This is a complete revision based on new reference data and modeling improvements. In addition, changes related to RL comment resolution on the CVDF Final Safety Analysis Report have been included.
## Engineering Change Notice

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**Project Title / Work Order**

SNF-2770, Rev 3  
_Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation_

**ECN No.** 647524

**EDT No.** N/A

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Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation

M. A. Medsker*, M. R. Piepho, P. R. Rittmann
Fluor Daniel Northwest, Inc., Richland, WA 99352
U.S. Department of Energy Contract DE-AC06-96RL13200

Abstract: This document provides the detailed accident analysis to support HNF-3553, Annex B, *Spent Nuclear Fuel Project Final Safety Analysis Report*, "Cold Vacuum Drying Facility Final Safety Analysis Report (FSAR)." All assumptions, parameters and models used to provide the analysis of the design basis accidents are documented to support the conclusions in the FSAR.

*NRE Inc.

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A-6400-073 (01/97) GEF321
## Record of Revision

**Title:** Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation

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COLD VACUUM DRYING FACILITY DESIGN BASIS
ACCIDENT ANALYSIS DOCUMENTATION

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Revision 3

October 1999
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<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARF</td>
<td>airborne release fraction</td>
</tr>
<tr>
<td>CSB</td>
<td>Canister Storage Building</td>
</tr>
<tr>
<td>CVDF</td>
<td>Cold Vacuum Drying Facility</td>
</tr>
<tr>
<td>DBA</td>
<td>design basis accident</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>HEPA</td>
<td>high-efficiency particulate air (filter)</td>
</tr>
<tr>
<td>HVAC</td>
<td>heating, ventilation, and air conditioning</td>
</tr>
<tr>
<td>LPF</td>
<td>leak path factor</td>
</tr>
<tr>
<td>MAR</td>
<td>material at risk</td>
</tr>
<tr>
<td>MCO</td>
<td>multi-canister overpack</td>
</tr>
<tr>
<td>PWC</td>
<td>process water conditioning</td>
</tr>
<tr>
<td>RF</td>
<td>respirable fraction</td>
</tr>
<tr>
<td>SCHe</td>
<td>safety-class helium</td>
</tr>
<tr>
<td>SCIC</td>
<td>safety-class instrumentation and control</td>
</tr>
<tr>
<td>SNF</td>
<td>spent nuclear fuel</td>
</tr>
<tr>
<td>SSC</td>
<td>structure, system, and component</td>
</tr>
<tr>
<td>TNT</td>
<td>trinitrotoluene</td>
</tr>
<tr>
<td>TSR</td>
<td>technical safety requirement</td>
</tr>
</tbody>
</table>

### 8-4-4
8-hour initial vacuum cycle, 4-hour subsequent vacuum cycles, 4-hour return to pressure between vacuum cycles
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1.0 INTRODUCTION

The calculations in this document address the design basis accidents (DBAs) selected for analysis in HNF-3553, Spent Nuclear Fuel Project Final Safety Analysis Report, Annex B, "Cold Vacuum Drying Facility Final Safety Analysis Report." The objective is to determine the quantity of radioactive particulate available for release at any point during processing at the Cold Vacuum Drying Facility (CVDF) and to use that quantity to determine the amount of radioactive material released during the DBAs. The radioactive material released is used to determine dose consequences to receptors at four locations, and the dose consequences are compared with the appropriate evaluation guidelines and release limits to ascertain the need for preventive and mitigative controls.

This chapter presents the methodology used to develop the potential accidents described in the following chapters. The accident analysis for each DBA starts with a description of the accident scenario and identifies the major assumptions. The next step is to determine the accident source term. 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 onsite evaluation guidelines or offsite release limits to determine the need for safety-class structures, systems, and components and technical safety requirements. Any required safety-class or safety significant structures, systems, and components are then identified.

1.1 DESIGN BASIS ACCIDENT SELECTION

The hazardous conditions identified by the CVDF hazard analysis (HNF-SD-SNF-HIE-004) have been used to select candidate accidents for more detailed analysis. The general selection criteria used are consistent with guidance provided in 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 is evaluated and documented."

The selection of candidate accidents is 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 consequence) 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 challenges to system safety. The 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 related to uncontrolled release of the material at risk (MAR). This ensures that at least one candidate accident is selected to represent each unique set of release conditions.

3. Creation of hazardous material release bins — After release attributes have been assigned, 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.

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. Chapters 2.0 through 7.0 analyze the accidents:

Chapter 2.0 Calculations for Gaseous Release

The bounding scenario for this accident category describes a pressurized release of helium gas and entrained contaminated particulate through a process line leak. The unmitigated consequences of this event do not exceed the offsite release limits but do exceed the onsite evaluation guidelines. No safety-class functions are required to mitigate this event. Safety-significant functions selected for this event include portions of the process general supply/exhaust heating, ventilation, and air conditioning (HVAC) system and process bay local exhaust HVAC and process vent system and the process bays and process water tank room differential pressure alarm. Mitigated consequences of this event are well below both offsite release limits and onsite evaluation guidelines.
Chapter 3.0 Calculations for Liquid Release

The bounding scenario for this accident category describes a pressurized leak of water and entrained contaminated particulate from the process water conditioning (PWC) piping. The unmitigated consequences of this event do not exceed the offsite release limits but do exceed the onsite evaluation guidelines. No safety-class functions are required to mitigate this event. Safety-significant functions selected for this event include portions of the process general supply/exhaust HVAC system (ductwork and high-efficiency particulate air [HEPA] filters for process water tank room) and the process water tank room differential pressure alarm. Mitigated consequences of this event are well below both offsite release limits and onsite evaluation guidelines.

Chapter 4.0 Calculations for Hydrogen Explosions Outside the Multi-Canister Overpack

The bounding scenario for this accident category describes an accumulation of hydrogen that is vented from the multi-canister overpack (MCO) into the local exhaust process ventilation system and mixed with air, followed by ignition and explosion of the hydrogen gas. The unmitigated consequences of this event do not exceed the offsite release limits but do exceed the onsite evaluation guidelines. No safety-class functions are required to prevent or mitigate this event. Safety-significant functions selected to prevent this event include portions of the process bay local exhaust HVAC and process vent system (ductwork and HEPA filters) and the cask vent flow rate. Mitigated consequences of this event are well below both offsite release limits and onsite evaluation guidelines.

Chapter 5.0 Calculations for Hydrogen Generation and Explosion within a Multi-Canister Overpack

The bounding scenario for this accident category describes the ignition and explosion of a hydrogen–air mixture inside an MCO. The unmitigated consequences of this event do not exceed the offsite release limits but do exceed onsite evaluation. No safety-class functions are required to prevent or mitigate this event. However, some safety-class features preventing the MCO thermal runaway reaction event and overpressurization events (i.e., multiple safety functions to detect process upsets, the safety-class helium (SCHe) system, portions of the tempered water [annulus] system, and the water isolation components) also prevent this accident, but in a safety-significant role. Because the designated safety features prevent and mitigate this event, both offsite release limits and onsite evaluation guidelines are satisfied.
Chapter 6.0 Calculations for Multi-Canister Overpack Thermal Runaway Reaction

The bounding scenario for this accident category describes an accident that is initiated by a reduction of heat removal from the MCO. The unmitigated consequences of this event exceed the offsite release limits for "anticipated unmitigated event" category, but not for "unlikely" category and the onsite evaluation guidelines. Safety-class features are required to prevent or mitigate this event. Safety-class features preventing the MCO thermal runaway reaction include safety functions to detect process upsets, the SCHe system, portions of the tempered water (annulus) system, and the water isolation components. Because the designated safety features prevent and mitigate this event, both offsite release limits and onsite evaluation guidelines are satisfied.

Chapter 7.0 Calculations for Multi-Canister Overpack Overpressurization

The bounding scenario for this accident category describes an overpressurization of an isolated MCO with no pressure relief. The pressure in an isolated MCO increases with the formation of hydrogen gas as a product of the uranium-water reaction. The MCO internal pressure would continue to increase until the MCO pressure boundary is breached or until the fuel or water are completely consumed. The overpressurization leads to a pressurized release of gas and contaminated particulate followed by an extended period of continuous release driven by the continued oxidation of the uranium inside the MCO. The unmitigated consequences of this event exceed both the offsite release limits and the onsite evaluation guidelines. Safety-class features selected to prevent this event include multiple safety functions to detect process upsets, the SCHe system, the 30 lb/in² vent line and the 150 lb/in² rupture disk. These safety-class features reduce the frequency and mitigate the occurrence of this event to well within the offsite release limits. Additional safety-significant features for confinement and filtration are identified to mitigate to onsite consequences to well below the onsite evaluation guidelines.

The consequences associated with each of the six bounding DBAs are summarized in Table 1-1.
1.2 RADIOLOGICAL 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 IIA, 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 for radiological dose calculations. 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 and is shown in Table 1-2.

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 CVDF. The particulate inventory of the MCO dominates the airborne release. The radionuclide inventory of the sludge also is bounded by the high-burnup Mark IV fuel. The radionuclide content of sludge, based on
Table 1-2. Composition of K Basins Fuel and the Dose per Unit of Intake.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity (Ci/MTU)</th>
<th>CEDE per unit intake&lt;sup&gt;b&lt;/sup&gt; (rem/μg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;sup&gt;3&lt;/sup&gt;H</td>
<td>2.61 E+01</td>
<td>2.5 E-03</td>
</tr>
<tr>
<td>&lt;sup&gt;14&lt;/sup&gt;C</td>
<td>5.53 E-01</td>
<td>1.2 E-03</td>
</tr>
<tr>
<td>&lt;sup&gt;60&lt;/sup&gt;Co</td>
<td>2.09 E+00</td>
<td>4.6 E-01</td>
</tr>
<tr>
<td>&lt;sup&gt;85&lt;/sup&gt;Kr</td>
<td>3.70 E+02</td>
<td>4.9 E-04</td>
</tr>
<tr>
<td>&lt;sup&gt;90&lt;/sup&gt;Sr&lt;sup&gt;e&lt;/sup&gt;</td>
<td>6.93 E+03</td>
<td>1.7 E+03</td>
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<td>&lt;sup&gt;99&lt;/sup&gt;Tc</td>
<td>2.19 E+00</td>
<td>1.8 E-02</td>
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<tr>
<td>&lt;sup&gt;113&lt;/sup&gt;Cd</td>
<td>2.78 E+00</td>
<td>4.3 E+00</td>
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<tr>
<td>&lt;sup&gt;134&lt;/sup&gt;Cs</td>
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<td>3.0 E-01</td>
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<td>9.66 E+03</td>
<td>3.1 E+02</td>
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<td>&lt;sup&gt;147&lt;/sup&gt;Pm</td>
<td>1.09 E+02</td>
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<td>&lt;sup&gt;151&lt;/sup&gt;Sm</td>
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<td>&lt;sup&gt;234&lt;/sup&gt;U</td>
<td>3.84 E-01</td>
<td>5.1 E+01</td>
</tr>
<tr>
<td>&lt;sup&gt;238&lt;/sup&gt;U&lt;sup&gt;0&lt;/sup&gt;</td>
<td>1.27 E-02</td>
<td>1.6 E+00</td>
</tr>
<tr>
<td>&lt;sup&gt;238&lt;/sup&gt;U</td>
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<td>9.0 E+00</td>
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<tr>
<td>&lt;sup&gt;238&lt;/sup&gt;U&lt;sup&gt;0&lt;/sup&gt;</td>
<td>3.31 E-01</td>
<td>3.9 E+01</td>
</tr>
<tr>
<td>&lt;sup&gt;237&lt;/sup&gt;Np&lt;sup&gt;0&lt;/sup&gt;</td>
<td>4.66 E-02</td>
<td>2.5 E+01</td>
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<td>&lt;sup&gt;239&lt;/sup&gt;Pu</td>
<td>1.33 E+02</td>
<td>5.2 E+04</td>
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<td>5.9 E+04</td>
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<td>&lt;sup&gt;241&lt;/sup&gt;Pu</td>
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<td>8.71 E-02</td>
<td>3.6 E+01</td>
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<tr>
<td>&lt;sup&gt;241&lt;/sup&gt;Am</td>
<td>4.34 E+02</td>
<td>1.9 E+05</td>
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<tr>
<td>&lt;sup&gt;242m&lt;/sup&gt;Am&lt;sup&gt;0&lt;/sup&gt;</td>
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<td>1.6 E+02</td>
</tr>
<tr>
<td>&lt;sup&gt;243&lt;/sup&gt;Am</td>
<td>2.78 E-01</td>
<td>1.2 E+02</td>
</tr>
<tr>
<td>&lt;sup&gt;244&lt;/sup&gt;Cm</td>
<td>4.47 E+00</td>
<td>1.1 E+03</td>
</tr>
</tbody>
</table>

* Combined K Basins inventories decayed to May 31, 1998: 1.0 Ci = 3.7 x 10<sup>10</sup> Bq.
<sup>b</sup> Fifty-year committed effective dose equivalent. The total was calculated by spreadsheet retaining three significant figures.

The following short-lived progeny nuclides are not shown in the table: <sup>90</sup>Y, <sup>117m</sup>Ba, <sup>231</sup>Th, <sup>241</sup>Th, <sup>233</sup>Pa, <sup>234</sup>Pa, <sup>237</sup>U, <sup>239</sup>Np, <sup>241</sup>Am, and <sup>242</sup>Cm. 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.
sample analyses, is reported in Volume 2 of HNF-SD-SNF-TI-009. Comparison of the observed activity of sludge samples (activity per mass of uranium) with high burnup Mark IA fuel indicates that Mark IA fuel bounds the sludge observations for sludge samples.

Because any environmental release of spent nuclear fuel (SNF) could have toxicological as well as radiological effects, both are computed for comparison with risk evaluation guidelines. From this comparison, the predominant risk of the spent fuel particles can be determined and controls can be identified that prevent or mitigate both risks, thus simplifying the analysis and presentation. A detailed comparison of the toxicological and radiological hazards presented by the spent fuel particles has been performed (HNF-SD-SNF-TI-059). The basic assumptions used to show that the radiological risk guidelines are more limiting than the toxicological risk guidelines are listed below.

- The risk evaluation guidelines for toxicological and radiological hazards (Sellers 1997) are the foundation for determining the severity of a postulated airborne release under accident conditions. Both sets of guidelines cover onsite and offsite receptors and distinguish three accident frequency categories. The projected radiological consequences of an accident must be less than the appropriate radiological guideline. Similarly, the toxicological consequences of an accident must be less than the corresponding toxicological guideline.

- The primary material released under accident conditions is SNF particulate matter, which is mostly oxides of uranium. The safety basis composition of SNF (HNF-SD-SNF-TI-015) is used in the comparison. It is assumed that the bounding case accidents do not introduce toxic chemicals in addition to the particulate or change the relative toxicological versus radiological hazard of the particulate inventory used in the comparison (i.e., the particulate is assumed to be a single material with both radiological and toxicological effects). Note that the most limiting chemical forms are assumed. For added conservatism, the radiological dose factors are the largest allowed, and the air concentration limits are the smallest allowed.

- Because SNF contains no corrosive chemicals, a conservative exposure averaging time of 15 minutes is used in the calculation of average air concentration. Note that the time-weighted permissible exposure limit is based on an 8-hour averaging time while the emergency response planning guidelines are based on a 1-hour averaging time.

