the HEPA filter on the cart, and the HEPA filter are safety-significant preventive and mitigative features on the tube vent and purge cart.

An additional mitigation consideration is particulate settling. The approximate time needed for the particulate to settle can be determined using a Stokes settling equation for a tranquil gas. For the gas and particulate in the CSB scenario, the terminal settling velocity of the particulate and the time required to settle are determined. For a 1- μm -diameter particulate of density 5 g/cm³, the time to settle to the bottom of a 40-ft-tall overpack storage tube is about 23 hours. For particulate larger than 1 μm in diameter, the settling time will be less than that calculated for 1 μm .

The tube vent and purge cart will be connected to the overpack storage tube plug to reinert the tube if the pressure in the tube falls below or above a predetermined range. A pressurized release from an MCO could occur at any time. If such a release has occurred and led to an increase overpack storage tube pressure, then it is unlikely that another quick release will occur. If the tube pressure has fallen below the specified range and a release is not known to have occurred, then a release is still possible. A similar event could occur at the MCO service station when this station is used to vent and purge a high-pressure cask. A high-pressure cask is considered an off-normal situation in which the MCO seal may be breached. Accordingly, the MCO service station's connecting valve, connecting hose, associated piping to the HEPA filter, and the HEPA filter are safety significant for worker safety.

8.4.2 Flammable Gas Explosion

Without mitigation, a flammable hydrogen gas mixture can form within the MCO and/or the overpack storage tube. A stoichiometric ratio of hydrogen and oxygen from air is not expected within the MCO, as the MCO is filled with helium at the CVDF and the production of hydrogen is greatly reduced if oxygen enters the MCO. A leak could develop in the MCO and allow the helium-hydrogen mixture to escape while hydrogen continues to be produced. Air can diffuse into the MCO after the MCO has depressurized to equilibrium pressure with the tube. If a stoichiometric mixture of oxygen in air with hydrogen is conservatively used to calculate the pressure immediately after ignition, the pressure within the MCO is calculated to be about 8 atm. If a detonation occurs, it can lead to an instantaneous overpressure of about 16 atm, due to the reflected pressure pulse wave within the essentially confined MCO. The MCO might sustain additional damage from this explosion but is expected to substantially withstand this instantaneous

overpressure. If about 14 g of particulate are released from the overpack storage tube to the environment, then dose consequences may be calculated as shown in the following example.

For the onsite worker (100 m), the calculated dose from this accident is

$$\begin{aligned} \text{EDE}_{\text{onsite}} &= (14 \text{ g}) (3.41 \times 10^{-2} \text{ s/m}^3) (3.33 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g}) \\ &= 70 \text{ rem.} \end{aligned}$$

It is possible for a hydrogen gas mixture to ignite within the overpack storage tube that is not inerted rather than within the MCO. This explosion would not necessarily lead to a significant radiological release, but would lead to large mechanical forces being applied to the OSTA. This scenario could result if hydrogen slowly escapes from the MCO into the tube and ignites. Because the tube plug could be sealed and mechanically locked into place, the pressure in the tube could be as high as 2.1 atm before the ignition. With a 2.1 atm starting pressure in the overpack storage tube, the explosion could lead to a detonation pressure pulse of about 30 atm in the overpack storage tube. The tube design pressure is 7.5 atm and its working pressure is 52 atm (CSB-RM-0011). The tube plug lockdown device design pressure is 6.1 atm, and its working pressure is about 27 atm. The tube plug will lift at a pressure of 1.6 atm if the lockdown device is not applied, and also at a pressure below the failure pressure of the tube if the plug mechanically locked into place. The tube would not suffer significant structural damage that would prevent it from continuing to perform its safety-class structural functions even if a detonation caused it to lose gaseous containment.

8.5 COMPARISON TO GUIDELINES

The unmitigated gaseous release accidents and the unmitigated hydrogen explosion accidents result from the MCO being damaged. The most likely cause of this damage is a drop of the MCO. Analysis for credible MCO drops has indicated that it is not possible for the a drop to cause an MCO to lose gaseous confinement if the MCO mechanical seal is of expected quality and is properly assembled. The bounding annual frequency for either the gaseous release or hydrogen explosion accident is estimated to be $1 \times 10^{-4}/\text{year}$, which is categorized into the unlikely event category. Unlikely events are those in which the annual frequency of occurrence is between 1.0×10^{-2} and 1.0×10^{-4} . For unlikely events, the radiological onsite risk evaluation guideline is 10 rem and the offsite accident release limit is 5 rem (Sellers 1997). Both the unmitigated gaseous release accidents and the unmitigated hydrogen explosion accidents result in onsite dose consequences that exceed onsite guidelines. Neither of these accidents lead to offsite dose consequences in excess of the limits.

The gaseous release accident, without subsequent flammable gas explosion, can be prevented or at least mitigated by requiring the OSTA to act as a secondary confinement to the MCO. The overpack storage tube and tube plug must be able to confine a pressurized gas to at least 2.1 atm. If the overpack storage tube and tube plug are designed to maintain gaseous confinement at a suitable pressure above 2.1 atm, the immediate release will be prevented.

The tubes are designed to withstand a pressure in excess of 7 atm. The tube plugs are sealed and have lockdown devices that hold the plug seal in place for internal tube pressures up to at least 6.1 atm (75 lb/in² gauge). If this lockdown device is in place, the tube will be sealed and no release will result from this accident.

A gaseous release accident followed by a flammable gas explosion in the overpack storage tube is precluded if the tube has been filled with inert gas. A similar risk of gaseous release and subsequent flammable gas explosion could occur at any time until the MCO is placed in the overpack storage tube and the tube is inerted. After the accident and until the MCO handling machine places the MCO in an overpack storage tube and the tube is inerted is considered an accident recovery time period. Appropriate accident mitigation or prevention will be determined by an accident recovery team during recovery. The gaseous release accident followed by a flammable gas explosion in the overpack storage tube is prevented by maintaining an inert environment in the tube.

After a gaseous release accident in the overpack storage tube, the tube vent and purge cart would be used to relieve the pressure from the tube through HEPA filters to reduce the potential for pressurized unfiltered relief of the overpack storage tube. If the filters are specified to operate at a particulate removal efficiency (below 10 μ m) of at least 99.9%, the resultant mitigated doses are reduced by a factor of 1,000. The onsite (100 m) mitigated dose from the gaseous release accident is therefore reduced from 70 rem to 0.07 rem, which is well below the onsite guideline of 10 rem. These mitigated dose consequences would also be applicable to a scenario where the MCO depressurized during the inerting operation using the cart. A summary of the doses expected from the MCO gaseous release accident and comparison to guidelines is given in Table 8-2.

Table 8-2. Dose Calculation Summary for a Multi-Canister Overpack Gaseous Release Accident Inside an Overpack Storage Tube Without Subsequent Flammable Gas Explosion.

Receptor location (distance, direction)	Duration (hours)	Unmitigated dose ^a , rem (Sv)	Evaluation guideline ^b / release limits, rem (Sv) unlikely ^c	Safety-significant mitigated dose, rem (Sv)
Onsite (100 m east)	<1	70 (7.0 E-01)	10.0 (1.0 E-01)	0.07 (7.0 E-3) ^d
Highway 240 (9,280 m west)	<1	4.8 E-02 (4.8 E-04)	--	4.8 E-05
Hanford Site boundary (17,390 m east)	<1	2.7 E-02 (2.7 E-04)	5.0 (5.0 E-02)	Accident prevented

^aFifty-year committed effective dose equivalent.

^bEvaluation guideline for onsite (100 m) receptor only.

^cUnlikely event frequency is 10⁻² to 10⁻⁴ per year.

^dInitial accident prevented, but potential dose from release of particulate through tube vent and purge cart filters is calculated.

The flammable gas explosions can simply be prevented if the overpack storage tubes are maintained free of oxygen. The fuel in the MCO produces hydrogen and oxygen gas, but nearly all the oxygen is expected to react with the fuel and remove it from the gas (HNF-SD-SNF-TI-040). If the tube environment is maintained free of air by maintaining helium in the tube, the hydrogen cannot form a flammable gas in the MCO or in the overpack storage tube. The overpack storage tube and tube plug are designed to provide a sealed environment that will not permit significant air ingress. The tube plug provides a port that can be used to periodically pressure-purge the overpack storage tube with inert helium gas. Immediately after an MCO is placed into the overpack storage tube, the tube can be pressure purged until essentially no oxygen remains within the tube. Without a flammable atmosphere inside the MCO or overpack storage tube, there can be no flammable gas explosion or resulting radiological release. The mitigated onsite dose from the flammable gas explosion accident is therefore reduced to 0 rem. The dose consequences from the flammable gas explosion within an overpack storage tube and the applicable guidelines are summarized for comparison in Table 8-3.

Table 8-3. Dose Calculation Summary for Flammable Gas Explosion
Accident with a Multi-Canister Overpack
Inside an Overpack Storage Tube.

Receptor location (distance, direction)	Duration (hours)	Unmitigated dose ^a , rem (Sv)	Evaluation guideline ^b / release limits, rem (Sv) unlikely ^c	Safety-significant mitigated dose, rem (Sv)
Onsite (100 m east)	<1	81 (0.81)	10.0 (1.0 E-01)	Accident prevented
Highway 240 (9,280 m west)	<1	5.5 E-02 (5.5 E-04)	--	Accident prevented
Hanford Site boundary (17,390 m east)	<1	3.1 E-02 (3.1 E-04)	5.0 (5.0 E-02)	Accident prevented

^aFifty-year committed effective dose equivalent.