- Air transport for very short durations is normally computed using a puff model. For the distances from release locations to the Site boundary, release durations less than 8 minutes could be modeled this way. Since the air concentration averaging time is 15 minutes, the puff model is not appropriate. Air transport is represented with a plume model for all release durations.
Long exposure times are a concern for chemical hazards. The air concentration guidelines use values with defined exposure times. If these times are exceeded, there is a potential for increased risk to the individuals downwind. The air concentration guidelines are conservatively reduced by the ratio of the assumed averaging time to the release duration to account for this possibility.

1.3 ACCIDENT RELEASE ESTIMATES

A major focus of accident analysis is providing bounding estimates of the quantity of radioactive material that can be released into the air as respirable-sized particles. Larger particles settle out and deposit on plant foliage and ground surfaces. It is primarily the respirable particles that reach the downwind receptors and produce a radiation dose.

Calculation of the mass released is broken into the components shown in the equation below.

\[ M = (MAR)(ARF)(RF)(LPF) \]

where

- **M** = mass released into the air as respirable particles (g)
- **MAR** = material at risk: the quantity of SNF that is involved in the postulated accident (g)
- **ARF** = airborne release fraction: the fraction of the MAR that becomes airborne when some kind of stress (e.g., thermal, explosive) is applied to the MAR during a postulated accident
- **RF** = respirable fraction: the fraction of the airborne materials that can be transported through air and inhaled into the human respiratory system, normally unit density spheres 10 μm or less in diameter (or their aerodynamic equivalent)
- **LPF** = leak path factor: the fraction of the airborne material that is transported through some confinement deposition or filtration process.

The value for MAR depends on which of the various caches of radioactive material in the CVDF is affected by the postulated accident. The MCO fuel and scrap payload is the largest single source of radioactive material. The next most important source is the accumulated particulate in the MCO. Additional sources are HVAC HEPA filters and the PWC system tanks and filters.

The particulate mass used for release estimates for the safety analyses is summarized in the data handbook (HNF-SD-SNF-TI-015) and is based on two recent documents: HNF-1527,
Estimates of Particulate Mass in Multi-Canister Overpacks, and HNF-SD-W441-CN-001, Spent Nuclear Fuel Inventory in Bulk MCO Water at the Cold Vacuum Drying Facility. The first document provides estimates of particulate inventory for all fuel handling activities following fuel washing at the K Basins up to release from the CVDF for transport to the Canister Storage Building. The second document provides average case and bounding case estimates for particulate generation during the period from fuel washing at the K Basins up to the successful draining of an MCO at the CVDF. The bounding case MCO is assumed to have the particulate masses shown in Table 1-3 at the processing points specified in the table.

Table 1-3. Representative Particulate Masses for the Bounding Multi-Canister Overpack.

<table>
<thead>
<tr>
<th>Process period</th>
<th>Particulate mass</th>
<th>Corresponding SNF mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediately after washing at K Basins</td>
<td>9.5 kg Al(OH)$_3$</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>20.9 kg UO$_2$</td>
<td>18.4 kg SNF</td>
</tr>
<tr>
<td>Between washing and start of drying operations at CVDF</td>
<td>15 kg UO$_2$</td>
<td>13.2 kg SNF</td>
</tr>
<tr>
<td>Between start of drying and transport from CVDF</td>
<td>10 kg UO$_2$</td>
<td>8.8 kg SNF</td>
</tr>
</tbody>
</table>

Note: Values shown in this table are found in HNF-SD-SNF-TI-015, Spent Nuclear Fuel Project Technical Databook, Rev. 6, Fluor Daniel Hanford, Incorporated, Richland, Washington. The conversion from uranium oxide to uranium metal uses the ratio of formula weights (0.88). It has been assumed that the Al(OH)$_3$ mass is equal to the cladding film mass.

CVDF = Cold Vacuum Drying Facility.
SNF = spent nuclear fuel.

The values selected for ARF and RF depend on the type of stress applied to the MAR during the accident scenario. The development of ARFs and subsequent doses to downwind receptors strives for realistic levels of conservatism. Bounding calculations usually assume the respirable fraction is one unless credible experimental data is available. The primary reference for release rates and fractions is DOE-HDBK-3010-94, Airborne Release Fraction/Rates and Respirable Fractions/Rates for Nonreactor Nuclear Facilities.

Leak path factors (LPFs) are normally one for unmitigated dose calculations. The typical mitigating feature that affects the LPF is HEPA filtration before release into the environment. Individual HEPA filter efficiency is greater than 99.97% for particles the filter is least efficient at removing. For accident mitigation calculations, reducing the environmental release by a factor of 1,000 (i.e., assume 99.90% efficiency) is adequate unless the accident may damage the HEPA filter.
1.4 DOSE CALCULATION METHOD

Individuals located downwind following a release of radioactive material into the air can receive radiation dose from the contaminated plume that drifts past them as well as from the residual surface contamination left by the plume. Exposure pathways from the passing plume include inhalation and external dose. Exposure pathways from residual contamination include external exposure, inhalation of resuspended material, and ingestion of contaminated foods.

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, these pathways are evaluated for the safety basis SNF composition of Table 1-2. It is shown that inhalation of contaminated air in the passing plume gives nearly all the resulting dose. External pathways give much smaller doses than internal pathways because of the characteristics of the SNF radionuclides. Internal pathways from residual contamination are excluded by the presence of emergency response plans to warn people not to eat food items from the contaminated areas.

The radiological dose to the bounding individual downwind is determined using the following equation:

\[ D = (M)(\chi/Q')(BR)(UD) \]

where

- \( D \) = 50-year committed effective dose equivalent from inhalation of a mixture of nuclides (rem)
- \( M \) = mass of SNF released into the air as respirable particles (g)
- \( \chi/Q' \) = time-integrated air transport factor (s/m³)
- \( BR \) = average inhalation rate during the release (m³/s)
- \( UD \) = 50-year committed effective dose equivalent from inhalation of a unit mass of SNF as respirable particles (438,000 rem/g SNF).

The quantity of respirable material released (M) is determined by the specific accident scenario. The quantity depends on the accident scenario and the selected values for MAR, ARF, RF, and LPF, as discussed in Section 1.3. The mass must be expressed in units of grams of SNF as metal rather than oxide.

The symbol \( \chi/Q' \) is the time-integrated normalized air concentration at a downwind receptor location. It includes the dilution of an airborne contaminant caused by atmospheric turbulence and diffusion. The methods described in NRC Regulatory Guide 1.145, Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants, are followed using the GXQ computer program (WHC-SD-GN-SWD-30002).
GXQ, Version 4.0, 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 exceedence to be computed. GXQ is an expert program. This means that it is intended to be used by individuals who are knowledgeable of the limits and applicability of the models implemented. The program has been reviewed and tested to verify that it implements its calculational models correctly (WHC-SD-GN-SWD-30003).

The NRC Regulatory Guide 1.145 model selects distances in each direction using the shortest distance in a 45° sector centered on the direction of interest. Air transport factors are computed for each wind direction and the largest value is selected. The hourly wind data collected at a given location are used to construct a distribution of potential values for a given wind direction, and also for the entire boundary. Values that are exceeded only 0.5% of the time for each wind direction, or 5.0% of the time for the entire boundary, are selected. For CVDF the sector maximum (0.5%) is always greater than the overall site value (5.0%) for ground-level emissions. Table 1-4 contains the air transport factors used to determine onsite and offsite consequences.

Exposures to the collocated worker onsite are bounded by the exposures of the individual at the 100-m location. The risk evaluation guidelines apply to this individual. The 100 Area Fire Station is an onsite location that has been used in previous K Basin safety analysis documents. It is included here for comparison purposes. Exposures to members of the public are bounded by the individuals located on the Columbia River and at the Hanford Site boundary. For assessment purposes, the U.S. Department of Energy (DOE) has directed (Sellers 1996) that the Hanford Site boundary be considered the location of the offsite receptor. Consequences at the near bank of the Columbia River are included for identifying any additional measures considered necessary to reduce the dose to individuals at this location.

None of the accidents analyzed in this document adjust the air transport factors for the finite size of the source (e.g., building wake corrections) or for the elevation of the release above ground level (e.g., stack effects). Correction for plume meander is credited for ground releases with release durations from 1 hour to 2 hours.

The breathing rate (BR) depends on individual exertion and exposure duration. All accidents analyzed assume onsite receptors are exposed for no more than 12 hours. Offsite receptors may be exposed for as long as 24 hours. It is assumed that within one day's time, emergency measures will have caused evacuation of offsite areas affected by the accident. Therefore, for the 12-hour exposure, the breathing rate used is the light activity rate of $3.33 \times 10^4 \text{ m}^3/\text{s}$ given in HNF-SD-SNF-TI-059. For the 24-hour exposure, a 24-hour average breathing rate of $2.64 \times 10^4 \text{ m}^3/\text{s}$ is used (HNF-SD-SNF-TI-059).
Table 1-4. Atmospheric Transport Factors Used in Accident Analyses for the Cold Vacuum Drying Facility.

<table>
<thead>
<tr>
<th>Receptor location description</th>
<th>Air transport factors for various release durations*</th>
<th>Logarithmic interpolation*</th>
<th>Chronic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acute</td>
<td>Meander</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Less than 1 hour</td>
<td>1 to 2 hours</td>
<td>12 hours</td>
</tr>
<tr>
<td>Onsite (100 m E)</td>
<td>7.32 E-02</td>
<td>1.24 E-02</td>
<td>6.28 E-03</td>
</tr>
<tr>
<td>Columbia River, near bank</td>
<td>2.44 E-03</td>
<td>4.25 E-04</td>
<td>1.99 E-04</td>
</tr>
<tr>
<td>(650 m W)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 Area Fire Station</td>
<td>1.60 E-04</td>
<td>7.82 E-05</td>
<td>2.73 E-05</td>
</tr>
<tr>
<td>(3,750 m ESE)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanford Site boundary</td>
<td>4.48 E-05</td>
<td>3.11 E-05</td>
<td>1.01 E-05</td>
</tr>
<tr>
<td>(10,090 m W)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Units for these values are seconds per cubic meter. In all cases the releases are assumed to be point sources at ground level to maximize the dose consequences. All values are from HNF-SD-SNF-TI-059, Rev. 2, 1999, A Discussion on the Methodology for Calculating Radiological and Toxicological Consequences for the Spent Nuclear Fuel Project at the Hanford Site, Fluor Daniel Hanford, Incorporated, Richland, Washington.

Air transport factors are computed by logarithmic interpolation between the 1 to 2-hour value and the annual average value.

For release durations less than 1 hour there is no adjustment for plume meander.


The 12-hour durations are used for onsite exposures and the 24-hour durations are used for offsite exposures. These are bounding exposure times.

The unit dose factor (UD) is the sum of the products of the activity per gram of SNF and the effective dose equivalent per unit activity inhaled. The products for each nuclide are shown in Table 1-2. Values for inhalation dose factor were taken from Federal Guidance Report Number 11, Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, and are listed in HNF-SD-SNF-TI-059 for SNF nuclides. The worst-case solubility assumptions were used to maximize the unit dose factor. However, more realistic (oxide) solubility assumptions only reduce the unit dose factor by 17%. The bounding value for the unit dose factor, 438,000 rem/g SNF inhaled, will be used in CVDF accident analyses.

Because gases (e.g., tritium, krypton) and volatile solids (e.g., iodine) are in the fuel matrix, some accidents could liberate these materials more readily than others. If the release is filtered, the particulate material is reduced while these gases and volatile elements pass through unimpaired. The end result could be that the downwind consequences must be determined using a nuclide mixture that differs significantly from the original spent fuel. Because the americium and plutonium isotopes account for more than 99% of the unit dose factor, increasing the amounts of the gases by a factor of 1,000 had no effect on the unit dose factor.
1.5 DOSE EVALUATION

The DOE-recommended radiological risk evaluation guidelines (Sellers 1997) are shown in Table 1-5. These criteria for identifying safety-class structures, systems, and components implement the guidance of DOE Order 6430.1A, General Design Criteria, 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>
<thead>
<tr>
<th>Event category</th>
<th>Frequency range (per year)</th>
<th>Onsite risk evaluation guidelines* rem</th>
<th>Offsite accident release limits* rem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticipated</td>
<td>1.0 E-01 to 1.0 E-02</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Unlikely</td>
<td>1.0 E-02 to 1.0 E-04</td>
<td>10</td>
<td>5.0</td>
</tr>
<tr>
<td>Extremely unlikely</td>
<td>1.0 E-04 to 1.0 E-06</td>
<td>25</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Note: All doses are committed effective dose equivalents.


The particulate estimates used for the DBA analyses are from HNF-SD-SNF-TI-015, Spent Nuclear Fuel Project Technical Databook.

1.6 REFERENCES


HNF-SD-W441-CN-001, *Spent Nuclear Fuel Inventory in Bulk MCO Water at the Cold Vacuum Drying Facility*


2.0 CALCULATIONS FOR GASEOUS RELEASE

2.1 PURPOSE AND OBJECTIVES

The multi-canister overpack (MCO) arrives at the Cold Vacuum Drying Facility (CVDF) from K Basins with the inside of the MCO vented to the shipping cask. Because it is possible for the cask–MCO gas space to be at greater than atmospheric pressure, the potential exists for an event to occur that relieves that pressure, and any entrained particulate matter from the MCO, to the environment. At the CVDF, the MCO is connected to process equipment that drains the water from the MCO and subsequently vacuum dries the contents of the MCO. Failure of this process equipment could result in the release of MCO process gases, and any entrained particulate matter from the MCO, to the environment. The calculation in this chapter is performed to determine the potential dose consequences resulting from the bounding gaseous release accident. Dose consequences are compared with dose guidelines to help ascertain the need for preventive and mitigative controls.

2.2 SCENARIO DEVELOPMENT

The CVDF hazard analysis (HNF-SD-SNF-HIE-004) identified and categorized a series of potential accidents as gaseous release accidents. This category includes those gaseous releases from the MCO, and from the cask during the time the cask is in communication with the MCO gas space, that have the potential to carry radioactive particulate matter out of the MCO. The hazard analysis included “Pressurized release of particulate due to hydride reactions” as a gaseous release accident, but this event is covered as part of the “MCO overpressurization accident” (see Chapter 7.0). The gaseous release accident category also includes leaks in process equipment caused by

- Dropping or crashing equipment into the process system
- External events such as earthquakes, or internal events such as fires, that damage the process lines
- Random failures of the process piping.

This set of accidents involves a slightly pressurized MCO exhausting, ultimately, to the environment. This condition could exist during helium purge operations immediately following bulk water draining and again immediately following vacuum drying. The frequency of random failures of the process system pressure boundary components, dropping or crashing equipment into the process system, and operator error may be derived from probability estimates in the event tree diagram shown in Appendix A, Figure A1-1, for helium leaking into the CVDF. The normal frequency derived from the probability estimates shown in the event tree puts this event into the "anticipated" category.
The scenario selected as the design basis accident (DBA) is a leak in a process line that allows the MCO to be purged to the environment. This event represents the bounding dose consequences and has the highest likelihood.

MCO draining is accomplished by opening the isolation valves (GOV 1*30, GOV 1*03) on the process water conditioning (PWC) line between the PWC system and the long axial process tube in the MCO (PWC-*01-SS-1", PWC-*03-SS-1", PWC-001-SS-1"). The PWC pumps create a vacuum in the PWC drain header via the eductor (PWC-EJR-4031). Pressure is applied to the filtered process exit port side of the MCO by supplying helium from the general service helium system. Water exiting the MCO from the long axial process tube connection does not pass through the MCO internal filter. When the bulk water is removed and helium fills the MCO drain line, the PWC system loses pressure suddenly as the helium expands into the PWC system. A leak in the MCO drain line at this time will result in a gaseous release accident. The gas could be released to any area of the CVDF that the drain line passes through, which includes all process bays and the process water tank room. At this phase of the cold vacuum drying process, the MCO could contain a maximum of 15 kg of particulate matter (see Section 1.3, Table 1-3).

After it is drained, the MCO is prepared for the drying process. The monitor and control system starts the continuous purge. The purge gas evaporates residual water in the MCO by maintaining a dry helium gas flow over the warm, wet surfaces of the MCO and the fuel. Helium is supplied to the long axial process tube of the MCO and exits the MCO from the filtered process exit port; thus the exiting gases pass through the MCO's internal high-efficiency particulate air (HEPA) filter. After purging, the vacuum drying phase of the process is performed. During this phase, the vacuum pump (VPS-P-2*11) is used to remove water vapor and noncondensable gases, which are drawn through the condenser (VPS-COND-2*13) and then exhausted to the process vent system. The vacuum drying cycle continues until the MCO pressure decreases to less than a predetermined value. At that time, a pressure-rise test is initiated. If the pressure-rise test fails, the MCO is purged with helium and the vacuum drying cycle is performed again; this process is repeated until the MCO passes the pressure-rise test.

A leak in the MCO purge line (VPS-*02-SS-1", VPS-*02-SS-2") or the port valve of the MCO during helium purge will result in a gaseous release accident (see the logic diagram in Figure 2-1). The leak allows a continuous release of pressurized helium carrying particulate that could be released to the process bay. Consequences of this accident are calculated based on a continuous release of 12 hours for onsite doses and 24 hours for offsite doses. These are the maximum reasonable exposure times at downwind receptor locations. During this phase of the cold vacuum drying process, an additional 10 kg of particulate could be generated, which means that the MCO could now contain a maximum of 25 kg of particulate matter (see Section 1.3, Table 1-3). This accident is selected as the bounding representative accident.

The representative gaseous release accident occurs during the helium purge operation. If a leak were to occur in the purge system, the particulate entrained in the helium purge gas would be released into the CVDF and ultimately into the environment. For the MCO containing the bounding quantity of radioactive particulate matter, such an unmitigated release to the environment could result in an onsite dose that exceeds the dose guidelines. The helium lost
because of the leak is made up by the helium supply system. The scenario is based on the following assumptions.

- The operating parameters are within the normal range, and the instrument and control system does not indicate that a problem exists.

- The time period associated with helium purge following draining is nominally 0.5 hours, and the time associated with the purge following the vacuum process is nominally 4 hours. However, for the purposes of this analysis, the purge gas will be assumed to flow throughout the bounding exposure period for both onsite and offsite receptors (12 and 24 hours, respectively).

- The instrumentation and control system design includes a high-pressure alarm and a low-pressure alarm for the process gas system. As long as the alarm setpoints are not violated, the helium system will attempt to maintain the helium pressure by increasing purge flow to the MCO.

2.3 SOURCE TERM ANALYSIS

Section 5.2.4 of DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions/Rates for Nonreactor Nuclear Facilities*, states that the value for the aerodynamic entrainment of "powders lying on a heterogeneous surface under debris or for static conditions within facilities" is $4.0 \times 10^4$/h with a respirable fraction of 1.0. The release rate under static conditions was chosen because the MCO purge flow rates are a few cubic feet per minute, so the flow velocities inside the MCO are limited.

The MCO HEPA filters are assumed to have failed. DOE Order 6430.1A, *General Design Criteria*, requires HEPA filters to be testable in their installed configurations. This is applied to the MCO filters to mean they must be testable when in place on the MCO. Since this is not possible, no credit can be taken for the MCO HEPA filters.

Because the representative accident could happen at the end of processing the MCO at the CVDF, the total 25 kg of particulate is used in this analysis (see Section 1.3, Table 1-3). The amount of uranium is calculated by multiplying the mass of uranium dioxide by the ratio of the atomic weight of uranium to the atomic weight of uranium dioxide. Therefore, the 25 kg of uranium dioxide particulate contains approximately 22 kg of uranium, which is the amount of the material at risk for this accident. The amount of respirable material released during the blowdown from the MCO is calculated using the following formula:

$$M = MAR \times ARR \times RF \times T$$
where

\[
\begin{align*}
\text{MAR} &= \text{material at risk (22 kg)} \\
\text{ARR} &= \text{airborne release rate (4.0 } \times 10^{-6}/\text{h)} \\
\text{RF} &= \text{respirable fraction (1.0)} \\
T &= \text{time (hours)}. \\
\end{align*}
\]

For a 12-hour release, the amount of respirable radionuclide material released is

\[
M = (22 \text{ kg SNF})(1,000 \text{ g/kg})(4.0 \times 10^{-6}/\text{h})(1.0)(12 \text{ h}) = 1.1 \text{ g SNF}.
\]

For a 24-hour release, the amount of respirable radionuclide material released is two times the 12-hour release, or 2.2 g spent nuclear fuel (SNF). It is assumed that the accident is terminated at the end of 24 hours (through actions such as rerouting the helium flow or repairing the process line).

2.4 CONSEQUENCE ANALYSIS

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

\[
D = M \times \frac{\chi}{Q'} \times \text{BR} \times \text{UD}
\]

where

\[
\begin{align*}
D &= \text{effective dose equivalent based on inhalation exposure only (rem)} \\
M &= \text{respirable quantity of SNF released into the air (g)} \\
\chi/Q' &= \text{air transport factor (s/m$^3$)} \\
\text{BR} &= \text{average inhalation rate during the release (m$^3$/s)} \\
\text{UD} &= \text{committed effective dose equivalent per gram SNF inhaled (438,000 rem/g SNF)}.
\end{align*}
\]

For the onsite receptor, the duration of worker exposure can be assumed to be 12 hours on the basis of anticipated 12-hour work shifts. For the offsite receptor, the duration of exposure is taken to be 24 hours. For releases occurring over a 12-hour or a 24-hour time period, the air transport factor ($\chi/Q'$) is the logarithmic interpolation between the 2-hour $\chi/Q'$ with plume meander and the annual average $\chi/Q'$ (HNF-SD-SNF-TI-059). All of the air transport factors used in this analysis are summarized in Table 1-4.

The light activity breathing rate of $3.33 \times 10^4$ m$^3$/s, as defined 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 the onsite receptor. For the offsite receptor, an average 24-hour breathing rate of $2.64 \times 10^4$ m$^3$/s is used.
The dose per unit of respirable material inhaled is $4.38 \times 10^5$ rem/g of fuel as specified in Table 1-2. All the material released from the building is treated as respirable (i.e., less than 10-μm aerodynamic diameter).

Using the respirable radionuclide release quantities calculated in Section 2.3, doses to various receptors are calculated as a function of leak duration. The results are summarized in Table 2-1.

### Table 2-1. Dose Calculation Summary for Gaseous Releases.

<table>
<thead>
<tr>
<th>Receptor location (distance, direction)</th>
<th>Duration (hours)</th>
<th>$\chi/Q^*$ (s/m$^3$) (without stack)</th>
<th>Unmitigated dose* (rem, Sv)</th>
<th>Evaluation guideline/release limits (rem, Sv), anticipated$^d$</th>
<th>Safety-significant mitigated dose (Sv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>12</td>
<td>6.28 E-03</td>
<td>1.0 (1.0 E-02)</td>
<td>1.0 (1.0 E-02)</td>
<td>0.001 (1.0 E-05)</td>
</tr>
<tr>
<td>Columbia River (650 m W)</td>
<td>12</td>
<td>1.99 E-04</td>
<td>0.032 (3.2 E-04)</td>
<td>--</td>
<td>3.2 E-05 (3.2 E-07)</td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>12</td>
<td>2.73 E-05</td>
<td>4.4 E-03 (4.4 E-05)</td>
<td>--</td>
<td>4.4 E-06 (4.4 E-08)</td>
</tr>
<tr>
<td>Hanford Site boundary (10,090 m W)</td>
<td>24</td>
<td>6.50 E-06</td>
<td>1.7 E-03 (1.7 E-05)</td>
<td>0.5</td>
<td>1.7 E-06 (1.7 E-08)</td>
</tr>
</tbody>
</table>


$^d$ Fifty-year committed effective dose equivalent.

$^d$ Evaluation guideline for onsite (100 m) receptor only.

$^d$ Anticipated event frequency is $>10^{-4}$ to $\leq 10^{-9}$ per year.

**Unmitigated Consequences.** The following dose calculation equation is used to calculate the dose to the onsite receptor.

$$D_{on site} = M \times \frac{\chi}{Q'} \times BR \times UD$$

$$= (1.1 \text{ g SNF})(6.28 \times 10^{-3} \text{ s/m}^3)(3.33 \times 10^{-4} \text{ m}^3/\text{s})(4.38 \times 10^5 \text{ rem/g})$$

$$= 1.0 \text{ rem (1.0 \times 10^{-2} Sv).}$$

The unmitigated dose consequences at the remaining receptor sites are calculated in the same manner and are shown in Table 2-1.
Mitigated Consequences. Since the unmitigated accident does not exceed release limits, no mitigated consequences were calculated for offsite doses. The release in the mitigated case is assumed to continue for the same period of time, but the building process general supply/exhaust heating, ventilation, and air conditioning (HVAC) system is credited with confinement of the release by maintaining a negative differential pressure and filtering the release via the HEPA filters in the system. The mitigated dose calculation includes the effects of the leak path factor involved with the radioactive material released exiting the building via the HEPA filters. For a HEPA filter efficiency of 99.9%, this leak path factor is 0.001 and is applied as indicated in the following equation.

\[
D_{\text{onsite}} = M \times \frac{\lambda}{Q'} \times \text{BR} \times \text{UD} \times \text{LPF}
\]

\[
= (1.1 \text{ g SNF})(6.28 \times 10^{-3} \text{ s/m}^3)(3.33 \times 10^{-4} \text{ m}^3/\text{s})(4.38 \times 10^5 \text{ rem/g})(0.001)
\]

\[
= 0.001 \text{ rem} (1.0 \times 10^{-5} \text{ Sv}).
\]

With safety-significant functions credited, mitigated onsite consequences for the event are 0.001 rem (1.0 \times 10^{-5} \text{ Sv}). The mitigated gaseous release consequences also are summarized in Table 2-1.

2.5 COMPARISON TO GUIDELINES

Comparison of Unmitigated Doses. The unmitigated frequency for gaseous release is in the anticipated category (i.e., an unmitigated frequency greater than \(10^{-2}\) per year) (see Appendix A). The unmitigated sequence considered the processing of 200 MCOs per year and a leak from either the flexible hose connections themselves or from installation error, the piping, or the valves. The unmitigated radiological offsite dose for this event is below offsite release limits, while the unmitigated onsite dose for an anticipated event is above onsite risk evaluation guidelines.

Comparison of Mitigated Doses. The mitigated frequency of the event tree sequences that represent this DBA as an unfiltered release is \(1 \times 10^{-5}\) per year, thus this mitigated DBA is extremely unlikely (see Appendix A). The mitigated sequence credited leak verification, local exhaust fan operation, loss of differential pressure in the process bays, response to loss of differential pressure, and HEPA filter functionality. With safety-significant features credited, the mitigated onsite dose for an extremely unlikely event is well below onsite risk evaluation guidelines.
2.6 SUMMARY OF SAFETY-CLASS STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

Under normal operating conditions, no unfiltered gaseous releases to the process bay or PWC tank room are expected. Under upset or accident conditions, safety-significant equipment is required in order to ensure dose consequences do not exceed onsite risk evaluation guidelines.

The checklist designators included in the accident bins, other than the accident selected as the DBA, represent additional accident sequences slightly different than the DBA. All of these binned accidents are bounded by the DBA because they have lesser or equivalent worst-case consequences and frequencies.

In addition to the DBA, accident scenarios in the G1 bin were identified in the hazard analysis, including random process line failure, line failure due to crane load drop, local or general exhaust HEPA filter failure, random ventilation system failure (differential pressure and filtration), and PWC drain line failure (process bay, spare bay, or PWC room) (HNF-SD-SNF-HIE-004). Because of the length of piping and numerous locations where a leak could occur (e.g., fittings, valves), the general approach taken for G1 bin gaseous releases is to mitigate a release. Confinement of the release is ensured by active ventilation and HEPA filtration. To support the confinement function, the differential pressure in each bay is monitored, and the standby power system (and selected isolation dampers) ensures maintenance of confinement under a loss of facility power. However, a leak in the PWC drain line is prevented rather than mitigated because that line travels through all bays and the spare bay before entering the PWC room. Confinement provided by the ventilation systems is not maintained in the spare bay and cannot be ensured in all process bays because one of the bays could have a rollup door open.

The safety-significant equipment designated to mitigate the dose consequences of the gaseous release accident analyzed in this section is described below.

Safety-class equipment (performing a safety-significant function) for confinement:

- Cask-MCO

  The cask-MCO is a major part of the pressure boundary for confinement of radioactive materials during processing; its integrity prevents a gaseous release.

Safety-significant equipment for confinement and filtration:

- Process bay local exhaust HVAC and process vent system (exhaust fans and plenums, duct work, HEPA filters)

  The process bay local exhaust HVAC and process vent system mitigates a gaseous release into the process bay by sweeping it through HEPA filters before it is discharged outside the facility.
Process bay local exhaust HVAC and process vent system process hood isolation damper and instrument air supply

Isolation dampers in the process bay local exhaust HVAC and process vent system process hood fail closed to ensure confinement by isolation of the unfiltered process hood. If power is lost, dampers will open with electrical power from the standby power system and instrument air supplied by the local dedicated tank. The hood isolation damper and instrument air supply operate in conjunction with the standby power system to facilitate HVAC operating while on standby power.

Process general supply/exhaust HVAC system (exhaust HEPA filter, exhaust duct work, isolation damper)

The process general supply/exhaust HVAC system mitigates a release into the process bay or process water tank room by filtering it before discharging it outside the facility. This ensures that leaks during processing or following bulk water drain (including PWC room) are captured. The process general supply/exhaust HVAC system also provides confinement in conjunction with the facility’s structure by maintaining a negative building pressure. Fail-closed exhaust dampers from the process bays and process water tank room isolate other flow paths and ensure that differential pressure is maintained.

Process bay recirculation HVAC system isolation dampers (outside air inlets)

The process bay recirculation HVAC system provides fail-closed outside air inlet dampers so the local exhaust on standby power can maintain process bay differential pressure.

Reference air system (reference air header, differential pressure alarms for both process bays and process water tank room)

The reference air system monitors the negative pressure in the process bays and process water tank room by providing differential pressure indication and alarms to the control room for operator response.

PWC line between the MCO and the process water tank room

The design and installation of the PWC transfer line provide confinement of contaminated process water and gases during transfer from the MCO to the PWC room.

Standby electrical power (diesel generator and process bay local exhaust HVAC and process vent system restart circuit)
The standby power system provides connections to restart the local exhaust fans and supporting equipment. Operation of the local exhaust on standby power will maintain building differential pressure sufficient for confinement during facility power outages. Assumptions made that require protection by technical safety requirements (TSRs) are listed below.

- Perform process connector leak test before processing

Before processing, a leak test must be performed to ensure that the process connectors do not leak. This test protects safety analysis assumptions relative to air inleakage into the MCO.