^bEvaluation guideline for onsite (100 m) receptor only.

^cUnlikely event frequency is 10⁻² to 10⁻⁴ per year.

8.6 SUMMARY OF SAFETY STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

Based on this analysis and other structural requirements for the tubes and tube assemblies, the safety equipment designated to prevent gas release events and flammable gas explosion in the overpack storage tubes are as follows.

- Overpack storage tubes (safety class) — Provide structural support and protection of MCOs to allow for proper passive cooling and criticality geometry control while maintaining gaseous confinement and enabling an inert gas atmosphere to be maintained.

- Overpack storage tube base assemblies (safety class) — Provide structural support of overpack storage tubes.
- Overpack storage tube plugs (safety significant) — Maintain gaseous confinement of the overpack storage tubes up to 2.1 atm pressure; contain pressure gauge to allow tube pressure to be monitored; have port that allows the overpack storage tube to be inerted, by pressure purge, with helium gas; have associated lockdown device to help maintain confinement and inert atmosphere.
- Cask servicing system connecting valve, connecting hose, associated piping, and the HEPA filter (safety significant) — Maintain gaseous and particulate confinement during cask venting operations.
- Bottom impact absorber (safety class) — Reduces acceleration and associated force on MCO that is dropped into tube so that unacceptable damage should not occur to MCO.
- Overpack plug cover (safety significant) — Protects overpack storage tube plug from damage from dropped or moving objects that could breach the gaseous confinement of the tube.
- Tube vent and purge cart connecting hose, interface piping, overpack storage tube plug quick-disconnect valve, and HEPA filter (safety significant) — Maintain gaseous confinement of radioactive particulate during purging operations.

8.6.1 Safety-Class Carbon Steel Base Slab Embeds

The carbon steel embeds for vault 1 are evaluated for the design basis earthquake based on the seismic loading from the storage tubes and the MCOs, which contain spent nuclear fuel and weigh up to 9,300 kg (20,500 lb). The embed-tube interface design accommodates the current design basis earthquake for tubes loaded with MCOs. The embeds and tube base assemblies work in concert to restrain the storage tube at the basemat elevation. Seismic analysis and the design of the embeds were performed to ACI-349, *Code Requirements for Nuclear Safety Related Concrete Structures*, standards and included the seismic interaction loads from two MCOs. Any future use of the embeds in vaults 2 and 3 must be evaluated against their original design, which was for seismic loading associated with the CSB mission.

There are no technical safety requirements applicable for the embed.

8.6.2 Overpack Storage Tube, Bellows Assembly, Tube Plugs, and Tube Base Assemblies

The overpack storage tube and tube plugs form a confinement barrier for the spent nuclear fuel contained in off-normal MCOs. The overpack storage tube and tube plug have four safety functions:

- Maintain the geometric configuration relied on for cooling and criticality geometry control
- Maintain an inert atmosphere to preclude combustion of hydrogen in the overpack storage tube
- Provide radiation shielding for operating area personnel
- Confine any particulate radionuclides released from off-normal MCOs during storage conditions.

The overpack storage tube also provides the confinement boundary between the vault and the MCO. The bellows isolate the operating area atmosphere from the vault's natural convection cooling and allow for the thermal expansion of the overpack storage tube. A 44-mm (1.7-in.) clearance between the lower bellows flange and the lower embed step helps to maintain overpack storage tube integrity during a potential MCO drop accident. The tube plug seals against the tube to prevent the egress of the overpack storage tube's inert atmosphere and the ingress of oxygen, as well as to contain potentially contaminated particulate releases from the MCO exterior surface. The tube plug also provides shielding for the operators. The bottom impact absorbers mitigate the effects of an MCO drop to keep the drop from breaching the MCO wall and/or the overpack storage tube, thus preventing the release of radionuclides into the vault atmosphere. The overpack storage tube wall provides the heat transfer surface for cooling by natural convection. The overpack storage tubes and the tube base assemblies provide structural support for the MCOs during design basis accidents, and a geometric array for cooling and criticality prevention. Tube base assemblies are provided with cooling passages to ensure that the overpack storage tube does not overheat the concrete floor of the vault basemat.

Technical safety requirements have been developed that require the following.

- All overpack storage tube plugs are in place when any MCOs are stored in the vault.

The accidents identified in the CSB hazard analysis (HNF-SD-SNF-HIE-001) that can lead to the gaseous release events in the overpack storage tubes are listed in Table 8-4 along with corresponding checklist designators; safety functions; and safety structures, systems, and components.

Table 8-4. Safety Function and Classification of Structures, Systems, and Components Involved in Recovery Actions Related to Gaseous Releases and Explosions from Overpack Storage Tubes. (2 sheets)

Checklist designator	Accident	Safety feature SSCs and TSRs	NRC ITS Class
OU-R-01 VL-J-06 OU-R-07 OU-R-09 OU-R-10	External or natural events cause air to be introduced into the overpack storage tube	<p>General safety function is prevent collapse of Canister Storage Building structures or loss of structural integrity of the facility when there is SNF in the facility</p> <p><u>Safety-class SSCs:</u></p> <ul style="list-style-type: none"> Standard and overpack storage tubes, operating deck, and vault—Provide structural integrity for all design basis natural phenomena hazard criteria when SNF is in the facility <p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> Operating building and support building—Provide structural integrity for all design basis natural phenomena hazard criteria when SNF is in the facility <p>No TSRs for recovery-related controls</p>	<p><u>ITS Category A:</u></p> <ul style="list-style-type: none"> Seismically qualified storage tubes, operating deck, and vault <p><u>ITS Category B:</u></p> <ul style="list-style-type: none"> Seismically qualified, tornado-hardened building
OA-B-07 OA-F-02	Gas release by the MCO into the tube	<p>General safety function is to contain radiological particulate</p> <p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> Overpack storage tube assemblies (storage tubes, tube plug, bellows, seal, lockdown, pressure gauge)—Contain radiological particulate for pressure up to 75 lb/in² gauge when MCO is in an overpack storage tube <p>No TSRs for recovery-related controls</p>	ITS classification is not applicable (<5 rem)
OA-J-06d	Loss of inert gas atmosphere in the overpack storage tube leading to hydrogen explosions in the overpack tubes	<p>General safety function is to prevent hydrogen detonation or deflagration from the off-normal MCO; preclude loss of inert gas and maintain inert gas atmosphere in overpack storage tube</p> <p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> Overpack storage tube assemblies (storage tubes, tube plug, seal, lockdown device, tube cover)—Preclude loss of inert gas and maintain inert gas atmosphere (to prevent oxygen ingress) in an overpack storage tube when there is an MCO in the overpack <p>No TSRs for recovery-related controls</p>	<p><u>ITS Category B:</u></p> <p>Overpack storage tube assemblies (storage tubes, tube plug, seals, lockdown device, tube cover)</p>

Table 8-4. Safety Function and Classification of Structures, Systems, and Components Involved in Recovery Actions Related to Gaseous Releases and Explosions from Overpack Storage Tubes. (2 sheets)

Checklist designator	Accident	Safety feature SSCs and TSRs	NRC ITS Class
OA-F-02	Damage to overpack storage tube plug assembly by falling, dropped, or colliding objects leading to hydrogen explosions in the overpack tubes	<p>General safety function is to prevent falling, dropped, or moving objects from impacting overpack storage tube plug assembly</p> <p><u>Safety-significant SSCs:</u></p> <ul style="list-style-type: none"> Overpack storage tube cover—Prevents objects from falling onto the tube plug and causing loss of gaseous confinement or inert gas atmosphere when there is an MCO in the overpack storage tube <p>No TSRs for recovery-related controls</p>	ITS classification is not applicable (<5 rem)

^aBuilding is safety significant consistent with waiver 1 to HNF-PRO-704, *Hazard and Accident Analysis Process*, Fluor Daniel Hanford, Incorporated, Richland, Washington.

^bThe corrosion is caused by a chemical reaction with the battery acid spilled from the purge cart battery.

ALARA = as low as reasonably achievable.

ITS = important to safety.

MCO = multi-canister overpack.

NRC = U.S. Nuclear Regulatory Commission.

SSC = structure, system, and component.

SNF = spent nuclear fuel.

TSR = technical safety requirement.

8.7 REFERENCES

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APPENDIX A
EVENT TREE ANALYSIS FOR DESIGN BASIS ACCIDENTS

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APPENDIX A

EVENT TREE ANALYSIS FOR DESIGN BASIS ACCIDENTS

A1.0 EVENT TREE FOR GASEOUS RELEASE IN THE CANISTER STORAGE BUILDING AT THE SAMPLING/WELD STATION

Figure A1-1 shows the event tree used to develop the probability of a gaseous release from a multi-canister overpack (MCO) at the Canister Storage Building (CSB) sampling/weld station.

Initiating event (Event IE) : 24 MCOs will be sampled at the CSB sampling/weld station for monitoring purposes three times each in the first year for a total of 72 MCO samples per year.

Sequence 1 Event L: The probability that the sample line will maintain leak integrity (no leaks) involves the MCO valve operator attachment to the MCO maintaining leak integrity, the flexible line inside the sample hood maintaining leak integrity, and the flexible line outside of the sample hood through the sample cart maintaining leak integrity.