The bounding accident (G.1) and the other accidents identified in the CVDF hazard analysis report (HNF-SD-SNF-HIE-004) that may potentially lead to a gaseous release are listed in Table 2-2 along with corresponding checklist designators from the hazard analysis report.

The accidents in the remaining bins require the following safety structures, systems, and components and TSRs, in addition to those identified for the DBA (G.1):

G.2  Gaseous release due to delays in shipping from the CVDF

The accident scenario identified in the hazard analysis for the G.2 bin represents a slow release from an MCO awaiting shipment from the CVDF (HNF-SD-SNF-HIE-004). The MCO is slightly pressurized by the fuel corrosion reaction and the MCO is leaking or a port valve was not properly closed. The control in the G2 bin prevents the gaseous release by preventing pressurization of the MCO that results from excessive free water remaining in the MCO.

Assumptions made that require protection by TSRs are listed below.

- Proof-of-dryness demonstration at the CVDF to minimize hydrogen generation within the MCO during transport to and storage at the Canister Storage Building

A proof-of-dryness demonstration must be successfully completed before the final pressure rebound test steps can begin.

G.3  Gaseous release due to line break caused by a seismic event

The accident scenario identified in the hazard analysis for the G.3 bin represents releases into the transfer corridor or process bay following a seismic event (HNF-SD-SNF-HIE-004). The seismic event is an unlikely event for which the onsite risk evaluation guideline is 10 rem. Because the worst-case gaseous release dose is less than 10 rem, the guideline is satisfied without controls.

No additional requirements result from analysis of this accident.
G.4  **Gaseous release caused by facility fire**

The accident scenario identified in the hazard analysis for the G 4 bin represents releases into the process bay caused by a facility fire (HNF-SD-SNF-HIE-004). The unmitigated frequency for the events in bin G4 is unlikely (HNF-SD-SNF-HIE-004) for which the onsite risk evaluation guideline is 10 rem. Since the worst-case gaseous release dose is less than 10 rem, the guideline is satisfied without controls.

No additional requirements result from analysis of this accident.
<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designation</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS¹</th>
</tr>
</thead>
</table>
| G.1. Gaseous release due to process line failure or HVAC failure (bounding accident, PB-H-06f) | PB-B-13a PB-F-05 PB-H-06d PB-H-06f PB-H-06g PB-H-06h PB-N-01 SB-N-01 PW-H-06 | Prevent/mitigate gaseous release outside the facility | Safety-class equipment (performing a safety-significant function) for confinement:  
• Cask-MCO  
Safety-significant equipment for confinement and filtration:  
• HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters)  
• HVAC/PV process hood isolation damper  
• HVACD system (exhaust HEPA filter, exhaust duct work, isolation dampers)  
• HVACB isolation dampers (outside air inlets)  
• PWC line between the MCO and the process water tank room  
• Standby electrical power (diesel generator and HVAC/PV system restart circuit)  
Safety-significant equipment for monitoring:  
• Reference air system (reference air header, differential pressure alarms for both process bays and process water tank room)  
TSR:  
• Perform process connector leak test before processing | B |

Defense in depth  
Continuous air monitors
<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS</th>
</tr>
</thead>
</table>
| G2: Gaseous release due to delays in shipping from the CVDF (slow leak) | PB-H-06i | Prevent out-of-specification MCO | Safety-class equipment (performing a safety-significant function) for confinement:  
  - Cask-MCO  
Safety-significant equipment for confinement and filtration:  
  - HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters)  
  - HVAC/PV process hood isolation damper  
  - HVACD system (exhaust HEPA filter, exhaust duct work, isolation dampers)  
  - HVACB isolation dampers (outside air inlets)  
  - Standby electrical power (diesel generator and HVAC/PV system restart circuit) | A | B |
|                     |                     |                | Safety-significant equipment for monitoring:  
  - Reference air system (reference air header, differential pressure alarms for both process bays and process water tank room) | B |
|                     |                     |                | TSR:  
  - Proof-of-dryness demonstration at the CVDF to minimize hydrogen generation within the MCO during transport to and storage at the CSB |
Table 2-2: Summary of Safety Features Required to Mitigate or Prevent the Consequences of a Gaseous Release. (4 sheets)

<table>
<thead>
<tr>
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<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS*</th>
</tr>
</thead>
</table>
| G.3: Gaseous release due to line break caused by a seismic event | TC-R-01 PB-R-01a OU-R-01a | Prevent gaseous release; These accidents meet guidelines for the unlikely event. | Defense-in-depth equipment for confinement and filtration:  
  - HVACC/PV system (exhaust fans and plenums, duct work, HEPA filters)  
  - HVACC/PV process hood isolation damper  
  - HVACD system (exhaust HEPA filter, exhaust duct work, isolation dampers)  
  - HVACB isolation dampers (outside air inlets)  
  - Standby electrical power (diesel generator and HVACC/PV system restart circuit) | **Defense-in-depth equipment for monitoring:**  
  - Reference air system (reference air header, differential pressure alarms for both process bays and process water tank room) |
| G.4: Gaseous release caused by facility fire | PB-L-01 PB-L-02 PB-L-03 PB-L-04 PB-L-05 PB-L-06 PB-L-07 PB-L-08 PB-L-09 PB-L-10 PB-L-13 PB-L-14 PB-L-15 PB-L-16 PB-P-02 OU-P-02a | Protect a processing bay against external fire (administrative area, transfer corridor, other nonprocessing bay) and limit the fire risk inside a processing process bay | No SSCs required. | **Defense-in-depth equipment for monitoring:**  
  - Reference air system (reference air header, differential pressure alarms for both process bays and process water tank room) |
Table 2-2: Summary of Safety Features Required to Mitigate or Prevent the Consequences of a Gaseous Release. (4 sheets)

<table>
<thead>
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</tr>
</thead>
</table>

*Checklist designators are from HNF-SD-SNF-HIE-004, 1999, Cold Vacuum Drying Facility Hazard Analysis, Rev. 4, Fluor Daniel Hanford, Incorporated, Richland, Washington.

U.S. Nuclear Regulatory Commission important-to-safety classifications: Category A = critical to safe operation, Category B = major impact on safety, and Category C = minor impact to safety.

CSB = Canister Storage Building
CVDF = Cold Vacuum Drying Facility
HEPA = high-efficiency particulate air (filter)
HVAC = heating, ventilation, and air conditioning
HVACB = process bay recirculation HVAC system
HVACCPV = process bay local exhaust HVAC and process vent system
HVACD = process general supply/exhaust HVAC system
ITS = important to safety
MCO = multi-canister overpack
NRC = U.S. Nuclear Regulatory Commission
PWC = process water conditioning
SSC = structure, system, and component
TSR = technical safety requirement
2.7 REFERENCES


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Figure 2-1. Logic Diagram for Gaseous Release.

- Pressurized gaseous release from MCO or connected process piping
  - PTOP
- Pressurized gases exist in MCO or connected process piping
  - P101
  - Process helium is supplied to short tube port of MCO for draining MCO water
    - P201
- Open pathway for pressurized gases to exit MCO or connected piping
  - P102
  - Process helium is supplied to long tube port of MCO for purge operation
    - P202
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3.0 CALCULATIONS FOR LIQUID RELEASE

3.1 PURPOSE AND OBJECTIVES

The multi-canister overpack (MCO) arrives at the Cold Vacuum Drying Facility (CVDF) from K Basins inside an MCO shipping cask with the MCO containing water covering the fuel. At the CVDF, the MCO is connected to process equipment that drains the water from the MCO. A leak in the pressurized portion of this process equipment during this draining operation could result in the release of MCO water, along with entrained particulate matter from the MCO, to the process water tank room and ultimately to the environment. The following calculation was performed to determine the potential dose consequences resulting from the bounding liquid release accident. Dose consequences are compared with dose guidelines to help ascertain the need for preventive and mitigative controls.

The spray leak in the process water conditioning (PWC) room is selected as the liquid release design basis accident (DBA) because it represents the bounding dose consequences and has a high likelihood. Non-pressurized liquid releases do not pose consequences that challenge guidelines.

3.2 SCENARIO DEVELOPMENT

The CVDF hazard analysis (HNF-SD-SNF-HIE-004) identified and categorized a series of potential accidents as liquid release accidents. This accident category consists of releases from leaks developing in the PWC system. The PWC system includes the piping and other hardware involved in removing MCO water from the MCO, filtering the water, and ultimately sending the water to a holding tank until it is processed by the K Basins integrated water treatment system. The liquid releases include leaks in the PWC system as the result of random mechanical failure of the system hardware, kinetic energy associated with dropping or running equipment into the system hardware, and external events such as earthquakes and fires. The structures, systems, and components designated to prevent or mitigate the liquid release are designated safety significant.

The range of possible leaks includes

- Leaks in the piping (PWC-006-SS-1 ½") that takes filtered processed water from the process water tank room to the holding tank
- Leaks in the MCO drain line (PWC-*01-SS-1"), which is at a slightly negative pressure
- Leaks from the pressurized piping (PWC-006-SS-1 ½", PWC-007-SS-1 ½", PWC-008-SS-1 ½", PWC-009-SS-1 ½", PWC-011-SS-1 ½") in the process water tank room.
Leaks of filtered processed water involve a lower concentration (relative to unprocessed water) of radionuclide particulate and therefore will not yield bounding consequences. Leaks from the MCO drain line (PWC-001-SS-1") will drain by gravity and spill to the process bay floor or process water tank room floor creating a pool. Because the MCO is pressurized with helium during draining, the size of the pool is limited to the volume of water that the backfill pressure can force from the MCO. The consequences of this spill are bounded by the water sprayed into the air as calculated for the pressurized leak in the PWC system.

The frequency of random leaks occurring in the process system pressure boundary components are identified from the sequence probabilities in the event tree diagram shown in Appendix A, Figure A2-1, for water spray leaks at the CVDF. The frequency of this event is shown to put this event into the "anticipated" category.

Unmitigated consequences for the bounding liquid release event are below offsite release limits; therefore, no safety-class functions are required to mitigate this event. Safety-significant functions selected to mitigate the onsite doses from this event include the process general supply/exhaust heating, ventilation, and air conditioning (HVAC) system and the process water tank room differential pressure alarm. Mitigated consequences of this event are well below both offsite release limits and onsite evaluation guidelines.

The bounding event is a leak in the pressurized PWC system piping (see the logic diagram in Figure 3-1) at the pump outlet where the PWC system pressure is the greatest. The leak sprays water containing particulate into the process water tank room, fills the room with respirable aerosols, and creates a pool of contaminated water on the floor of the room. Additional particulate is released to the room from the pool's surface through aerodynamic resuspension and evaporation. During the MCO water draining operation, the water entrains radioactive particulate in the MCO. The particulate is released during the spray and ultimately released to the environment. For an MCO containing the bounding quantity of radioactive particulate matter, such an unmitigated release to the environment could result in an onsite dose that exceeds the dose guidelines.

The following assumptions are used in the analysis.

- The total quantity of water available for release into the process water tank room is 650 L. At the start of processing, there are 500 L in the MCO and 150 L in the receiver tanks (PWC-TK-4032, PWC-TK-4033). The water in the receiver tanks is used to prime the pump (PWC-P4035, PWC-P-4036; only one operating) in the PWC system and provide recirculation through the ejector (PWC-EJR-4031) to establish vacuum on the drain header (PWC-001-SS-1").

- The density of the dry aerosol particulate is assumed to be 5.0 kg/L (HNF-SP-1201). The maximum density of this particulate is assumed to be 10.0 kg/L (HNF-1523).

- The spray release develops during pumping of the process water in the line from (PWC-005-SS-1") the PWC circulation water pumps. This is the point in the system
with the highest pressure, 60 lb/in² gauge. The liquid temperature is assumed to be 46 °C. The viscosity of water at this temperature is 0.588 centipoise (5.88 x 10⁻⁴ Pa-s).

- The inventory at risk is the contents of the process water receiver tanks (650 L of water) and 10% of the particulate from a single MCO (1.5 kg) (see Appendix B, Section B8.0). The estimate of 10% is based on prototype tests using cerium oxide (CeO₂) powder. The cerium oxide powder appears to represent spent nuclear fuel (SNF) particulate due to its high density (6.9 kg/L) and small particle size (0-10 μm). Residual particulate in the PWC tanks is not included in the release calculation because the system purifies the water from previous MCO drain operations and any residual would add a negligible amount to the postulated suspended solids concentration that sprays from the leak. It is conservatively assumed that all the water in the process water receiver tanks (PWC-TK-4031, PWC-TK-4032) is involved in the spray release accident.

- During the MCO draining operation, the drained liquid circulates around a loop that includes a pump, two tanks, and an ejector. Following the draining, the PWC system is reconfigured to circulate the contaminated MCO drain water through ion exchange modules (PWC-IXM-4037, PWC-IXM-4038; one is standby). Eventually the filtered liquid is transferred through a filter (PWC-F-4042) to a holding tank (PWC-TK-4001). There is no limit on the established length of time that the water can be recirculated through the ion exchange module. Therefore this accident is evaluated for a spray leak continuing for both 12 and 24 hours. These are bounding exposure times for onsite and offsite receptors downwind (HNF-SD-SNF-TI-059).

3.3 SOURCE TERM ANALYSIS

During the course of a liquid release accident, a fraction of the sprayed water falls to the floor and collects in a pool; this pool contributes a relatively small amount to the released source term. The spray release accident source term has three components that will be included in the dose calculations:

- Particulate released with the spray of water
- Particulate resuspended from the surface of the pool of water
- Particulate released by evaporation from the pool of water.

Spray of Water. Some fraction of the solution issuing from a leak will atomize, carrying suspended SNF particulate with it. The droplets quickly evaporate leaving behind SNF particles with some water still trapped in the pores.

Large leaks lead to less atomization while small holes lead to lower leak rates. The SPRAY computer program (WHC-SD-GN-SWD-20007) has been used to find the bounding case hole diameter with the largest respirable release rate. The SPRAY program describes the
atomization of a liquid jet due to the kinetic energy of the jet itself. Because atomization of a
liquid jet is a random process, the resultant spray consists of a wide range of drop sizes and must
be represented by a distribution rather than a single parameter. The SPRAY program computes
the fraction of droplets that are below a limiting diameter input by the user. It also varies the leak
size to find the leak with the greatest respirable leak rate. The documentation
(WHC-SD-GN-SWD-20007) includes user guide, verification tests, and configuration control.

One of the first input parameters to the SPRAY program determines whether the leak
comes from a crack or a hole. A crack has much higher respirable release fractions than a hole.
Since the pipes are new stainless steel, and the operational use is expected to be about 2 years,
cracks are not expected under normal conditions. A seismic event could produce a crack but has
a much lower probability of occurring. In addition, a seismic event would shutdown the pumping
operation, ending the spray leak. Thus a leak is most likely due to a weld imperfection (i.e. hole)
rather than a fatigue or corrosion induced crack, or failure of a flange connection. Other user
input to the program includes the water pressure, the PWC liquid density and viscosity, and the
largest droplet diameter that evaporates to respirable-sized particles.

Water Pressure. The water pressure is assumed to be 60 lb/in², the maximum pressure
expected from the PWC pump.

Liquid Density and Viscosity. The PWC liquid viscosity is that of water at 46 °C, namely,
0.588 centipoise (5.88 x 10⁻⁴ Pa-s). The PWC water density is derived in Appendix B,
Section B8.0, to be 1.00208 kg/L. This is based on a total of 1.5 kg of SNF particulate
suspended in 650 L of solution. The dry density of the porous SNF particulate is assumed to be
5.0 kg/L, as measured in K Basins sludge (HNF-SP-1201). The theoretical density is assumed to
be 10.0 kg/L (see HNF-1527 and HNF-1523). When the pore space is filled with water, the
particle density is computed to be 5.5 kg/L (see Appendix B, Section B8.0).