The probability that the MCO valve operator attachment to the MCO will maintain leak integrity is estimated as 0.99. The value of 0.01 is the estimated operator error of 1 in a hundred that the operator will not tighten the bolts on the valve operator attachment such that a leak can occur between the attachment and the MCO.

The probability that a flexible line inside the sample hood will maintain leak integrity is 0.999984 ($1 - [4E-06/h * 4h]$). The value of 4E-06/h is a value for lightly stressed hose based on DP-1633, *Component Failure-Rate Data with Potential Applicability to a Nuclear Fuel Reprocessing Plant* (page 18). The failure rate for lightly stressed hose was used as surrogate for the failure rate for flexible hose in the sampling/weld station because no failure data was readily available for flexible hose. Also, the failure rate for lightly stressed hose is more conservative than for piping leaks. Failure rates for piping seem inappropriate for flexible hose because the flexibility of the hose also makes it more likely to fail than piping. The four hours used in the above calculation represents an estimated amount of time that the flexible hose will be used for sampling for each MCO sampling occurrence.

The probability that a flexible line outside the sample hood, from the hood through the sample cart, will maintain leak integrity is 0.999984 ($1 - [4E-06/h * 4h]$). The value of 4E-06/h is a value for lightly stressed hose based on DP-1633 (page 18). The failure rate for lightly stressed hose was used as surrogate for the failure rate for flexible hose in the sampling/weld station because no failure data was readily available for flexible hose. Also, the failure rate for lightly stressed hose is more

conservative than for piping leaks. Failure rates for piping seem inappropriate for flexible hose because the flexibility of the hose also makes it more likely to fail than piping. The four hours used in the above calculation represents an estimated amount of time that the flexible hose will be used for sampling for each MCO sampling occurrence.

If the sample line leak integrity is maintained from MCO port 2 through the sample cart, no gaseous release will occur from the sampling/weld station, thus no release consequence. The likelihood of no releases occurring is the multiplication of the probabilities maintaining leak integrity calculated above ($0.99 * 0.999984 * 0.999984 = 0.989968$ or approximately 0.99) times the number of MCOs sampled per year ($0.989968/\text{MCO sampled} * 72 \text{ MCOs sampled/year} =$ approximately 71/year. Another way to reach the same result is sum the failure probabilities and subtract them from 1 ($1 - [0.01 + 0.000016 + 0.000016] = 0.989968$ or approximately 0.99) times the number of MCOs sampled per year ($0.989968/\text{MCO sampled} * 72 \text{ MCOs sampled/year} =$ approximately 71/year).

- Sequence 2 Event L: The probability that the sample line will leak involves a leak of the MCO valve operator attachment to the MCO, a leak of the flexible line inside the sample hood, and a leak of the flexible line outside of the sample hood through the sample cart.

The probability that the MCO valve operator attachment to the MCO will leak is estimated as 0.01. The value of 0.01 is the estimated operator error of 1 in a hundred that the operator will not tighten the bolts on the valve operator attachment such that a leak can occur between the attachment and the MCO.

The probability that a flexible line inside the sample hood will leak is 0.000016 ($4\text{E-}06/\text{h} * 4\text{h}$). The value of $4\text{E-}06/\text{h}$ is a value for lightly stressed hose based on DP-1633 (page 18). The failure rate for lightly stressed hose was used as surrogate for the failure rate for flexible hose in the sampling/weld station because no failure data was readily available for flexible hose. Also, the failure rate for lightly stressed hose is more conservative than for piping leaks. Failure rates for piping seem inappropriate for flexible hose because the flexibility of the hose also makes it more likely to fail than piping. The four hours used in the above calculation represents an estimated amount of time that the flexible hose will be used for sampling for each MCO sampling occurrence.

The probability that a flexible line outside the sample hood, from the hood through the sample cart, will leak is 0.000016 ($4\text{E-}06/\text{h} * 4\text{h}$). The value of $4\text{E-}06/\text{h}$ is a value for lightly stressed hose based on DP-1633 (page 18). The failure rate for lightly stressed hose was used as surrogate for the failure rate for flexible hose in the sampling/weld station because no failure data was readily available for flexible hose. Also, the failure rate for lightly stressed hose is more conservative than for piping leaks. Failure rates for piping seem inappropriate for flexible hose because the flexibility of the hose also makes it more likely to fail than piping. The four

hours used in the above calculation represents an estimated amount of time that the flexible hose will be used for sampling for each MCO sampling occurrence.

If the sample line leaks and no high-efficiency particulate air filtration is credited, an unfiltered gaseous release will occur from the sampling/weld station. The likelihood of a release occurring is the sum of the probabilities leaks calculated above ($0.01 + 0.000016 + 0.000016 = 0.010032$ or approximately 0.01) times the number of MCOs sampled per year ($0.010032/\text{MCO sampled} * 72 \text{ MCOs sampled/year} = \text{approximately } 0.7/\text{year}$).

REFERENCE

DP-1633, 1982, *Component Failure-Rate Data with Potential Applicability to a Nuclear Fuel Reprocessing Plant*, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, South Carolina.

Figure A1-1. Event Tree Used to Develop Multi-Canister Overpack Gas Release Probability at the Canister Storage Building Sampling/Weld Station.

Number of samples from validation MCOs in the first year	Sampling lines remain intact	Seq. Freq.	Seq. #	Result
IE	L			
72 IE	1.00E-02 L	7.13E+01 7.22E-01	1 2	Safe Potential unfiltered gaseous release

Gaseous release from a MCO at sampling station CSBFGAS1.TRE 9-02-98

A2.0 EVENT TREE FOR HYDROGEN EXPLOSIONS INSIDE A MULTI-CANISTER OVERPACK AT THE CANISTER STORAGE BUILDING

The event tree maps the sequence of events that could lead to a hydrogen explosion inside the MCO. The event tree for a hydrogen explosion during cask venting is shown in Figure A2-1.

The first event on the tree is labeled "MCO SAMPLING." This item accounts for the fact that the events leading up to a hydrogen explosion start with the operation that samples the cask. It also shows the activity will occur three times for each of the 24 monitoring MCOs received at the CSB, or a total of 72 times per year.

The second event is labeled "NORMAL SAMPLE." This item evaluates the effect of inadvertently depressurizing the MCO rather than only removing enough gas for the sample. The probability of this occurring is taken to be 0.01 per MCO, as shown in Figure A2-1.

The third event is labeled "HE RECHARGE." This item evaluates the inadvertent presence of oxygen in the helium system. This could happen two ways. The first way assumes the helium lines are depressurized for maintenance, filled with air, and not purged prior to use. The estimated probability for this failure is 0.01 per year due to operator error. The second way assumes the helium supplier fills the helium supply tanks or supply truck with oxygen. Because multiple errors on the suppliers part are necessary for it to occur, it is assigned a probability of 0.0001 per year as shown on Figure A2-1.

The overall probability for the explosion inside the MCO depends on which failure occurs at the third step. If air is present in the helium lines, the overall probability is 7.2×10^{-3} per year. If oxygen is present in the helium supply, the overall probability is 7.2×10^{-5} per year. This accident may therefore be in either the "unlikely" or "extremely unlikely" category.

Figure A2-1. Event Tree Showing Consequences of a Hydrogen Explosion During Helium Recharge at the Sampling/Weld Station.

MCO is sampled	MCO is depressurized only enough to take sample	MCO is recharged with only helium	Seq. Freq.	Seq. #	Result
MCO SAMPLES	NORMAL SAMPLE	HE RECHARGE			
72 MCO SAMPLES	SAMPLE VOLUME 1.00E-02 TOTALLY VENTED	HE ONLY ADDED 1.00E-04 OXYGEN ADDED	7.13E+01	1	Safe
			7.20E-01	2	Safe
			7.20E-05	3	Onsite dose

H2 Explosion Inside MCO at Sample Station CS8FIH1.TRE 9-22-98

A3.0 EVENT TREES FOR HYDROGEN EXPLOSIONS EXTERNAL TO THE MULTI-CANISTER OVERPACK AT THE CANISTER STORAGE BUILDING

The Figure A3-1 event tree maps the sequence of events that could lead to a hydrogen explosion outside the multi-canister overpack. The event tree includes both initiators and mitigation. The diagrams for the hydrogen explosions discussed earlier are presented in this appendix.

A3.1 EVENT TREE FOR HYDROGEN EXPLOSION DURING CASK VENTING

The event tree for a hydrogen explosion during cask venting is shown in Figure A3-1. The first event on the tree is labeled "CASK VENT." This item accounts for the fact that the events leading up to a hydrogen explosion start with the operation that vents the cask. It also shows the activity will occur at least once for each multi-canister overpack received at CSB.

The second event is labeled "MCO." This item evaluates the presence of a leak from the MCO to the transportation cask which exceeds the leakage criteria. The upper branch indicates that the leakage is within the criteria. The lower branch indicates that the MCO leaks faster than the criteria. The calculations assume the leak rate is 10,000 times the leak rate criteria for a mechanically sealed MCO. According to DP-1633, *Component Failure-Rate Data with Potential Applicability to a Nuclear Fuel Reprocessing Plant*, the failure rate for O-ring seals leaking is 1×10^{-6} per hour. Multiplying this by the number of hours in a year gives about 0.01 per year per MCO. An additional failure to detect the leak must occur at the Cold Vacuum Drying Facility. Thus, the overall failure probability is 1×10^{-4} per year per MCO, as shown in Figure A3-1.