Largest Droplet Diameter that Will Evaporate down to Respirable-Sized Particulate
Airborne particles are respirable if their aerodynamic diameter is less than 10 μm. The term
"aerodynamic diameter" is defined to be the diameter of a unit-density sphere with the same
settling velocity. The actual diameter and aerodynamic diameter of SNF particles is related as
shown in the equation below (Hinds 1982).

\[ D_{\text{SNF}} = (D_{\text{AED}})^{[(S)(\rho_{\text{AED}})/(\rho_{\text{SNF}})]^{1/6}} \]

where

\[ D_{\text{SNF}} = \text{diameter of an SNF particle with the same settling speed as a unit density sphere of diameter } D_{\text{AED}} \]
\[ D_{\text{AED}} = \text{diameter of a unit density sphere (10 μm)} \]
\[ S = \text{shape factor for the SNF particle (assume 1.0 [spherical])} \]
\[ \rho_{\text{aed}} = \text{density of the unit density sphere (1.00 kg/L)} \]

\[ \rho_{\text{SNF}} = \text{density of the wet SNF particle (5.50 kg/L).} \]

Therefore,

\[ D_{\text{SNF}} = (10 \, \mu\text{m}) \left[ (1.0)(1.0 \, \text{kg/L})/(5.5 \, \text{kg/L}) \right]^{1/3} = 4.26 \, \mu\text{m}. \]

Note that slip correction factors have not been included because they are normally applied to much smaller diameter particles. Using the slip correction formula in Hinds (1982) leads to a maximum respirable particle diameter only 1% smaller.

From the discussion in Appendix B, Section B8.0, the formulas shown below can be derived. The first equation gives the ratio of the total volume of a droplet to the volume occupied by the wet particle. The second equation gives the density of the solution with suspended particulate. The third equation gives the density of the particle after its pores are filled with water.

\[
\frac{V_{\text{tot}}}{V_b + V_c} = \frac{(\rho_{\text{part, dry}})(\rho_{\text{solids}} - \rho_{\text{water}})}{(\rho_{\text{solids}})(\rho_{\text{tot}} - \rho_{\text{water}})} = \frac{\rho_{\text{part, wet}} - \rho_{\text{water}}}{\rho_{\text{tot}} - \rho_{\text{water}}}
\]

\[
\rho_{\text{tot}} = \rho_{\text{water}} + (M_c/V_{\text{tot}})(1 - \rho_{\text{water}}/\rho_{\text{solids}})
\]

\[
\rho_{\text{part, wet}} = (\rho_{\text{water}}) + (\rho_{\text{part, dry}}) - (\rho_{\text{water}})(\rho_{\text{part, dry}})/(\rho_{\text{solids}})
\]

where

- \( M_a \) = mass of the water surrounding the suspended particle (kg)
- \( V_a \) = volume of the water surrounding the suspended particle (L)
- \( M_b \) = mass of the water stored in pores of the suspended particle (kg)
- \( V_b \) = volume of the water stored in pores of the suspended particle (L)
- \( M_c \) = mass of the solid material inside the particulate (kg)
- \( V_c \) = volume of the solid material inside the particulate (L)
- \( \rho_{\text{water}} \) = density of pure water (1.0 kg/L)
- \( \rho_{\text{solids}} \) = density of the solid portion of the particulate (10.0 kg/L)
\[ \rho_{\text{PART, DRY}} = \text{density of the dry, porous particulate matter (5.0 kg/L)} \]

\[ \rho_{\text{PART, WET}} = \text{density of the particle after the porous portion is filled with water (5.5 kg/L)} \]

\[ M_{\text{TOT}} = M_a + M_b + M_c \]

\[ V_{\text{TOT}} = V_a + V_b + V_c \]

\[ \rho_{\text{TOT}} = \text{density of the MCO drain water with suspended particulate (1.00208 kg/L [see Appendix B, Section B8.0])} \]

Spherical particles are assumed because irregular shapes have no simple relationship between particle volume and particle diameter. Input to the SPRAY code requires a value for the diameter of the largest droplet that will become a respirable particle when it evaporates. The volume can be calculated from the formula above, but the diameter needed to represent a nonspherical particle is not known. With spherical volumes, the particle diameter ratio is proportional to the cube root of the volume ratio. Note that SNF particles are not spherical but have been assumed spherical in order to have a clear relationship between droplet diameter and particle diameter. The ratio of solution droplet diameter to particulate diameter can then be written

\[ \frac{D_{\text{DROPLET}}}{D_{\text{PARTICLE}}} = \left(\frac{V_{\text{TOT}}}{V_b + V_c}\right)^{1/3} \]

**Results.** The final step is to insert values for the various parameters. The density of water (\(\rho_{\text{WATER}}\)) is 1.0 kg/L. The density of the solids inside the particle (\(\rho_{\text{SOLIDS}}\)) is 10.0 kg/L, while the density of the dry particle (\(\rho_{\text{PART, DRY}}\)) is 5.0 kg/L. Finally, the overall droplet density (\(\rho_{\text{TOT}}\)) is 1.00208 kg/L (see Appendix B, Section B8.0). The solution droplet diameter that evaporates down to a 4.26-\(\mu\)m particle diameter is computed as shown below.

\[ \frac{V_{\text{TOT}}}{V_b + V_c} = \frac{(5 \text{ kg/L})[(10 \text{ kg/L}) - (1 \text{ kg/L})]}{(10 \text{ kg/L})[(1.00208 \text{ kg/L}) - (1 \text{ kg/L})]} = 2,160 \]

\[ D_{\text{DROPLET}} = (4.26 \mu\text{m})(2,160)^{1/3} = 55.1 \mu\text{m} \]

This limiting diameter (55.1 \(\mu\)m) and solution density (1.00208 kg/L) were input to the SPRAY code to obtain the bounding release fractions. The SPRAY program output is listed in Appendix C. The optimum hole diameter was found to be 642 \(\mu\)m. The bounding leak rate from this hole is \(4.54 \times 10^{-6} \text{ m}^3/\text{s}\), of which 9.23 \(\times 10^{-8} \text{ m}^3/\text{s}\) is respirable. Note that these leak rates correspond to 16.3 L/h (total) and 0.332 L/h (respirable).

The total volume of liquid released from the PWC system, as well as the respirable mass that becomes airborne from the spray leak depends on the duration of the leak. Equations to represent these quantities are shown below.
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\[ M_{\text{SPRAY}} = (LR_{\text{SPRAY}})(T_{\text{LEAK}})(M_{\text{SNF}})/(V_{\text{TOT}}) \]

\[ V_{\text{LEAK}} = (LR_{\text{LEAK}})(T_{\text{LEAK}}) \]

where

\[ M_{\text{SPRAY}} = \text{mass of SNF airborne as respirable particles by atomization during the leak (g)} \]
\[ LR_{\text{SPRAY}} = \text{leak rate for respirable particles computed by the SPRAY code (0.332 L/h)} \]
\[ T_{\text{LEAK}} = \text{duration of the leak (h)} \]
\[ M_{\text{SNF}} = \text{total mass of SNF in the PWC system (1,320 g SNF)} \]
\[ V_{\text{TOT}} = \text{total volume of liquid in the PWC system (650 L)} \]
\[ V_{\text{LEAK}} = \text{volume of PWC solution that has leaked from the PWC system (L)} \]
\[ LR_{\text{LEAK}} = \text{total leak rate computed by the SPRAY code (16.3 L/h)} \]

Note that the mass of SNF (1,320 g) is used rather than the mass of particulate (1,500 g) to calculate the mass airborne. Note also that the leak must continue for at least 40 hours for the PWC system to lose its entire inventory of liquid (650 L). The bounding exposure times at downwind receptor locations (i.e., 12 hours onsite and 24 hours offsite) apply to this release. The environmental release may be terminated after 24 hours through actions such as pump shutdown and spill cleanup.

The masses of SNF released by atomization as respirable particles after 12 hours and 24 hours are shown below.

12 hour \[ M_{\text{SPRAY}} = (0.332 \text{ L/h})(12 \text{ h})(1,320 \text{ g SNF})/(650 \text{ L}) = 8.09 \text{ g SNF} \]

24 hour \[ M_{\text{SPRAY}} = (0.332 \text{ L/h})(24 \text{ h})(1,320 \text{ g SNF})/(650 \text{ L}) = 16.18 \text{ g SNF} \]

**Release by Resuspension from the Pool.** With respect to resuspension, DOE-HDBK-3010-94, *Airborne Release Fraction/Rates and Respirable Fractions/Rates for Nonreactor Nuclear Facilities*, Section 3.1, suggests that for aerodynamic entrainment and resuspension indoors, on a heterogenous surface (stainless steel, concrete), and with low airspeeds from normal facility ventilation flows, a bounding airborne release rate is \( 4.0 \times 10^{-7} \text{ L/h} \). Since the spray leak pool volume increases linearly with time, the surface area is assumed to increase linearly with time also. This is a bounding assumption because the pool may encounter boundaries that prevent increases in surface area. With a bulk leak rate of 16.3 L/h, the volume of the pool will be 391 L after 24 hours. Assuming an average depth of 1 cm, the wet surface area is 39.1 m² (420 ft²) at the end of 24 hours. The resuspension rate from this growing pool increases...
linearly with time. The total amount resuspended from the pool increases with the square of the time, as shown below. The factor of $(1/2)$ comes from the time integration.

$$M_{\text{RESUS}} = (\frac{1}{2})(R_{\text{RESUS}})(LR_{\text{LEAK}})(T_{\text{LEAK}})^2(M_{\text{SNF}})/(V_{\text{TOT}})$$

where

- $M_{\text{RESUS}}$ = mass of SNF airborne as respirable particles by resuspension from the puddle (g)
- $R_{\text{RESUS}}$ = respirable release rate from the surface of a puddle by resuspension ($4 \times 10^{-7}$/h)
- $LR_{\text{LEAK}}$ = total leak rate computed by the SPRAY code (16.3 L/h)
- $T_{\text{LEAK}}$ = duration of the leak (h)
- $M_{\text{SNF}}$ = total mass of SNF in the PWC system (1,320 g SNF)
- $V_{\text{TOT}}$ = total volume of liquid in the PWC system (650 L).

The masses of SNF released by resuspension as respirable particles after 12 hours and 24 hours are shown below.

$$12 \text{h } M_{\text{RESUS}} = (\frac{1}{2})(4 \times 10^{-7}/\text{h})(16.3 \text{ L/h})(12 \text{ h})^2(1,320 \text{ g SNF})/(650 \text{ L}) = 0.0010 \text{ g SNF} .$$

$$24 \text{h } M_{\text{RESUS}} = (\frac{1}{2})(4 \times 10^{-7}/\text{h})(16.3 \text{ L/h})(24 \text{ h})^2(1,320 \text{ g SNF})/(650 \text{ L}) = 0.0038 \text{ g SNF} .$$

**Release by Evaporation from the Pool.** With respect to evaporation, an upper bound of $5.3 \times 10^{-7}$ for the airborne release fraction (ARF) for suspended particulate resulting from evaporation stresses is found in DOE-HDBK-3010-94, Section 3.2. This ARF is based on a 2-hour sampling time for air flowing at 0.5 m/s over small quantities of concentrated plutonium nitrate solution heated to 90 °C. These conditions lead to greater emissions than those expected for evaporation from the pool during the spray leak. Since the spray leak pool volume increases linearly with time, the surface area is assumed to increase linearly with time as described earlier. This is a bounding assumption because the pool may encounter boundaries that prevent increases in surface area. The release of suspended particulate due to evaporation from this growing pool increases linearly with time. The total amount of suspended particulate released from the pool increases with the square of the time, as shown below. The factor of $1/2$ comes from the time integration.

$$M_{\text{EVAP}} = (\frac{1}{2})(R_{\text{EVAP}})(LR_{\text{LEAK}})(T_{\text{LEAK}})^2(M_{\text{SNF}})/(V_{\text{TOT}})$$
where

\[ M_{\text{EVAP}} = \text{mass of SNF airborne as respirable particles by evaporation from the puddle (g)} \]

\[ R_{\text{EVAP}} = \text{respirable release rate from the surface of a puddle by evaporation} \]

\[ (5.2 \times 10^{-7}/2 \text{ h} = 2.6 \times 10^{-7}/\text{h}) \]

\[ L_{\text{LEAK}} = \text{total leak rate computed by the SPRAY code (16.3 L/h)} \]

\[ T_{\text{LEAK}} = \text{duration of the leak (h)} \]

\[ M_{\text{SNF}} = \text{total mass of SNF in the PWC system (1,320 g SNF)} \]

\[ V_{\text{TOT}} = \text{total volume of liquid in the PWC system (650 L).} \]

The masses of SNF released by evaporation as respirable particles after 12 hours and 24 hours are shown below.

\[ 12 \text{ h} \ M_{\text{EVAP}} = (½)(2.6 \times 10^{-7}/\text{h})(16.3 \ \text{L/h})(12 \text{ h})^2(1,320 \text{ g SNF})/(650 \text{ L}) = 0.0006 \text{ g SNF} . \]

\[ 24 \text{ h} \ M_{\text{EVAP}} = (½)(2.6 \times 10^{-7}/\text{h})(16.3 \ \text{L/h})(24 \text{ h})^2(1,320 \text{ g SNF})/(650 \text{ L}) = 0.0025 \text{ g SNF} . \]

**Quantity of Respirable Radioactive Material Released during Spray Leak.** The quantity of respirable radioactive material released by the various components of the spray leak, along with the sum of the releases from resuspension and evaporation, is provided in Table 3-1. From the release quantities presented in Table 3-1, it can be seen that the combined resuspension and evaporation from the pool is three orders of magnitude lower than the spray release. Thus, a spill of contaminated water might result in a localized spread of contamination but would not result in a significant release. If the water were filtered (e.g., a spill sometime after passing through the ion-exchange modules), the release would be even less.

<table>
<thead>
<tr>
<th>Release component</th>
<th>Mass releaseda</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Release duration 12 hours</td>
</tr>
<tr>
<td>Atomization by the spray</td>
<td>8.09 g</td>
</tr>
<tr>
<td>Resuspension from puddle</td>
<td>0.0010 g</td>
</tr>
<tr>
<td>Evaporation from puddle</td>
<td>0.0006 g</td>
</tr>
<tr>
<td>Sum of resuspension and evaporation</td>
<td>0.0016 g</td>
</tr>
</tbody>
</table>

*The mass released is grams of SNF (uranium metal), rather than grams of particulate (uranium oxide).
3.4 CONSEQUENCE ANALYSIS

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

\[ D = M \times \frac{\chi}{\bar{Q}} \times BR \times UD \]

where

- \( D \) = effective dose equivalent based on inhalation exposure only (rem)
- \( M \) = respirable SNF quantity released into the air (g)
- \( \chi/\bar{Q} \) = air transport factor (s/m³)
- \( BR \) = average inhalation rate during the release (m³/s)
- \( UD \) = committed effective dose equivalent per gram SNF inhaled.