The third event is labeled "DEPRESSURIZE." This item evaluates the effect of venting duration. The upper branch indicates that the flow from the cask is normally throttled to reduce the hydrogen concentration in the exhaust. The lower branch indicates that the cask pressure is relieved suddenly so that there is an explosive concentration hydrogen and air in the exhaust. A probability of 0.01 is assigned to this failure since it is personnel related.

The fourth event is labeled "IGNITION." This item accounts for the location of the ignition source in the portable exhaust. The upper branch indicates the explosion occurs in the ductwork, leading to possible injury of personnel nearby. The lower branch indicates the explosion occurs in the high-efficiency particulate air filter, releases radioactivity to the environment. The overall probability of an explosion is 1×10^{-4} per year. This places the accident in the "unlikely" category.

A3.2 EVENT TREE FOR A HYDROGEN EXPLOSION DURING MULTI-CANISTER OVERPACK HANDLING

The event tree for a hydrogen explosion during cask venting is shown in Figure A3-2. The first event on the tree is labeled "MCO MOVEMENT." This item accounts for the fact that the events leading up to a hydrogen explosion start with relocating an MCO using the MCO handling machine (MHM). It also shows the activity will occur at least once for each multi-canister overpack received at CSB.

The second event is labeled "MHM." This item evaluates the effect of an accident which immobilizes the MHM and disables its ventilation system. An example is a power failure lasting two days. The upper branch indicates that no malfunction has occurred and the lower branch indicates that the 2 days without ventilation used in the calculations has occurred. From WHC-EP-0811, *Analysis of Power Loss Data for the 200 Area Tank Farms in Support of K Basin SAR Work*, the projected frequency for a 2 day power outage is about 0.001, as shown in Figure A3-2.

The third event is labeled "MCO." This item evaluates the presence of a leak from the MCO to the transportation cask which exceeds the leakage criteria. The upper branch indicates that the leakage is within the criteria. The lower branch indicates that the MCO leaks faster than the criteria. The calculations assume the leak rate is 10,000 times the leak rate criteria for a mechanically sealed MCO. According to DP-1633 the failure rate for O-ring seals leaking is 1×10^{-6} per hour. Multiplying this by the number of hours in a year gives about 0.01 per year per MCO, as shown in Figure A3-2.

The fourth event is labeled "IGNITION." This item accounts for the location of the ignition source in the MHM. The upper branch indicates the explosion occurs inside the MHM, leading to possible damage to the MHM. The lower branch indicates the explosion occurs in the high-efficiency particulate air filter, releases radioactivity to the environment. The overall probability of an explosion is 1×10^{-3} per year. This places the accident in the "unlikely" category.

A3.3 EVENT TREE FOR A HYDROGEN EXPLOSION DURING MULTI-CANISTER OVERPACK STORAGE

The event tree for a hydrogen explosion during MCO storage is shown in Figure A3-3. The first event on the tree is labeled "STORAGE TUBE." This item accounts for the fact that the events leading up to this hydrogen explosion start with the placement of the MCO in a storage tube. It also shows the activity will occur at least once for each MCO scheduled for gas sampling.

The second event is labeled "MCO." This item evaluates the presence of a leak from the MCO to the transportation cask which exceeds the leakage criteria. The upper branch indicates that the leakage is within the criteria. The lower branch indicates that the MCO leaks faster than the criteria. The calculations assume the leak rate is 10,000 times the leak rate criteria for a mechanically sealed MCO. According to DP-1633 the failure rate for O-ring seals leaking is

1×10^{-6} per hour. Multiplying this by the number of hours in a year gives about 0.01 per year per MCO, as shown in Figure A3-3.

Since the storage tubes may also have MCOs which have been sealed by welding, an estimate of excessive leakage was made for these also. From EGG-SSRE-8875, *Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs*, the probability of welded pipe failure is about 1×10^{-9} per foot per hour. Multiplying by the approximate number of feet of weld (20 ft) and the number of hours in a year (8,760 hours) gives a probability of 1×10^{-4} per year per MCO. Since there are about 10 times more welded MCOs handled per year (200) than mechanically sealed MCOs (24), the excessive leakage probability is 10 times lower than that of the mechanically sealed MCOs.

The third event is labeled "IGNITION." This item accounts for the presence of an ignition source in the storage tube. The upper branch indicates an ignition source does not exist while the lower branch indicates an ignition source exists. The overall probability of an explosion is 0.12 per year. This places the accident in the "anticipated" category.

A3.4 EVENT TREE FOR A HYDROGEN EXPLOSION DURING MULTI-CANISTER OVERPACK SAMPLING

The event tree for a hydrogen explosion during MCO sampling is shown in Figure A3-4. The first event on the tree is labeled "SAMPLING." This item accounts for the fact that the events leading up to a hydrogen explosion start with relocating an MCO to the sample pit. It also shows the activity will occur at least once for each multi-canister overpack scheduled for sampling.

The second event is labeled "HOSE." This item evaluates the effect of a failure of the sample hose connection that leads to a release of activity from the MCO into the sample hood. The upper branch indicates that no malfunction has occurred and the lower branch indicates that the connection failure has occurred. To approximate the probability of this event, the leakage probability for check valves was used. From DP-1633 the probability for a check valve failing to close is 0.001 per operation. Additional considerations are the failure of lightly stressed hose (4×10^{-6} per hour) and the external leakage of a valve (3×10^{-8} per hour).

The third event is labeled "GAS." This item evaluates whether the leak rate from the failed connection is enough to produce a flammable mixture in the sample hood. The upper branch indicates that the hydrogen concentration is below the lower flammable limit. The lower branch indicates that the hydrogen concentration is above the lower flammable mixture.

The fourth event is labeled "IGNITION." This item accounts for the location of the ignition source in the sample hood. The upper branch indicates the explosion occurs inside the hood, leading to possible injury to personnel. The lower branch indicates the explosion occurs in the high-efficiency particulate air filter, releases radioactivity to the environment. The overall probability of an explosion is 0.02 per year. This places the accident in the "anticipated" category.

A3.5 REFERENCES

DP-1633, 1982, *Component Failure-Rate Data with Potential Applicability to a Nuclear Fuel Reprocessing Plant*, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, South Carolina.

EGG-SSRE-8875, 1990, *Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs*, EG&G Idaho, Idaho National Engineering Laboratory, Idaho Falls, Idaho.

WHC-EP-0811, 1994, *Analysis of Power Loss Data for the 200 Area Tank Farms in Support of K Basin SAR Work*, Westinghouse Hanford Company, Richland, Washington.

Figure A3-1. Event Tree Showing Consequences of a Hydrogen Explosion During Cask Venting.

Figure A3-2. Event Tree Showing Consequences of a Hydrogen Explosion During Multi-Canister Overpack Handling.

Figure A3-3. Event Tree Showing Consequences of a Hydrogen Explosion During Multi-Canister Overpack Storage.

Figure A3-4. Event Tree Showing Consequences of a Hydrogen Explosion During Multi-Canister Overpack Sampling.

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APPENDIX B

**ISO-PC OUTPUT TO ESTIMATE HIGH-EFFICIENCY
PARTICULATE AIR FILTER LOADING**

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APPENDIX B**ISO-PC OUTPUT TO ESTIMATE HIGH-EFFICIENCY
PARTICULATE AIR FILTER LOADING**

ISO-PC Version 1.98 (WHC-SD-WM-UM-030) computes dose rates from X-rays, gamma rays, and bremsstrahlung radiation for simple arrangements of source and shields. The user selects the geometry and supplies values for dimensions and activities of the various isotopes present in the source region.

The ISO-PC program is the result of extensive revisions to the original ISOSHLD-II program (BNWL-236). Validation was carried out for the bremsstrahlung calculations (BNWL-236-SUP1). Other portions of the calculations have been verified (WHC-SD-SQA-CSWD-303).

In the present application, the geometry was the rectangular slab with slab shields. The source is 61 cm tall, 61 cm wide, and 30 cm thick (24 in. tall, 24 in. wide, and 12 in. thick). The dose point is to the side, so the apparent thickness is 61 cm (24 in.). A thin layer (1 mm [0.04 in.]) of iron represents the filter housing. The dose point is 5.08 cm (2 in.) from the housing, which is 2.54 cm (1 in.) from the filter.

A high-efficiency particulate air (HEPA) filters are made of fiberglass and wood, and weigh about 18 kg (40 lb). Therefore, the HEPA filter array was modeled as a homogenized region with a density of 0.16 g/cm³. HEPA filters are made of fiberglass, so the source region was modeled as Hanford sand with this density to represent the filter media.

The isotopes with significant gamma emissions were used in the source. Amounts found in the safety basis list were used (HNF-SD-SNF-TI-059). Since the amounts are for one metric ton of fuel, a source scale factor of 1.5×10^{-6} was used in the program input to reduce the source to 1.5 g of fuel. Program output is listed below. Note that the input file (HEPA) is appended to the output.