For the onsite receptor, the duration of worker exposure can be assumed to be 12 hours on the basis of an anticipated 12-hour work shift. For the offsite receptor, the duration of exposure is taken to be 24 hours (HNF-SD-SNF-TI-059). For releases occurring over a 12-hour or a 24-hour time period, the air transport factor \( \chi/\bar{Q} \) is the logarithmic interpolation between the 1 to 2-hour \( \chi/\bar{Q} \) with plume meander and the annual average \( \chi/\bar{Q} \), as recommended in NRC Regulatory Guide 1.145. All of the air transport factors used in this analysis are summarized in Table 1-4.

The light activity breathing rate of \( 3.33 \times 10^{-4} \) m³/s, as defined 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 the onsite receptor. For the offsite receptor, an average 24-hour breathing rate of \( 2.64 \times 10^{-4} \) m³/s is used.

The dose per unit of respirable material inhaled is \( 4.38 \times 10^{3} \) rem/g of fuel as specified in Table 1-2. All the material released from the building is treated as respirable (i.e., less than 10-μm aerodynamic diameter).
Unmitigated Consequences. For the collocated worker (100 m east of the CVDF) during a 12-hour leak event, the dose from the spray atomization portion of the leak is

\[ D_{\text{on site}} = M \times \frac{X}{Q'} \times BR \times UD \]
\[ = (8.09 \ \text{g SNF})(6.28 \times 10^{-3} \ \text{s/m}^3)(3.33 \times 10^{-4} \ \text{m}^3/s)(4.38 \times 10^5 \ \text{rem/g SNF}) \]
\[ = 7.4 \ \text{rem (0.074 Sv)}. \]

Using the respirable radionuclide releases from Table 3-1 and the air transport factors from Table 1-4, doses at the various receptor locations as a function of the spray leak duration are calculated as demonstrated below. The results are summarized in Table 3-2.

Mitigated Consequences. The release in the mitigated case is assumed to continue for the same period of time, but the building process general supply/exhaust HVAC system is credited with confinement of the release by maintaining a negative differential pressure and filtering the release via the high-efficiency particulate air (HEPA) filters in the system. The mitigated dose calculation includes the effects of the leak path factor involved with the radioactive material released exiting the building via the HVAC system HEPA filters. In-place testing of HEPA filters ensures their efficiencies are greater than 99.97%. However, to simplify modeling and to be conservative, a HEPA filter efficiency of 99.9% is assumed. For a HEPA filter efficiency of 99.9%, this leak path factor is 0.001 and is applied as indicated in the following equation.

\[ D_{\text{on site}} = M \times \frac{X}{Q'} \times BR \times UD \times \text{LPF} \]
\[ = (8.09 \ \text{g})(6.28 \times 10^{-3} \ \text{s/m}^3)(3.33 \times 10^{-4} \ \text{m}^3/s)(4.38 \times 10^5 \ \text{rem/g})(0.001) \]
\[ = 7.4 \times 10^{-3} \ \text{rem}. \]

With safety-significant functions credited, mitigated onsite consequences for the event are 7.4 \times 10^{-3} \ \text{rem}.

3.5 COMPARISON TO GUIDELINES

Comparison of Unmitigated Doses. Event tree sequences indicate an unmitigated frequency for the liquid release DBA is in the anticipated category (i.e., an unmitigated frequency greater than 10^{-2} per year) (see Appendix A). The unmitigated sequence considered the processing of 200 MCOs per year and a leak from either the PWC pump, the piping, PWC valves, or the flexible hose connections. The unmitigated radiological offsite dose for this event is below offsite release limits, while the unmitigated onsite dose for an anticipated event is above onsite risk evaluation guidelines.
Table 3-2. Dose Calculation Summary for Liquid Release.

<table>
<thead>
<tr>
<th>Receptor location (distance, direction)</th>
<th>Duration (hours)</th>
<th>$\chi/Q'$ (s/m$^3$) (without slack)$^a$</th>
<th>Unmitigated dose$^b$ (rem (Sv))</th>
<th>Evaluation guideline$^c$/release limits (rem (Sv)), anticipated$^d$</th>
<th>Safety-significant mitigated dose (rem (Sv))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>12 (spray)</td>
<td>6.28 E-03</td>
<td>7.4 (0.074)</td>
<td>1.0 (1.0 E-02)</td>
<td>7.4 E-03 (7.4 E-05)</td>
</tr>
<tr>
<td></td>
<td>12 (pool)</td>
<td>6.28 E-03</td>
<td>1.5 E-03 (1.5 E-05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>7.4 (0.074)</td>
<td></td>
<td>7.4 E-03 (7.4 E-05)</td>
</tr>
<tr>
<td>Columbia River (650 m W)</td>
<td>12 (spray)</td>
<td>1.99 E-04</td>
<td>0.23 (2.3 E-03)</td>
<td>--</td>
<td>2.3 E-04 (2.3 E-06)</td>
</tr>
<tr>
<td></td>
<td>12 (pool)</td>
<td>1.99 E-04</td>
<td>4.6 E-05 (4.6 E-07)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>0.23 (2.3 E-03)</td>
<td>--</td>
<td>2.3 E-04 (2.3 E-06)</td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>12 (spray)</td>
<td>2.73 E-05</td>
<td>0.032 (3.2 E-04)</td>
<td>--</td>
<td>3.2 E-05 (3.2 E-07)</td>
</tr>
<tr>
<td></td>
<td>12 (pool)</td>
<td>2.73 E-05</td>
<td>6.4 E-06 (6.4 E-08)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>0.032 (3.2 E-04)</td>
<td>--</td>
<td>3.2 E-05 (3.2 E-07)</td>
</tr>
<tr>
<td>Hanford Site Boundary (10,090 m W)</td>
<td>24 (spray)</td>
<td>6.50 E-06</td>
<td>1.2 E-02 (1.2 E-04)</td>
<td>0.5</td>
<td>1.2 E-05 (1.2 E-07)</td>
</tr>
<tr>
<td></td>
<td>24 (pool)</td>
<td>6.50 E-06</td>
<td>4.7 E-06 (4.7 E-08)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>1.2 E-02 (1.2 E-04)</td>
<td>0.5</td>
<td>1.2 E-05 (1.2 E-07)</td>
</tr>
</tbody>
</table>


$^b$Fifty-year committed effective dose equivalent.

$^c$Evaluation guideline for onsite (100 m) receptor only.

$^d$Anticipated event frequency is $>10^{-5}$ to $\leq 10^{-5}$ per year.

Comparison of Mitigated Doses. The mitigated frequency of the event tree sequences that represent this DBA as an unfiltered release is $4 \times 10^{-6}$ per year, thus this mitigated DBA is extremely unlikely (see Appendix A). The mitigated sequence credited differential pressure monitoring in the PWC room, operator response to shut off the pump, and general exhaust HVAC system HEPA filter functionality. With safety-significant features credited, the mitigated onsite dose for an extremely unlikely event is well below onsite risk evaluation guidelines.
3.6 SUMMARY OF SAFETY-CLASS STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

Under normal operating conditions, no liquid releases to the process bay or process water tank room are expected. Under upset or accident conditions, safety-significant equipment is required in order to ensure dose consequences do not exceed onsite risk evaluation guidelines.

The checklist designators included in the accident bins, other than the accident selected as the DBA, represent additional accident sequences slightly different than the DBA. All of these binned accidents are bounded by the DBA because they have lesser or equivalent worst-case consequences and frequencies.

In addition to the DBA, an accident was identified in the L1 bin representing a spray leak from a random line failure in the PWC room (HNF-SD-SNF-HIE-004). The controls in the L1 bin provide mitigation of the liquid release (spray) by HEPA filtration. The filtration function is monitored, and if it is lost, compensatory measures are taken to make sure that a release cannot occur.

The safety-significant equipment designated to prevent or mitigate the dose consequences of the liquid release accident analyzed in this section is described below:

Safety-significant equipment for confinement and filtration:

- Process general supply/exhaust HVAC system (exhaust HEPA filter, exhaust duct work)

The process general supply/exhaust HVAC system mitigates a spray leak in the process water tank room by filtering it before discharging it outside the facility. The process general supply/exhaust HVAC system also provides confinement in conjunction with the facility's structure by maintaining a negative building pressure.

- Reference air system (reference air header, differential pressure alarms for process water tank room)

The reference air system monitors the negative pressure in the process water tank room by providing differential pressure indication and alarms to the control room for operator response. Such monitoring ensures that the air in the PWC room is being drawn into the process general supply/exhaust HVAC system so that the credited filtration function is being performed.

Assumptions made that require technical safety requirement (TSR) controls are listed below:

- Stop PWC pump operation on loss of differential pressure in the PWC room
If differential pressure is lost in the PWC room, PWC pump operation must be terminated. This control ensures that a spray leak does not occur at a time when filtration by the general exhaust system is not available.

The bounding liquid release accident (L.1) and the other accidents identified in the CVDF hazard analysis report (HNF-SD-SNF-HIE-004) that may potentially lead to a liquid release are listed in Table 3-3 along with corresponding checklist designators from the hazard analysis.

The accidents in the remaining bins require the following safety structures, systems, and components and TSRs, in addition to the ones identified for the DBA (L.1):

L.2 Spray release due to facility fire

The accident scenarios identified in the hazard analysis for the L.2 bin represent a spray leak in the PWC room caused by a fire (HNF-SD-SNF-HIE-004). The control in the L.2 bin precludes a liquid release (spray) by precluding the possibility of a significant fire. Although the worst-case liquid release consequences are less than the onsite risk evaluation guideline of 10 rem for the unmitigated fire (an unlikely event according to HNF-SD-SNF-HIE-004), the control is credited to preclude the possibility of multiple sprays.

Assumptions made that require protection by TSRs are listed below:

- Combustible loadings limited

  While an MCO is present in the facility, combustible loadings are limited as determined by the fire hazard analysis (SNF-4268). These limits ensure that any fire in the CVDF does not result in uncontrolled releases (e.g., fire-caused loss of process control).

L.3 Spray release due to line break caused by a seismic event

The accident scenario identified in the hazard analysis for the L.3 bin represents a spray leak in the PWC room following a seismic event (HNF-SD-SNF-HIE-004). For this event, which is unlikely in the unmitigated case, no controls are necessary because the event meets all onsite risk evaluation guidelines and offsite release limits. The unmitigated frequency for the seismic event is unlikely (HNF-SD-SNF-HIE-004), for which the onsite risk evaluation guideline is 10 rem. Because the worst-case liquid release is less than 10 rem, the guideline is satisfied without controls.

Defense in depth

- PWC system (seismic detector and pump interlock)

  The PWC system's seismic detector provides a signal to the PWC pump shutdown interlock to stop the process water pumps during a seismic event.
### Table 3-3: Summary of Safety Features Required to Mitigate or Prevent a Liquid Release

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS^7</th>
</tr>
</thead>
</table>
| L.1 Spray release due to piping failure (bounding accident; PW-H-06) | PW-H-06 PW-N-01 | Prevent/mitigate release outside the facility | Safety-significant equipment for confinement and filtration:  
* HVACD system* (exhaust HEPA filter, exhaust duct work)  
Safety-significant equipment to provide monitoring:  
* Reference air system (reference air header, differential pressure alarms for process water tank room) whenever the PWC pump is operating  
TSR:  
* Stop PWC pump operation on loss of differential pressure in PWC room  
Defense in depth:  
* Continuous air monitors in the room  
* PWC room floor design to contain spills and spray  
* Liquid level detection alarm on PWC skid | B |
| L.2 Spray release due to fire | PW-L-02 PW-L-08 PW-L-14 PW-L-16 | Prevent/mitigate a fire in the process water tank room | TSR:  
* Combustible loadings limited  
Defense in depth:  
* Fire protection system | B |
| L.3 Spray release due to a seismic event | OU-R-01b | Prevent/mitigate liquid spray release outside the facility | No safety SSCs required.  
Defense in depth:  
* PWC system (seismic detector and pump trip) | |


^7U.S. Nuclear Regulatory Commission important-to-safety classifications: Category A = critical to safe operation, Category B = major impact on safety, Category C = minor impact to safety.

No emergency power is needed to power the fans. In case of loss of power, the PWC process will be stopped.

HEPA = high-efficiency particulate air (filter)  
HVACD = process general supply/exhaust HVAC system  
ITS = important to safety  
NRC = U.S. Nuclear Regulatory Commission  
PWC = process water conditioning  
SSC = structure, system, and component  
TSR = technical safety requirement
3.7 REFERENCES


Figure 3-1. Logic Diagram for Spray Leak Release.
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4.0 CALCULATIONS FOR HYDROGEN EXPLOSIONS OUTSIDE THE MULTI-CANISTER OVERPACK

4.1 PURPOSE AND OBJECTIVES

There are occasions during the handling of a cask-multi-canister overpack (MCO) in the Cold Vacuum Drying Facility (CVDF) when significant concentrations of hydrogen could be found in piping and other components outside the MCO. Several cases are described in the sections that follow. The most significant accident in terms of probability and consequences is a hydrogen explosion that occurs during cask venting. This operational accident is initiated by events within the CVDF.

In all the postulated accident sequences, hydrogen is allowed to accumulate because of processing delays, equipment malfunctions, or catastrophic events. The general sequence of events leading to a hydrogen explosion is shown in Figure 4-1. To read the figure begin at the bottom and move upward. The sequence begins when enough hydrogen has accumulated in components outside the MCO. The three conditions necessary for this accumulation in a reasonable time frame are uranium metal, water, and elevated temperatures: the uranium and water are reactants, and the elevated temperature speeds the reaction. In the next step, the accumulated hydrogen escapes the MCO and mixes with air to form a combustible mixture of hydrogen and air. In the final step, this mixture is ignited. Since it takes very little energy to begin the hydrogen–oxygen combustion, it will be assumed that ignition sources are present where needed. The combustion could be initiated by static electricity within ventilation ducting, a small particle of uranium hydride, or static electricity in the spray nozzles in the water storage tanks.

Of the evaluated scenarios, the hydrogen explosion during cask venting is selected as the design basis accident (DBA) because it provides the bounding dose consequences and has the greatest likelihood.

4.2 HYDROGEN EXPLOSION DURING CASK VENTING

4.2.1 Scenario Development

As the MCO is transported to the CVDF, it warms up. During the 24-hour shipping window, enough hydrogen accumulates in the void space to raise the cask pressure to several atmospheres. When the cask is vented, before the cask lid is removed, the excess hydrogen is directed into the process bay local exhaust system several feet downstream of the process skid. A flow restriction in the hose reduces the hydrogen flow rate, keeping the hydrogen concentration in the ductwork below 1% provided the normal air flow exists in the exhaust system.
If the flow restriction were not in place (because of a fabrication omission that was not detected upon receipt at CVDF), the hydrogen could be released to the process bay local exhaust system in less than 1 second. The hydrogen concentration in the exhaust duct could be nearly stoichiometric with air. Since the hydrogen enters the local exhaust system near the location at which it exits the process bay, the explosion would occur outside the process bay. If this mixture were to burn near the process bay local exhaust high-efficiency particulate air (HEPA) filters, the pressure wave would dislodge activity from the filter and rupture the ductwork, leading to an environmental release.

A flammable hydrogen and air mixture also could occur near the HEPA filter if the process bay local exhaust flow rate were to decrease substantially at the time the cask was vented. This decreased flow rate could be caused by a power failure, damage to the exhaust fan, or inadvertent closing of a damper. When the flow resumes, the \( \text{H}_2 \) from one bay mixes with air from the other three bays to give nearly stoichiometric concentrations at the local exhaust filters. An explosion near the HEPA filter array leads to a significant environmental release of the radioactivity accumulated on the HEPA filters. The projected dose to an individual 100 m downwind exceeds the onsite dose evaluation guideline if the filter loading is above the limiting amount. The explosion is not expected to injure any personnel in the process bay because the vent line joins the local exhaust system some distance from the process skid.