Run started at 10:28:29 02/20/98

ISO-PC Version 1.98 August 1994
 originally ISOSHL-D-II; RIBD was removed

Please send questions or comments to:
 Paul D. Rittmann, PhD CHP 509-376-8715
 Westinghouse Hanford Company H6-30
 PO Box 1970 Richland, WA 99352

Title Line from Library File (ISO-PC.LIB):
 Attenuation & Buildup for 30 Groups; Photon & Beta Production 2/14/96 PDR

Run Title: CSB Portable HEPA Filter with 1.5 g SNF Fuel (Safety Source)

2" to the side

Table of Source Activity:

Scale Factor = 1.500E-06

Isotope Name	Initial Values	Final Curies
CO- 60	2.09E+00	3.135E-06
SR- 90	6.93E+03	1.040E-02
Y - 90	6.93E+03	1.040E-02
CD-113M	2.78E+00	4.170E-06
CS-134	6.47E+00	9.705E-06
CS-137	9.66E+03	1.449E-02
BA-137M	9.14E+03	1.371E-02
PM-147	1.09E+02	1.635E-04
SM-151	1.02E+02	1.530E-04
EU-154	1.13E+02	1.695E-04
EU-155	1.06E+01	1.590E-05

2" to the side

Shield Composition, g/cc

	Shield 1	Shield 2	Shield 3	Shield 4
AIR	0.000E+00	1.200E-03	0.000E+00	1.290E-03
HAN SOIL	1.600E-01	0.000E+00	0.000E+00	0.000E+00
IRON	0.000E+00	0.000E+00	7.860E+00	0.000E+00

SNF-3328 REV 1

Totals: 1.600E-01 1.200E-03 7.860E+00 1.290E-03

E, MeV Linear Attenuation, per cm (last region is air)

0.015	1.952E+00	1.904E-03	4.622E+02	2.046E-03
0.025	4.535E-01	5.710E-04	1.096E+02	6.138E-04
0.035	1.817E-01	3.408E-04	4.186E+01	3.664E-04
0.045	9.853E-02	2.639E-04	2.035E+01	2.837E-04
0.055	6.493E-02	2.317E-04	1.178E+01	2.491E-04
0.065	4.872E-02	2.153E-04	7.715E+00	2.314E-04
0.075	3.981E-02	2.032E-04	5.451E+00	2.184E-04
0.085	3.442E-02	1.944E-04	4.096E+00	2.090E-04
0.095	3.091E-02	1.878E-04	3.237E+00	2.019E-04
0.150	2.288E-02	1.636E-04	1.541E+00	1.758E-04
0.250	1.835E-02	1.374E-04	9.660E-01	1.477E-04
0.350	1.603E-02	1.207E-04	7.923E-01	1.298E-04
0.475	1.408E-02	1.066E-04	6.768E-01	1.146E-04
0.650	1.227E-02	9.313E-05	5.813E-01	1.001E-04
0.825	1.099E-02	8.357E-05	5.172E-01	8.984E-05
1.000	1.002E-02	7.622E-05	4.700E-01	8.194E-05
1.225	9.058E-03	6.882E-05	4.239E-01	7.398E-05
1.475	8.246E-03	6.250E-05	3.860E-01	6.718E-05
1.700	7.669E-03	5.813E-05	3.602E-01	6.249E-05
1.900	7.243E-03	5.478E-05	3.420E-01	5.889E-05
2.100	6.882E-03	5.176E-05	3.268E-01	5.564E-05
2.300	6.573E-03	4.896E-05	3.141E-01	5.263E-05
2.500	6.304E-03	4.654E-05	3.033E-01	5.003E-05
2.700	6.072E-03	4.445E-05	2.942E-01	4.778E-05
3.000	5.776E-03	4.196E-05	2.830E-01	4.511E-05
3.600	5.323E-03	3.868E-05	2.669E-01	4.158E-05
4.500	4.842E-03	3.485E-05	2.521E-01	3.746E-05
5.500	4.474E-03	3.145E-05	2.428E-01	3.381E-05
6.600	4.198E-03	2.894E-05	2.371E-01	3.111E-05
8.600	3.898E-03	2.578E-05	2.325E-01	2.771E-05

2" to the side

Source Shields Distance to Detector, X = 6.872E+01 cm
 Slab Slab Source Volume = 1.116E+05 cc
 Source Mass = 1.786E+04 grams
 Thickness = 6.100E+01 cm Height = 6.100E+01 cm Width = 3.000E+01 cm
 Integration Specs: NTHETA = 15 NPSI = 27 DELR = 3.050E+00 cm
 Total Intervals: 8.100E+03 (photon source is the 1st region)
 Shield Thickness: 6.100E+01, 2.540E+00, 1.000E-01, 5.080E+00 cm
 Distances from Dose Point to the Outside of
 (1) Source Region: 7.720E+00 cm (2) Next Layer: 5.180E+00 cm
 Dose Buildup Data for Shield 2 with Effective Atomic Number 7.26
 Source Scale Factor was 1.500E-06
 Fluence-to-Dose Conversion: Photons in Air

Average E, MeV	Source Total photons/sec	Fluence to Dose Factor	Energy Fluence MeV/sq.cm/sec	Dose Rate R/hr
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0.015	1.798E+07	8.183E-05	4.919E-19	4.025E-23
0.025	9.529E+06	1.656E-05	7.181E-04	1.189E-08
0.035	4.263E+07	6.084E-06	3.885E+00	2.364E-05
0.045	5.573E+06	3.203E-06	6.422E+00	2.057E-05
0.055	2.787E+06	2.216E-06	8.751E+00	1.939E-05
0.065	2.326E+06	1.827E-06	1.106E+01	2.022E-05
0.075	2.067E+06	1.664E-06	1.246E+01	2.074E-05
0.085	2.023E+06	1.603E-06	1.476E+01	2.367E-05
0.095	1.637E+06	1.592E-06	1.416E+01	2.255E-05
0.150	1.074E+07	1.728E-06	1.517E+02	2.621E-04
0.250	2.837E+06	1.935E-06	6.608E+01	1.279E-04
0.350	1.148E+06	2.019E-06	3.637E+01	7.344E-05
0.475	9.253E+05	2.043E-06	3.788E+01	7.739E-05
0.650	4.595E+08	2.029E-06	2.416E+04	4.903E-02
0.825	1.401E+06	1.983E-06	8.924E+01	1.770E-04
1.000	1.899E+06	1.923E-06	1.422E+02	2.734E-04
1.225	2.632E+06	1.850E-06	2.359E+02	4.364E-04
1.475	2.525E+05	1.775E-06	2.685E+01	4.766E-05
1.700	1.761E+04	1.712E-06	2.135E+00	3.655E-06
1.900	9.848E+02	1.660E-06	1.325E-01	2.199E-07
2.100	6.196E+02	1.613E-06	9.159E-02	1.477E-07
2.300	1.181E+00	1.592E-06	1.903E-04	3.030E-10

Totals:	5.679E+08 photons/sec		2.502E+04	5.066E-02 R/hr
				= 3.631E-09 amp/kg

Closing: This is the end of the portable exhauster HEPA Case !!

Finish run at 10:28:52 02/20/98

Input File (HEPA.) is shown below:

```

0      2 CSB Portable HEPA Filter with 1.5 g SNF Fuel (Safety Source)
2" to the side
&Input IGeom= 10, SLTH= 30, Y= 61, T= 61,2.54,0.1, X= 68.72,
NShld= 3, JBuf= 2, NTheta= 15, NPsi= 27, DelR= 3.0,
SFact= 1.5E-6, Weight(472)= 2.09,
Weight(82)= 6930,0,6930, Weight(206)= 2.78,
Weight(319)= 6.47, Weight(335)= 9660, 9140,
Weight(388)= 109, Weight(403)= 102,
Weight(415)= 113, Weight(418)= 10.6 &
HEPA 21 0.16
air 3 0.0012
1 duct 9 7.86
This is the end of the portable exhauster HEPA Case !!
&Input Next= 6 &

```

Note: There is a 1 inch gap between the filter and the housing.
The source activities are for one metric ton uranium (1E6 gU).

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APPENDIX C

**KEY INPUT PARAMETERS FOR THERMAL RUNAWAY FUEL REACTIONS
INSIDE A MULTI-CANISTER OVERPACK**

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APPENDIX C

KEY INPUT PARAMETERS FOR THERMAL RUNAWAY FUEL REACTIONS INSIDE A MULTI-CANISTER OVERPACK

Key input parameters used in the analysis for the bounding multi-canister overpack (MCO) with Mark IV fuel under off-normal events at the Canister Storage Building (CSB) are shown in Table C-1. Notes are provided following the table. Most parameters are for one scrap basket and four fuel baskets, but some of the key data, like water content in the uranium hydrate, is for two scrap baskets and three fuel baskets in order to provide bounding MCO conditions.

Table C-1. Key Input Parameters for CSB Thermal Runaway Analysis. (2 sheets)

Parameter	Value	Reference
HEAT GENERATION PARAMETERS: power, reaction area, reaction rate		
Bounding decay power (776 W for five fuel baskets)	740.8 W per MCO	HNF-SD-SNF-TI-015 Note 1
Scrap fuel reaction surface area	4.5 m ²	HNF-SD-SNF-TI-015
Fuel reaction area	3.16 m ²	HNF-SD-SNF-TI-015
Reaction rate multiplier	10	HNF-SD-SNF-TI-015
Rate multiplier for uranium hydride (bounding hydride mass for MCO with 2 scrap baskets)	12 - fuel basket 12 - scrap basket (5.13 kg per MCO)	HNF-SD-SNF-TI-015 Note 2
RADIATION HEAT TRANSFER PARAMETERS: emissivity, view factors		
Scrap fuel emissivity	0.7	HNF-SD-SNF-TI-015
Cladding emissivity	0.43	HNF-SD-SNF-TI-015 Note 3
Inner shield plug emissivity	0.3	HNF-SD-SNF-TI-015
MCO wall emissivity	0.3	HNF-SD-SNF-TI-015
Cask, MCO bottom, and outer shield plug emissivity	0.25	FAI/98-40 Note 4
View factors and gap distances between fuel rods and MCO wall	8 x 8 matrix	FAI/98-40 Note 5
CONDUCTION HEAT TRANSFER PARAMETERS: mass, conductivity, specific heat, temperature		
Effective fuel-cladding mass density	18,573.3 kg/m ³	Note 6

Table C-1. Key Input Parameters for CSB Thermal Runaway Analysis. (2 sheets)

Parameter	Value	Reference
Uranium (scrap) mass density at 100 °C	19,000 kg/m ³	Holden 1958 Note 7
Stainless steel mass density at 100 °C	8,000 kg/m ³	TID 26666 Note 8
Maximum fuel mass load (Mark IV fuel)	980 kg - scrap basket 1,268 kg - fuel basket 6,052 kg per MCO	HNF-SD-SNF-TI-015
Effective fuel/clad thermal conductivity	24.2 W/m/K	Note 9
Stainless steel thermal conductivity	16.0 W/m/K	TID 26666
Effective fuel-cladding and uranium specific heat	122.67 J/kg/K	Note 10
Stainless steel specific heat	500.0 J/kg/K	TID 26666
Free residual water in cracks after CVD, arriving at CSB	0.2 kg per MCO	HNF-SD-SNF-TI-015
Water in uranium hydrates, $\text{UO}_3 \cdot 2\text{H}_2\text{O}$	1.19 kg per MCO with 2 SBs	HNF-SD-SNF-TI-015 Note 11
Water in aluminum hydroxide, and aluminum+iron hydrates in sludge	3.32 kg per MCO with 2 SBs	HNF-SD-SNF-TI-015
Bounding MCO wall temperature	132 °C	CSB-HV-0014
CONVECTIVE HEAT AND MASS TRANSFER PARAMETERS: gas volume, flow area, flow rate		
Scrap basket gas volume	0.153 m ³	Note 12
Upper fuel (2 fuel baskets) volume	0.186 m ³	Note 13
Lower fuel (2 fuel baskets) volume	0.199 m ³	Note 14
Fine scrap porosity	0.40	Note 15
Course scrap porosity	0.723	Note 16
Flow area in scrap basket bottom	0.013 m ²	Note 17

CSB = Canister Storage Building.

CVD = cold vacuum drying.

MCO = multi-canister overpack.

SB = scrap basket.

- Note 1 Bounding decay heat rate — The bounding decay power (i.e., decay heat rate) is given as 776 W per MCO with five Mark IV fuel baskets (155.2 W per fuel basket or 620.8 W for four fuel baskets), so the specific heat rate is 0.1224 W/kgU for Mark IV fuel (HNF-SD-SNF-TI-015). The scrap basket for Mark IV fuel has a maximum fuel loading of 980 kg (HNF-SD-SNF-TI-015), so the scrap basket has a maximum decay power of about 120 W ($980 \text{ kgU} \times 0.1224 \text{ W/kgU}$). Hence, the bounding decay power (i.e., decay heat rate) is 740.8 W per MCO ($620.8 \text{ W} + 120 \text{ W}$) with four Mark IV fuel baskets and one Mark IV scrap basket.
- Note 2 Rate multiplier for uranium hydride (UH_3) — Oxygen (and water) reacts faster with uranium hydride than with just uranium metal. The current hydride model (HNF-2256) calculates the enhanced reaction rate by increasing the effective surface area of reaction through the use of a rate multiplier. In the current hydride model, the hydrides in the MCO are strongly coupled thermally to the uranium fuel. Hence, any increase in hydride temperature is dissipated in the larger uranium fuel mass, resulting in a temperature increase for the entire fuel element. This analysis uses hydride rate multipliers that are shown in HNF-SD-SNF-TI-015, *Spent Nuclear Fuel Project Technical Databook*. The bounding mass loading of UH_3 in the MCO is 5.13 kg (1.97 kg in three fuel baskets, 3.16 kg in two scrap baskets) (HNF-SD-SNF-TI-015). The computer simulations used a constant rate multiplier of 12 in the simulations for all time, which means that the hydride mass consumption was turned off in the simulations in order to be conservative and not count on a depleting hydride mass for safety.
- Note 3 Cladding emissivity — Cladding emissivity is used for the combined fuel-cladding composite heat element in the model because the cladding covers the fuel element on the outside, keeping the uranium fuel hidden. The emissivity of Zircaloy-2 ranges from 0.43 at high temperatures or thin oxide coating to 0.7 (HNF-SD-SNF-TI-015) at normal temperatures and thicker zirconium oxide layers. The more conservative lower value of 0.43 was chosen, which will cause less heat to radiate from the fuel-cladding heat elements to the wall.
- Note 4 Cask, MCO bottom, and outer shield plug emissivity — The emissivity of the cask, MCO bottom plate, and the outer shield plug was decreased to 0.25 from 0.30 in HNF-SD-SNF-TI-015 in order to conservatively reduce the heat removal rate from the MCO (HNF-2256) and cask.
- Note 5 View factors and gap distances between fuel rods and MCO wall — The view factors and gap distances between the fuel rods in the fuel basket and the MCO wall, which are used in the radiative heat transfer model and convection heat transfer model for an MCO fuel basket, are documented in the HANSF code document (FAI/98-40). However, the view factors used in this analysis differ slightly from those in the code document. The view factors for this analysis, and for the two-scrap basket report (HNF-2256), are described in detail in Appendix D of HNF-SD-SNF-CN-023, *Thermal Analysis of Cold Vacuum Drying of Spent Nuclear Fuel*.

Note 6

Effective fuel-cladding mass density — Since the cladding volume is merged with the fuel volume in the HANSF code (FAI/98-40), an effective mass density is needed for the combined fuel and cladding. To simplify the derivation, the inner fuel element and cladding are assumed to have the same effective mass density as the outer fuel element and its cladding. The total volume for the fuel elements and cladding in the HANSF code is 0.31752 m^3 (FAI/98-40). Since the maximum fuel mass for 216 Mark IV elements (four fuel baskets) is $5,072 \text{ kg}$ (23.48 kg per element [HNF-SD-SNF-TI-015]), the volume of the fuel is about 0.26695 m^3 , which is calculated by dividing the volume by the fuel density, $19,000 \text{ kg/m}^3$ at 100°C (Holden 1958). The cladding volume is found by subtracting the fuel volume from the total volume:

$$V_{\text{cladding}} = V_{\text{total}} - V_{\text{fuel}} = 0.31752 \text{ m}^3 - 0.26695 \text{ m}^3 = 0.05057 \text{ m}^3 .$$

Multiplying the density of the Zircaloy-2 cladding, $6,541 \text{ kg/m}^3$ (UNI-M-61), by the volume of cladding gives a cladding mass of 330.8 kg :

$$M_{\text{cladding}} = 6,541 \text{ kg/m}^3 \times 0.05057 \text{ m}^3 = 330.8 \text{ kg} .$$

For thermal calculations, it is essential that the effective mass (and density) and specific heat product be conserved and, therefore, equal to the sum of the fuel and cladding parts:

$$(M \times C_p)_{\text{eff}} = M_{\text{fuel}} \times C_{p\text{-fuel}} + M_{\text{cladding}} \times C_{p\text{-cladding}}$$

where $C_{p\text{-fuel}} = 122.67 \text{ J/kg/K}$ (HNF-SD-SNF-TI-015) and $C_{p\text{-cladding}} = 306.1 \text{ J/kg/K}$ (WCAP-3269-41) .

For convenience, the effective specific heat is set equal to the specific heat of uranium and the effective mass calculated, which can be done since it's the product that must be conserved. Hence, the equation above becomes the following after dividing by the uranium specific heat:

$$\begin{aligned} M_{\text{eff}} &= M_{\text{fuel}} + M_{\text{cladding}} \times C_{p\text{-cladding}}/C_{p\text{-fuel}} \\ &= 5,072 \text{ kg} + 330.8 \text{ kg} \times (306.1 \text{ J/kg/K} \div 122.67 \text{ J/kg/K}) \\ &= 5,897.4 \text{ kg} . \end{aligned}$$

Since the Zircaloy-2 cladding has a higher heat capacity than uranium, the effective mass (in regards to mass times heat capacity product) is larger than just the sum of the masses. Using the calculated effective combined mass of the fuel and cladding above, the effective density of the fuel-cladding composite is simply the effective mass divided by the total volume:

$$\rho_{\text{eff}} = M_{\text{eff}}/V_{\text{total}}$$

$$= 5,897.4 \text{ kg}/0.31752 \text{ m}^3$$

$$= 18,573.3 \text{ kg}/\text{m}^3$$

The temperature dependence of densities, specific heats, and conductivities is ignored in the analysis because the HANSF code does not have the capability to handle temperature-dependent material properties (FAI/98-40). In order to be consistent, the material parameter values were chosen at around 100 °C and rounded off.