4.2.2 Source Term Analysis

The venting operation is postulated to occur 24 hours after closure at K Basins, which means the full shipping window is being used. According to the hydrogen generation rates in Appendix B, Table B-1, a total of 8.29 gmoles of \( \text{H}_2 \) is generated in the cask-MCO between the time it is sealed at K Basins and vented at CVDF. A small fraction of this hydrogen may be dissolved in the water, but is ignored in the analysis.

The void space in the cask-MCO during shipment is estimated to be 41.2 L. This is based on a void layer 4.25 in. thick and 20 in. in diameter at the top of the MCO. In addition, a void space 0.6 in. thick between the outside of the MCO and the inside of the cask is treated as a circular cylindrical shell 16 in. tall with a diameter of 24 in. The space between the bottom of the cask lid and the top of the MCO is represented as a cylinder 1 in. tall with a diameter of 24 in. (The dimensions and volume of the void space are not critical to the conclusions below.) The void space is filled at the K Basins with helium at a pressure of 3 lb/in\(^2\) gauge (HNF-SD-SNF-OCD-001). Using the ideal gas law, it can be determined that the cask initially contains 2.06 gmoles of helium. The gas temperature is assumed to be 20 °C because the helium is added before the cask-MCO heats up during transport.

After a slow, hot trip to the CVDF, the gas temperature in the MCO is assumed to be 35 °C. This temperature is several degrees below the temperatures given in the safety analysis report for packaging (HNF-SD-TP-SARP-017) after arrival at CVDF. The gas temperature assumption has minimal effect on the calculated fraction of cask-MCO gas that leaves during venting. At this temperature, there are at most 0.09 gmoles of water vapor in the void space in
addition to the 2.06 gmoles of helium and 8.29 moles of hydrogen. The hydrogen concentration in the cask–MCO is \((8.29/10.44) = 79.4\%\). The pressure in the cask at the time it is vented is 6.41 atm, or 79.6 lb/in² gauge. This calculation is shown below.

\[ P = (n) (R) \frac{T}{V} \]
\[ P = (10.44 \text{ moles})(0.082058 \text{ L-atm/mole/K})(308.15 \text{ K})/(41.2 \text{ L}) \]
\[ P = 6.41 \text{ atm} \]

where

- \(P\) = pressure in the cask (6.41 atm)
- \(n\) = number of moles of gas (10.44 moles)
- \(R\) = ideal gas constant (0.082058 L-atm/mole/K)
- \(T\) = temperature of gas (308.15 K [35 °C])
- \(V\) = volume of gas (41.2 L).

The gas in the cask is vented to the local exhaust system at atmospheric pressure and at a temperature of 30 °C. The quantity of hydrogen vented is computed in two steps. The first step is to compute the quantity of the hydrogen–helium mixture that will remain inside the cask–MCO during venting. The second step is to subtract this from the total inside the cask–MCO. Finally, the fraction of the moles that are hydrogen is used to calculate quantity of hydrogen that is vented. The quantity of the hydrogen–helium mixture left inside the cask–MCO at atmospheric pressure and 35 °C after venting is computed using the ideal gas law.

\[ n = (P) \frac{(V)}{(R)} \frac{1}{(T)} \]
\[ n = (1 \text{ atm})(41.2 \text{ L})/(0.082058 \text{ L-atm/mole/K})/(308.15 \text{ K}) \]
\[ n = 1.63 \text{ gmoles} \]

where

- \(n\) = number of moles of gas (1.63 gmoles)
- \(P\) = pressure of gas inside the MCO after venting (1 atm)
- \(V\) = volume of gas left in the MCO after venting (11.2 L)
- \(R\) = ideal gas constant (0.082058 L-atm/mole/K)
- \(T\) = temperature of gas (308.15 K [35 °C]).
The quantity of the hydrogen–helium gas mixture that leaves the cask during venting is the total minus the residual:

\[ 10.44 \text{ gmoles} - 1.63 \text{ gmoles} = 8.81 \text{ gmoles}. \]

The final step is to calculate the quantity of hydrogen that leaves the cask and enters the process bay local exhaust heating, ventilation, and air conditioning (HVAC) and process vent system. Of the 10.44 moles of gas mixture, 8.29 moles (79.4%) are hydrogen. Thus the amount of hydrogen vented is calculated as shown.

\[ (8.81 \text{ gmoles vented}) (0.794 \text{ H}_2) = 7.00 \text{ gmoles H}_2. \]

The flow rates for both hydrogen and air entering the duct are needed to evaluate hydrogen concentrations in the process bay local exhaust HVAC and process vent ductwork. To estimate the rate at which the hydrogen in the cask enters the process bay local exhaust HVAC and process vent system, the vent connection on the lid of the cask has a diameter of 0.5 in. The bounding flow rate from the cask is given by the flow rate through a 0.5 inch diameter orifice. The first consideration is whether the flow velocity out the hole is at the speed of sound or not. Gases cannot exit a hole faster than the speed of sound. The minimum pressure in the cask needed to produce sonic flow is given by the following formula (Crowl and Louvar 1990).

\[ P_{\text{inside}} = P_{\text{outside}} \left( \frac{\gamma + 1}{2} \right)^\frac{\gamma}{\gamma - 1} \]

where

- \( P_{\text{inside}} \) = minimum pressure inside the cask that produces sonic flow (49.2 lb/in\(^2\) absolute)
- \( P_{\text{outside}} \) = pressure outside the cask (14.7 lb/in\(^2\) absolute)
- \( \gamma \) = ratio of the heat capacities at constant pressure and volume for the hydrogen–helium mixture (1.435).

Notice that the limiting pressure depends only on the pressure outside the cask and the value of \( \gamma \) for this gas. For monatomic gases like helium, \( \gamma \) is 1.67, while for diatomic gases like hydrogen and air, \( \gamma \) is 1.40. The weighted average \( \gamma \) was computed for the hydrogen–helium mixture using the heat capacity formula shown in Appendix B, Section B3.0. The minimum pressure in the cask needed for sonic flow has been calculated to be 49.2 lb/in\(^2\) absolute. The expected pressure in the cask (i.e., 6.41 atm, or 94.3 lb/in\(^2\) absolute) is enough to cause sonic flow.

The next consideration is the duration of the flow. The actual mass flow rate through the hole is computed using the following formula (Crowl and Louvar 1990).
\[
\dot{Q}_{\text{choke}} = C_{\text{dis}} A P_{\text{cask}} \left[ \frac{\gamma g M}{R T_{\text{cask}}} \left( \frac{2}{\gamma + 1} \right) \right]^{(\gamma + 1)/(\gamma - 1)}
\]

where

\begin{align*}
Q_{\text{choke}} &= \text{mass flow rate out the hole (lbm/s)} \\
C_{\text{dis}} &= \text{discharge coefficient (assumed to be 1.0)} \\
A &= \text{cross-sectional area of the 0.5-in.-diameter hole (0.1963 in\(^2\))} \\
g &= \text{gravity conversion factor (32.17 lbm-ft/s\(^2\)/lb)} \\
M &= \text{average molecular weight of the vented gas (2.546 lbm/lbmole)} \\
R &= \text{ideal gas constant (1,545.4 ft-lb/lbmole/°R)} \\
T_{\text{cask}} &= \text{absolute temperature of the gas in the cask (554.7 °R [35 °C])}.
\end{align*}

Note that the molecular weight is the mole-weighted average of the weights of the hydrogen, helium, and water vapor present in the cask. The sonic flow rate, calculated using the equation, is 22.3 gmole/s (0.125 lbm/s). Flow through a flexible line would be somewhat slower. Nevertheless, the majority of the hydrogen in the cask is vented to the local exhaust system in less than 1 second. To estimate gas concentrations in the duct, it is assumed that all 7.00 gmole of H\(_2\) enter the duct in 1 second.

Note that if the vent connection to the cask leaked at a high rate, the hydrogen would form a flammable cloud near the operator. Combustion of this cloud could lead to serious injury or even death of the operator.

The flow rate in the process bay local exhaust HVAC and process vent system is 1,300 ft\(^3\)/min, which is equivalent to 24.66 gmole/s. During the 1 second that the cask-MCO is vented, 8.81 gmoles are from the cask-MCO and the remainder (15.85 gmoles) are air. At this point the average hydrogen concentration in the ductwork is about 28% \([7.00 \text{ gmole}]/[24.66 \text{ gmole}]\). This is high enough that a detonation is possible.

At 30% hydrogen in air, the measured detonation cell size (NUREG/CR-2726) is about 0.6 in. It has been observed that a detonation will not propagate in pipes with diameter less than one-third of this cell size (NUREG/CR-2726). Since the local exhaust duct diameter is 10 in., this concentration of hydrogen can be expected to form a detonation shock wave if an ignition source is present. One second represents a flow length of about 40 ft of ductwork. Thus if the hydrogen entered the duct near the cask-MCO, the hydrogen detonation would adversely affect all of the...
mezzanine work space near the local exhaust ductwork. This could injure the workers who are performing the venting operation if the vent connection were near their work location in the process bay. However, the vent line joins the exhaust duct several feet from the process hood. Thus, it is unlikely that the operator connecting the vent line would be seriously injured from such an explosion.

If the hydrogen in the duct did not explode but mixed with air from other bays, it would still be above the lower explosive limit (4%) for hydrogen. If this hydrogen were ignited near the process bay local exhaust HVAC and process vent HEPA filters, the blast wave could damage the HEPA filters and their housing, allowing radioactive contamination on the filters to enter the process bay or the environment.

The amount of radioactivity released to the environment by a hydrogen explosion near the local exhaust HEPA filters is estimated using bounding assumptions. For example, it is assumed that the HEPA filter housing reads 115 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 housing to the side of the filters. Since the filters must be changed by hand, the exposure to personnel during changeout of filters would be excessive if a dose rate limit were not in place. From Appendix B, Table B-9, the local exhaust filters read 0.88 mR/h when they contain 1 g spent nuclear fuel (SNF). This includes a factor of 10 to account for possible loss of $^{137}$Cs due to radioactive decay and greater solubility in water. Thus to read 115 mR/h the filters must contain a total of 131 g SNF.

When the hydrogen, helium, and air mixture ignites in the process bay local exhaust filter, a portion of the activity on the prefilter and HEPA filter is dislodged and becomes airborne. This airborne radioactivity may be inhaled by persons downwind.

The fraction of the activity on a HEPA filter that may be released by an explosion impacting the filter media is discussed in Appendix B, Section B7.0. The bounding release fraction (0.01) is applied to the material at risk (MAR) (131 g SNF) to give a total release of 1.31 g SNF. The respirable fraction is 1.0, hence the respirable quantity released is 1.31 g SNF.

4.2.3 Consequence Analysis

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

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

\[ D = \text{effective dose equivalent based on inhalation exposure only (rem)} \]
\[ M = \text{respirable particulate quantity released into the air (grams)} \]
\[ \chi/Q' = \text{air transport factor (s/m')} \]
\[ BR = \text{average inhalation rate during the release (m}^3/\text{s)} \]
\[ UD = \text{committed effective dose equivalent per unit gram inhaled.} \]

The respirable particulate quantity is the 1.31 g fuel calculated in Section 4.2.2. The value for \( \chi/Q' \), the light activity breathing rate, and the dose per unit of respirable material inhaled are as specified in Section 1.4.

**Unmitigated Consequences.** The unmitigated dose to the onsite receptor is calculated as follows:

\[
D_{\text{on site}} = M \times \frac{\chi}{Q'} \times BR \times UD
\]
\[
= (1.31 \text{ g})(7.32 \times 10^{-2} \text{ s/m}^3)(3.33 \times 10^{-4} \text{ m}^3/\text{s})(4.38 \times 10^3 \text{ rem/g})
\]
\[
= 14 \text{ rem (0.14 Sv).}
\]

The dose consequences at the remaining receptor sites are calculated in the same manner and are shown in Table 4-1.

**Mitigated Consequences.** Mitigation of the cask venting accident involves (1) preventing flammable concentrations in the process bay local exhaust duct work, and (2) ensuring the HEPA filter loading is low enough that a flammable gas explosion in the filters would not release enough activity to the environment to exceed the onsite risk evaluation guideline.

A flammable mixture in the duct work may result from two situations: (1) rapid venting of the cask into normal process bay local exhaust air flow, or (2) venting of the cask into a duct with no air flow. The first situation is prevented by the presence of a flow-reducing orifice in the vent line and small diameter piping. The second situation is prevented by a valve that is interlocked to local exhaust flow in each bay. If local exhaust flow is lost during the venting operation, the flow of gas from the cask is halted. Both the design of the vent line and the reliability of the process bay local exhaust system ensure that there is only a low probability of a flammable mixture forming.
Table 4-1. Dose Calculation Summary for Hydrogen Explosion at the Process Bay Local Exhaust Heating, Ventilation, and Air Conditioning and Process Vent System Filters.

<table>
<thead>
<tr>
<th>Receptor location (distance, direction)</th>
<th>Duration (hours)</th>
<th>( \chi Q^* ) (s/m³) (without stack or plume meander)</th>
<th>Unmitigated dose(^a) (rem (Sv))</th>
<th>Risk guideline(^b) release limits (rem (Sv)) anticipated(^d)</th>
<th>Safety-significant mitigated dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>&lt;1</td>
<td>7.32 E-02</td>
<td>14 (0.14)</td>
<td>1.0 (10 E-02)</td>
<td>10 (0.10)</td>
</tr>
<tr>
<td>Columbia River (650 m W)</td>
<td>&lt;1</td>
<td>2.44 E-03</td>
<td>0.47 (4.7 E-03)</td>
<td>--</td>
<td>0.33 (0.0033)</td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>&lt;1</td>
<td>1.60 E-04</td>
<td>3.1 E-02 (3.1 E-04)</td>
<td>--</td>
<td>0.022 (2.2 E-04)</td>
</tr>
<tr>
<td>Hanford Site boundary (10,090 m W)</td>
<td>&lt;1</td>
<td>4.48 E-05</td>
<td>8.6 E-03 (8.6 E-05)</td>
<td>0.5 (5.0 E-03)</td>
<td>6.1 E-03 (6.1 E-05)</td>
</tr>
</tbody>
</table>


\(^b\)Fifty-year committed effective dose equivalent.

\(^c\)Evaluation guideline for onsite (100 m) receptor only.

\(^d\)Anticipated event frequency is >10⁻³ to ≤10⁻¹ per year.

The activity on the process bay local exhaust filters can be limited by limiting the dose rate near the filters. Routine surveys are performed by radiological control technicians to measure dose rates near the filters. The routine measurements ensure that the filter dose rates do not exceed administrative criteria chosen to limit exposure to workers who must change the filters. Normally, filters are changed if the differential pressure indicates reduced flow rates. Excessive dose rates can also trigger a filter change. Filter changes involve contact handling of the filters and may result in large personnel doses if the filter dose rates are high.

To ensure that onsite risk evaluation guidelines would not be exceeded from a hydrogen explosion involving the local exhaust HEPA filters, a limitation on the dose rate near the filter housing has been developed. A dose rate of 82 mR/h on contact at the filter housing corresponds to 94 g of SNF on the filters, assuming that the relative amounts of \(^{137}\)Cs and \(^{241}\)Am are 10 times lower on the filters than in the safety-basis SNF. The explosion would release 1% of the activity (bounding) on the filters, so that 0.94 g of SNF would be released as respirable particles. This release would result in an onsite dose of 10 rem (see Table 4-1), which is equal to the onsite risk evaluation guideline for unlikely events. The conservative nature of the dose calculation combined with the reduced frequency of the mitigated event ensures that this dose rate limit (82 mR/h) is adequate to protect onsite workers.