- Note 7 Uranium mass density — The mass density of uranium is about 19,000 kg/m³ at 100 °C. Since the HANSF code (FAI/98-40) does not include temperature-dependent material parameters, approximate values are used. The standard reference temperature of 100 °C was chosen because it's higher than normal operating temperatures but lower than most temperatures during off-normal conditions.
- Note 8 Stainless steel mass density — The mass density of 304L stainless steel is about 8,000 kg/m³ at 100 °C (TID 26666). See the discussion above in Note 10 about temperature-dependent material properties.
- Note 9 Effective fuel-cladding thermal conductivity — Since the fuel elements and cladding are combined in the model, an effective thermal conductivity is needed to represent the combined materials. Although the cladding has a lower conductivity, the conductivity of both metals is high, so the calculation of an effective thermal conductivity is not important to the calculational results.

The effective thermal conductivity, K_{eff} , was estimated using the following equation, which is valid for conductors connected in series such as the fuel and cladding in the radial direction:

$$x_{\text{total}}/K_{\text{eff}} = x_{\text{fuel}}/K_{\text{fuel}} + x_{\text{cladding}}/K_{\text{cladding}}$$

where

K_{fuel} = thermal conductivity of spent fuel (26.9 W/m/K [Kaufman 1962])

K_{cladding} = thermal conductivity of Zircaloy-2 cladding (13.4 W/m/K [WCAP-3269-41])

x_{total} = total radial thickness of fuel element and cladding ($x_{\text{fuel}} + x_{\text{cladding}}$).

Since the cladding mass is about 7% of the spent fuel mass (HNF-SD-SNF-TI-015) and the cladding density is about one-third of the fuel density, the cladding was estimated to have about 20% ($\sim 7\% \times 3$) of the combined fuel-cladding volume for both inner and outer fuel elements on the average. The thickness is proportional to the volume, therefore the cladding thickness is

estimated to be $0.2 \times x_{\text{fuel}}$, making the total thickness $1.2 \times x_{\text{fuel}}$. Substituting these values into the equation above, the value of K_{eff} is derived to be 24.2 W/m/K, which is close to fuel conductivity value.

- Note 10 Effective fuel-cladding (and uranium) specific heat — As discussed in Note 9, which derived the effective mass density, the effective specific heat for the combined fuel and cladding elements was chosen to be equal to the uranium specific heat, 122.67 J/kg/K at 100 °C (Kaufman 1962). This choice was in conjunction with the effective mass density calculation since it is the product of mass density and specific heat that must be conserved (i.e., the specific heat of the cladding is included in the effective mass density [see Note 9]).
- Note 11 The water in hydrates was increased to 1.16 kg for this report in order to provide extra margin over the hydrate water reported elsewhere (e.g., 0.65 kg [HNF-SD-SNF-TI-015]). However, for the "normal" suite of 13 runs, case 0, which simulates a complete drying cycle with tests, the hydrate water was reduced to 0.72 kg (HNF-1527) because the decomposing hydrates can affect the rebound pressure tests after vacuum drying.
- Note 12 Scrap basket volume — Based on the latest design drawings (HNF-SD-SNF-DR-003), the scrap basket has a free volume of 0.153 m³ when it contains 980 kg of uranium metal and no cladding. This volume includes the 0.0533-m (2.1-in) gap between the scrap basket and the bottom of the MCO assembly (below the shield plug) and 0.0159 m³ void space (manifold) in the MCO assembly (HNF-2833) that is always open to the MCO on top. The scrap basket volume excludes the volume of the stainless steel parts, support post inner volumes, and insert inner volume. The total length of the inner MCO is 3.6 m (141.85 in.) which includes a 0.0533-m (2.1-in.) gap above the scrap basket and a 0.0381-m (1.5-in) gap between the bottom fuel basket and the top of MCO bottom plate. The inner radius of the MCO is 0.2921 m (11.5 in.).
- Note 13 Upper fuel volume (two fuel baskets) — The two upper fuel baskets are combined into one control volume in the HANSF model (FAI/98-40). The free volume for the two fuel baskets, excluding the stainless steel volume and inner volume of support posts and insert, is 0.186 m³ based on the design drawings (HNF-SD-SNF-DR-003).
- Note 14 Lower fuel volume (two fuel baskets) — The bottom two fuel baskets have a combined free volume of 0.199 m³. This volume includes the 0.0381-m (1.5-in) gap below the bottom fuel basket and above the MCO bottom plate with a volume of 0.013 m³ and excludes the stainless steel volume and inner volume of support posts and insert.
- Note 15 Fine scrap porosity — The porosity of the fine scrap fuel (0.25 in. to 1 in. maximum dimension) in the scrap basket is the void or gas space fraction (void volume divided by total volume) in the total scrap volume when the scrap is completely dry. The porosity of porous media such as a course sand is about 0.35

to 0.45. The porosity of fine scrap was calculated to be in the same range (HNF-SD-SNF-CN-017). A fine scrap porosity of 0.40 was chosen for this analysis.

Note 16 Course scrap porosity — The largest dimension of the course scrap will not be less than 1 in. or greater than 3 in. The total open volume of an empty scrap basket is 0.16762 m^3 (total inner volume minus the insert and copper fin volumes). The fine scrap volume is 0.01592 m^3 , and the course scrap volume is 0.1517 m^3 . The total solid scrap volume is calculated by dividing the total bounding scrap mass, 980 kg, by the fuel mass density, $19,000 \text{ kg/m}^3$, resulting in a total solid volume of 0.05158 m^3 . The solid (fuel) volume in the fine portion is 0.6 (1-porosity) times the total fine scrap volume, 0.01592 m^3 , resulting in 0.009552 m^3 . Hence, the coarse scrap solid volume is 0.05158 m^3 minus the fine scrap solid volume, 0.009552 m^3 , for a value of 0.042028 m^3 . Dividing the coarse scrap solid volume by the total coarse scrap volume gives the solid fraction of $0.042028 \text{ m}^3 \div 0.1517 \text{ m}^3 = 0.27707$ for the coarse portion. Hence, the porosity of the coarse scrap is just $1.0 - 0.27707$ for a coarse scrap porosity value of 0.72293.

Note 17 Flow area in scrap basket bottom — The flow area at the bottom of the scrap basket is the only flow area available for the scrap and the total gas release out of the top of the MCO during vacuum drying. Since copper shims have been added between the outer scrap basket and MCO wall, the upward flow has nowhere to go except through the bottom of the scrap basket. The scrap basket bottom has 108 open 0.5-in. diameter holes (HNF-SD-SNF-DR-003) in it. Hence, the total flow area is calculated as follows:

$$\begin{aligned} A_{SB} &= 108 \times 3.14159 \times (0.5 \times 0.0254/2)^2 \text{ m}^2 \\ &= 108 \times 1.2668 \times 10^{-4} \text{ m}^2 \\ &= 0.0137 \text{ m}^2 \end{aligned}$$

which was truncated to 0.013 m^2 in order to constrict the gas flow through the scrap basket a little more to account for the wire screen covering part of the holes.

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APPENDIX D
PEER REVIEW CHECKLISTS

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SNF-3328 REV 1

CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-3328, Rev. 1, *Canister Storage Building Design Basis Accident Analysis Documentation*, Chapter 1.0, "Introduction"

Scope of Review: Entire chapter

Author: B. S. Lew

Yes No NA

☐	☐	☐	*	Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
☐	☐	☐		Problem completely defined.
☐	☐	☐		Accident scenarios developed in a clear and logical manner.
☐	☐	☐		Necessary assumptions explicitly stated and supported.
☐	☐	☐		Computer codes and data files documented.
☐	☐	☐		Data used in calculations explicitly stated in document.
☐	☐	☐		Data checked for consistency with original source information as applicable.
☐	☐	☐		Mathematical derivations checked including dimensional consistency of results.
☐	☐	☐		Models appropriate and used within range of validity or use outside range of established validity justified.
☐	☐	☐		Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.
☐	☐	☐		Software input correct and consistent with document reviewed.
☐	☐	☐		Software output consistent with input and with results reported in document reviewed.
☐	☐	☐		Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.
☐	☐	☐		Safety margins consistent with good engineering practices.
☐	☐	☐		Conclusions consistent with analytical results and applicable limits.
☐	☐	☐		Results and conclusions address all points required in the problem statement.
☐	☐	☐		Format consistent with appropriate NRC Regulatory Guide or other standards
☐	☐	☐	*	Review calculations, comments, and/or notes are attached.

☒ ☐ ☐ Document approved.

JAY LAVENDER
 Reviewer (Printed Name and Signature)

9/8/99
 Date

* Any calculations, comments, or notes generated as part of this review should be signed, dated and attached to this checklist. Such material should be labeled and recorded in such a manner as to be intelligible to a technically qualified third party.

Chapter supports August submittal of FSAR

CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-3328, Rev. 1, Canister Storage Building Design Basis Accident Analysis Documentation, Chapter 2.0, "Rearrangement of Multi-canister Overpack Internals"

Scope of Review: Entire chapter

Author: J. C. Lavender

Yes No NA

☒ ☐ ☐ *

Rev 1 addressed DOE ACRs made to CSB PSAR, 8/91. This peer review is limited to these revisions. This

Previous reviews complete and cover analysis, up to scope of this review, Chapter with no gaps. will be significant re-written due to

☒ ☐ ☐

Problem completely defined.

☒ ☐ ☐

Accident scenarios developed in a clear and logical manner.

☒ ☐ ☐

Necessary assumptions explicitly stated and supported.

☒ ☐ ☐ *new analyses of*

Computer codes and data files documented.

☒ ☐ ☐ *assumption on*

Data used in calculations explicitly stated in document.

☒ ☐ ☐ *depth of shears by*

Data checked for consistency with original source information as applicable.

☒ ☐ ☐ *MITT*

Mathematical derivations checked including dimensional consistency of results.

☒ ☐ ☐ *see open docs*

Models appropriate and used within range of validity or use outside range of established validity justified.

☒ ☐ ☐ *PSAR*

Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.

☐ ☐ ☒

Software input correct and consistent with document reviewed.

☐ ☐ ☒

Software output consistent with input and with results reported in document reviewed.

☒ ☐ ☐

Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.

☒ ☐ ☐

Safety margins consistent with good engineering practices.

☒ ☐ ☐

Conclusions consistent with analytical results and applicable limits.

☒ ☐ ☐

Results and conclusions address all points required in the problem statement.

☒ ☐ ☐

Format consistent with appropriate NRC Regulatory Guide or other standards

☐ ☐ ☒ *

Review calculations, comments, and/or notes are attached.

☒ ☐ ☐ ☐

Document approved.

Reviewer (Printed Name and Signature)

Date

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CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-3328, Rev. 1, *Canister Storage Building Design Basis Accident Analysis Documentation*, Chapter 3.0, "Calculations for Gaseous Release from the Multi-canister Overpack"

Scope of Review: Entire chapter

Author: B. S. Lew

Yes No NA

☒ ☐ ☐ *	Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
☒ ☐ ☐	Problem completely defined.
☒ ☐ ☐	Accident scenarios developed in a clear and logical manner.
☒ ☐ ☐	Necessary assumptions explicitly stated and supported.
☐ ☐ ☒	Computer codes and data files documented.
☒ ☐ ☐	Data used in calculations explicitly stated in document.
☒ ☐ ☐	Data checked for consistency with original source information as applicable.
☐ ☐ ☒	Mathematical derivations checked including dimensional consistency of results.
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☒ ☐ ☐	Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.
☒ ☐ ☐	Safety margins consistent with good engineering practices.
☒ ☐ ☐	Conclusions consistent with analytical results and applicable limits.
☒ ☐ ☐	Results and conclusions address all points required in the problem statement.
☒ ☐ ☐	Format consistent with appropriate NRC Regulatory Guide or other standards
☐ ☐ ☒ *	Review calculations, comments, and/or notes are attached.
☒ ☐ ☐	Document approved.

Paul Rittmann
Reviewer (Printed Name and Signature)

9-9-99
Date

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CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-3328, Rev. 1, *Canister Storage Building Design Basis Accident Analysis Documentation*, Chapter 4.0, "Calculations for Multi-canister Overpack Internal Hydrogen Explosion"

Scope of Review: Entire chapter

Author: P. D. Rittmann

Yes No NA

☒ ☐ ☐ *

Per 1 reviewer DOE RCRS made to CSP EARL, 8/29/99. This peer review is limited to those revisions. This reviewer acknowledges that certain DOE RCRS remain open.
Previous reviews complete and cover analysis, up to scope of this review, with no gaps. *BSC*

☒ ☐ ☐

Problem completely defined.

☒ ☐ ☐

Accident scenarios developed in a clear and logical manner.

☒ ☐ ☐

Necessary assumptions explicitly stated and supported.

☒ ☐ ☐

Computer codes and data files documented, *per revisions as applicable*

☒ ☐ ☐

Data used in calculations explicitly stated in document, *per T7-15*

☒ ☐ ☐

Data checked for consistency with original source information as applicable.

☒ ☐ ☐

Mathematical derivations checked including dimensional consistency of results.

☒ ☐ ☐

Models appropriate and used within range of validity or use outside range of established validity justified, *per T7-15*.

☒ ☐ ☐

Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations, *per revisions as applicable*.

☒ ☐ ☐

Software input correct and consistent with document reviewed, *per revisions as applicable*

☒ ☐ ☐

Software output consistent with input and with results reported in document reviewed, *per revisions as applicable*

☒ ☐ ☐

Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references, *per T7-15*

☒ ☐ ☐

Safety margins consistent with good engineering practices.

☒ ☐ ☐

Conclusions consistent with analytical results and applicable limits.

☒ ☐ ☐

Results and conclusions address all points required in the problem statement.

☒ ☐ ☐

Format consistent with appropriate NRC Regulatory Guide or other standards

☐ ☒ *

Review calculations, comments, and/or notes are attached, *see markings*

☒ ☐ ☐

Document approved.

[Signature]
Reviewer (Printed Name and Signature)

9/8/99
Date

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CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-3328, Rev. 1, *Canister Storage Building Design Basis Accident Analysis Documentation*, Chapter 5.0, "Calculations for Multi-Canister Overpack External Hydrogen Explosion"

Scope of Review: Entire chapter

Author: P. D. Rittman

Yes No NA

☒ ☐ ☐ *

Rev 1 addressed DOE RCR made to CSB PSAL, BPP. This peer review is limited to those revisions. This reviewer recognizes that certain DOE RCRs remain open. BPP

☒ ☐ ☐

Problem completely defined.

☒ ☐ ☐

Accident scenarios developed in a clear and logical manner.

☒ ☐ ☐

Necessary assumptions explicitly stated and supported, per revisions as applicable.

☒ ☐ ☐

Computer codes and data files documented, per revisions as applicable.

☒ ☐ ☐

Data used in calculations explicitly stated in document.

☒ ☐ ☐

Data checked for consistency with original source information as applicable.

☒ ☐ ☐

Mathematical derivations checked including dimensional consistency of results.

☒ ☐ ☐

Models appropriate and used within range of validity or use outside range of established validity justified, per T1-15

☒ ☐ ☐

Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations, per revisions as applicable.

☒ ☐ ☐

Software input correct and consistent with document reviewed.

☒ ☐ ☐

Software output consistent with input and with results reported in document reviewed.

☒ ☐ ☐

Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references, per T1-15

☒ ☐ ☐

Safety margins consistent with good engineering practices.

☒ ☐ ☐

Conclusions consistent with analytical results and applicable limits.

☒ ☐ ☐

Results and conclusions address all points required in the problem statement.

☒ ☐ ☐

Format consistent with appropriate NRC Regulatory Guide or other standards, as applicable.

☒ ☐ ☐

Review calculations, comments, and/or notes are attached, see markings

☒ ☐ ☐

Document approved.

Reviewer (Printed Name and Signature)

Date

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CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-3328, Rev. 1, *Canister Storage Building Design Basis Accident Analysis Documentation*, Chapter 6.0, "Calculations for Thermal Runaway Reactions Inside the Multi-canister Overpack"

Scope of Review: Entire chapter

Author: M. G. Piepho and P. D. Rittmann

Yes No NA

☒ ☐ ☐ *

Previous reviews complete and cover analysis, up to scope of this review, with no gaps.

☒ ☐ ☐

Problem completely defined.

☒ ☐ ☐

Accident scenarios developed in a clear and logical manner.

☒ ☐ ☐

Necessary assumptions explicitly stated and supported.

☒ ☐ ☐

Computer codes and data files documented, per reviewer's as applicable

☒ ☐ ☐

Data used in calculations explicitly stated in document.

☒ ☐ ☐

Data checked for consistency with original source information as applicable, per reviewer

☒ ☐ ☐

Mathematical derivations checked including dimensional consistency of results, as applicable

☒ ☐ ☐

Models appropriate and used within range of validity or use outside range of established validity justified, per T7-15

☒ ☐ ☐

Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.

☒ ☐ ☐

Software input correct and consistent with document reviewed, per reviewer's as applicable

☒ ☐ ☐

Software output consistent with input and with results reported in document reviewed.

☒ ☐ ☐

Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references, per T7-15

☒ ☐ ☐

Safety margins consistent with good engineering practices.

☒ ☐ ☐

Conclusions consistent with analytical results and applicable limits.

☒ ☐ ☐

Results and conclusions address all points required in the problem statement.

☒ ☐ ☐

Format consistent with appropriate NRC Regulatory Guide or other standards

☐ ☐ ☒ *

Review calculations, comments, and/or notes are attached, see markups

☒ ☐ ☐

Document approved.

Reviewer (Printed Name and Signature)

Date

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SNF-3328 REV 1

CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-3328, Rev. 1, *Canister Storage Building Design Basis Accident Analysis Documentation*, Chapter 7.0, "Calculations for Violation of Design Temperature Criteria"

Scope of Review: Entire chapter

Author: B. S. Lew

Yes No NA

☐	☐	☐	*	Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
☐	☐	☐		Problem completely defined.
☐	☐	☐		Accident scenarios developed in a clear and logical manner.
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☒ ☐ ☐

Document approved.

Reviewer (Printed Name and Signature)

JAY LAVENDER

9/8/99

Date

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Chapter supports August Submittal of FSAR.

SNF-3328 REV 1

CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-3328, Rev. 1, *Canister Storage Building Design Basis Accident Analysis Documentation*, Chapter 8.0, "Calculations for Recovery Actions Related to Gaseous Releases and Explosions from Overpack Storage Tubes"

Scope of Review: Entire chapter

Author: B. S. Lew

Yes No NA

☐	☐	☐	*	Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
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☐	☐	☐		Accident scenarios developed in a clear and logical manner.
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☒ ☐ ☐

Document approved.

JAY LAVENDER
Reviewer (Printed Name and Signature)

9/8/99
Date

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Chapter supports August submittal of FAR