4.2.4 Comparison with Guidelines

**Comparison of Unmitigated Doses.** Event tree sequences indicate that the unmitigated frequency for this external hydrogen explosion is in the anticipated category (i.e., an unmitigated...
frequency greater than $10^2$ per year) (see Appendix A). The unmitigated sequence considered the processing of 200 MCOs per year and sufficient hydrogen accumulation in cask prior to venting. The unmitigated radiological offsite dose for this event is below offsite release limits, while the unmitigated onsite dose for an anticipated event is above onsite risk evaluation guidelines.

**Comparison of Mitigated Doses.** The mitigated frequency of the event tree sequences that represent this external hydrogen explosion and unfiltered release is $2 \times 10^{-6}$ per year, thus this mitigated event is extremely unlikely (see Appendix A). The mitigated sequence credited installation of flow restriction in the cask vent line, local exhaust running, and HEPA filter loading. With safety-significant features credited, the mitigated onsite dose for an extremely unlikely event is below onsite risk evaluation guidelines (i.e., 25 rem).

**4.2.5 Safety Equipment and Controls**

The safety equipment, controls, and defense-in-depth features designed to prevent and mitigate a hydrogen explosion during venting are found in Section 4.9.

**4.3 RUPTURE OF MULTI-CANISTER OVERPACK RUPTURE DISK BECAUSE OF SEALING AT K BASINS**

**4.3.1 Scenario Development**

When the MCO leaves the K Basins, the MCO port valves are open to allow any generated hydrogen to vent into the cask void space. If the MCO port valves were inadvertently closed at the K Basins because of an operator error, the pressure in the MCO could exceed the rupture disk design pressure of 150 lb/in² gauge. It is assumed that the MCO void space is smaller than normal because of a partial loss of the air bubble under the MCO shield plug at the time the shield plug is attached to the MCO. To maximize hydrogen generation, it is assumed that the shipment occurs on a hot day and that a generous portion of the allowed shipping window is used. The appropriate combination of time and temperature allows the rupture disk to give way after the cask lid is removed at CVDF, but before the MCO connections are made. (These connections would depressurize the MCO before the rupture disk gave way.) The local exhaust hood may or may not be in place at the time the rupture disk gives way.

The gases released during the rapid depressurization of the MCO are carried away by the process bay local exhaust system, vent to the process bay, or some combination of these two. The process bay local exhaust system would carry the hydrogen and air mixture to the HEPA filter bank. An explosion could occur at any location between the MCO and the exhaust stack. If this mixture were to burn near the HEPA filters, the pressure wave would dislodge radioactive particulate from the filter and rupture the ductwork. In the unmitigated case this leads to an environmental release. If the mixture were to burn in the local exhaust ductwork in the process bay, serious injury to workers could occur because the flammable gas enters the local exhaust
system near workers. No injury to personnel is expected, however, because the quantity of hydrogen released is no greater than that released in the cask venting accident. Personnel standing near the local exhaust ductwork at the time of the explosion could experience ear drum rupture, but the pressure wave and fragments from the ductwork would not be life-threatening.

4.3.2 Source Term Analysis

The volume of the MCO void space is normally assumed to be 21.9 L. However, this value could be higher or lower, depending on how the MCO shield plug is attached to the MCO while under water. If a partial loss of the air bubble under the shield plug occurs, then a smaller void volume may be assumed. Because the void volume must be less than 21 L for this accident to occur, a void volume of 20 L will be used.

The MCO is assumed to be inadvertently sealed at the K Basins, trapping air at atmospheric pressure and a temperature of 20 °C. This means 0.83 gmoles of air are locked in the MCO. After a slow, hot trip to the CVDF, the MCO contains 8.29 gmoles hydrogen and 0.04 gmoles water vapor (100% relative humidity) for a total of 9.16 gmoles. Hydrogen accounts for 90.15% of the gas. At the assumed gas temperature of 35 °C, the MCO pressure is 156 lb/in² gauge.

The same methods used in calculating discharges for the hydrogen explosion during venting (Section 4.2) are used here to estimate discharges. At 35 °C and atmospheric pressure, the MCO contains 0.87 gmoles of gas. Thus, the rupture of the MCO rupture disk discharges a total of 8.38 gmoles of gas, and \((0.896) (8.38 \text{ gmoles}) = 7.51 \text{ gmoles}\) of hydrogen are suddenly released. This is a small increase over the cask venting accident. Based on calculations for the cask venting accident, the MCO is assumed to discharge all the excess gas in 1 second.

If the local exhaust hood is not in place at the time the rupture disk breaks, the gas discharges into the process bay and explodes, potentially causing serious injury. If the exhaust hood is in place, the flammable gas mixture forms in the local exhaust duct. The gas could explode in the duct or move to the HEPA filter array and explode inside the filter housing. The air is diluted approximately four-to-one when it leaves the process bay, but the hydrogen concentration is still above the lower explosive limit.

The amount of radioactivity released to the environment by a hydrogen explosion near the local exhaust HEPA filters is estimated using bounding assumptions. For example, it is assumed that the HEPA filter housing reads 115 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 housing to the side of the filters. Since the filters must be changed by hand, the exposure to personnel during changeout of filters would be excessive if a dose rate limit were not in place. From Appendix B, Table B-9, the local exhaust filters read 0.88 mR/h when they contain 1 g SNF. This includes a factor of 10 to account for possible loss of \(^{137}\text{Cs}\) due to radioactive decay and greater solubility in water. Thus to read 115 mR/h, the filters must contain a total of 131 g SNF.
4.3.3 Consequence Analysis

The potential consequences of sealing the MCO at the K Basins include serious injury or death, as well as significant environmental releases of SNF. These consequences are divided into two cases: one with the local exhaust hood in place at the time the rupture disk gives way and one without the local exhaust hood in place.

A sudden release from the MCO before the local exhaust hood is in place would entrain a portion of the particulate attached to the underside of the MCO guard plate. The MAR is estimated in Appendix B, Section B6.0 to be 4.4 g SNF. Using the release fraction for pressurized releases through powders gives a total release of 8.9 mg SNF as respirable particles. Since the amount released is very much less than the release from HEPA filters, the bounding scenario is the HEPA filter blast (see Table 4-1).

If the hydrogen released into the process bay mixes with air to stoichiometric proportions, the hydrogen concentration is 29.4% while the oxygen concentration is 14.7%. The flammable cloud located above the top of the MCO is assumed to be roughly spherical, with radius of about 0.5 m. Lethal injury (by lung hemorrhage) is possible (probability is greater than 1%) within 1.1 m of the center of the puff. Eardrum ruptures occur out to 4 m from the center of the puff with greater than 1% probability (see Appendix B, Section B4.0). It is therefore possible for a worker to be seriously injured or killed if the worker is standing next to the top of MCO at the time the rupture disk gives way. This is a rather narrow time window because the interval between cask lid removal and installation of the vent hood is about 1.25 hours, and workers are not in close proximity to the MCO the entire time. In addition, discovery that the port valve for the filtered process exit port is already closed could lead to recovery actions that would lower the probability of serious injury.

If the release is captured by the vent hood, the hydrogen concentration in the process bay local exhaust system is about 30.5%. If this mixture were to explode in the process bay local exhaust duct, serious injury is unlikely because of the small diameter of the duct (10 in.) compared to the lethal diameter for the free-air explosion in the bay (86 in.). In effect, the energy of the blast is spread over a larger region, so very little is close enough to the worker to cause serious injury. The remaining possibility is that the flammable gas mixture ignites in the process bay local exhaust, and a portion of the radioactive particulate on the prefilter and HEPA filter is dislodged and becomes airborne. This accident produces the same dose consequences as the cask venting accident described in Section 4.2. The bounding release fraction and respirable fraction for HEPA filter blasts leads to an airborne release of 1.31 g SNF in period less than 1 hour. The doses calculated from this are shown in Table 4-1. Note that this release is much larger than the amount projected to be released in the pressurized discharge to the process bay. The mitigated and unmitigated doses for this release are calculated in Section 4.2.3.
4.3.4 Comparison with Guidelines

Comparison of Unmitigated Doses. Event tree sequences indicate that the unmitigated frequency for the external hydrogen explosion is in the anticipated category (i.e., an unmitigated frequency greater than $10^{-2}$ per year). The unmitigated sequence considered the processing of 200 MCOs per year and sufficient hydrogen accumulation in cask prior to venting. The unmitigated radiological offsite dose for this event is below offsite release limits, while the unmitigated onsite dose for an anticipated event is above onsite risk evaluation guidelines.

Comparison of Mitigated Doses. The mitigated frequency of the event tree sequences that represent this external hydrogen explosion and unfiltered release is $2 \times 10^{-6}$ per year, thus the mitigated event is extremely unlikely. The mitigated sequence credits local exhaust running and limited HEPA filter loading. With safety-significant features credited, the mitigated onsite dose for an extremely unlikely event is below onsite risk evaluation guidelines (i.e., 25 rem).

4.3.5 Safety Equipment and Controls

The safety equipment, controls, and defense-in-depth features designed to prevent and mitigate a hydrogen explosion during venting are found in Section 4.9.

4.4 PRESSURE RELIEF CAUSED BY DELAY DURING DRAINING

4.4.1 Scenario Development

No gas leaves the MCO while the MCO is being drained and water is being transferred to the process water conditioning (PWC) receiver tanks. Hydrogen accumulates and helium is added to help push the water from the MCO. If there were a delay of several hours during the drain operation, hydrogen production could be significant. The added hydrogen could pressurize the MCO to the point that the rupture disk breaks and releases MCO gas and particulate matter into the process bay. This accident has been analyzed in Chapter 7.0.

4.5 PROCESS WATER CONDITIONING RECEIVER TANK EXPLOSION

4.5.1 Scenario Development

No gas leaves the MCO while the MCO is being drained and water is being transferred to the PWC receiver tanks. Hydrogen accumulates inside the MCO and helium is added to help push the water from the MCO. If there were a delay of several hours during the draining operation, hydrogen production could be significant. Such a delay could result from conditions in the PWC receiver tank room that prohibit completion of the drain. For example, if the PWC...
receiver tank high-level indication failed and gave a false indication that the receiver tanks were full, interlocks would prevent further draining until the condition was corrected. Failure of an exhaust fan could create a delay during draining. A delay also could be caused if the operator failed to lower the water level in the PWC receiver tanks prior to draining. As the drain progressed, the high-level alarm would shut down the transfer into the tanks. Since these are all off-normal events, the process for correcting the condition could require days to complete. The additional hydrogen generated during the delay would pressurize the MCO and some of the piping.

When draining resumes, the hydrogen-rich gas mixture enters the PWC receiver tanks. If the PWC receiver tanks were not purged with helium before the drain operation began, the air in the tanks would form a flammable mixture with the hydrogen-helium mixture that is pushed over. An explosion in one or both of the receiver tanks would lead to the environmental release of a portion of any radioactive contamination in the tanks. Note that a delay of a few hours is not enough time for significant amounts of air to diffuse from the local exhaust system into the tanks. However, any air leaks into the PWC tanks would provide adequate air to form an explosive mixture because the local exhaust system would draw air into the tanks.

The MAR in the PWC receiver tanks is assumed to be 10% of the removable particulate inventory of one MCO. This estimate is based on experimental data collected at the CVDF prototype, in which cerium oxide powder was used to represent SNF particulate. Further discussion, including dose rate projections, is contained in Appendix B, Section B8.0. Using conservative release fractions from DOE-HDBK-3010-94, Airborne Release Fractions/Rates and Respirable Fractions/Rates for Nonreactor Nuclear Facilities, not enough radioactive material is released to exceed the onsite risk evaluation guide.

4.5.2 Source Term Analysis

It is assumed that the fuel temperature is 50 °C and the gas temperature is 50 °C during draining of the MCO. The air is assumed to be saturated with water, and the hydrogen generation rate shifts from the wet corrosion formula to the moist corrosion formula as the MCO drains. In addition, the hydride present on the fuel is assumed to react and generate additional hydrogen gas. It is assumed that the hydrogen concentration in the MCO void space at the start of draining is 90%. In effect, the initial purge of the MCO has been omitted. (A starting concentration of 10% also is used for comparison.) From Appendix B, Section B1.1, Table B-3, the hydrogen concentration is 10% near the end of draining. The MCO gas inventory is 2.4 gmoles hydrogen, 19.3 gmoles helium, and 2.3 gmoles water vapor.

During draining of the MCO, helium is added at a rate necessary to maintain a pressure of about 19.7 lb/in² absolute. The hydrogen gas generated in the MCO reduces somewhat the need for helium. At the time the MCO is nearly empty, the delay occurs during which most of the hydrogen is generated. A 2-hour delay before gas breakthrough increases the hydrogen inventory to 8.25 gmoles. The composition of the gas in the MCO before breakthrough will be assumed to
be 8.25 gmoles H₂, 13.44 gmoles helium, and 2.30 gmoles water vapor. In a 500-L MCO volume, the pressure is still 1.27 atm. At atmospheric pressure the gas volume is 635 L (22.5 ft³).

When the helium-hydrogen mixture in the MCO transfers to the PWC system, it is assumed to mix with air in the two receiver tanks. The model described in Appendix B, Section B9.3, is used to represent the concentrations in the receiver tanks. Relevant input parameters are listed in Table 4-2. It also is assumed that the first 10% of the volume from the MCO is not affected by the helium being added. These represent possible combinations of values, not necessarily bounding cases. The effect of different assumptions is discussed after the example.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MCO</th>
<th>First PWC tank</th>
<th>Second PWC tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank volume</td>
<td>17.7 ft³</td>
<td>20.1 ft³</td>
<td>23.4 ft³</td>
</tr>
<tr>
<td>Gas volume before draining MCO</td>
<td>1.0 ft³</td>
<td>19.0 ft³</td>
<td>19.0 ft³</td>
</tr>
<tr>
<td>Mixing factor before draining MCO</td>
<td>0.95</td>
<td>0.85</td>
<td>0.3</td>
</tr>
<tr>
<td>Gas volume after draining MCO</td>
<td>22.5 ft³</td>
<td>10.2 ft³</td>
<td>10.2 ft³</td>
</tr>
<tr>
<td>Mixing factor after draining MCO</td>
<td>0.95</td>
<td>0.9</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Notes: The mathematical model is developed in Appendix B, Section B9.3. Poor mixing in the second tank is represented with a mixing factor of 0.3, which means that 70% of the gas added to this tank does not mix with the gas already in the tank but leaves unmixed. The mixing factor increases after the MCO is finished draining because of the decrease in the gas volume over the liquid.

The MCO gas volume has been increased because the gas pressure is above atmospheric pressure at 1.27 atm (4 lb/in² gauge).

MCO = multi-canister overpack
PWC = process water condensate.

There is minimal hydrogen generation in the PWC receiver tanks because of the absence of unreacted uranium metal and the low radiation levels. The particulate carried over from the MCO is oxides of uranium rather than unreacted metal. The radiolysis process is slow inside the MCO and virtually nonexistent inside the PWC receiver tanks.

As the hydrogen in the MCO flows into the first receiver tank, the hydrogen and helium concentrations increase while the air concentration in the tank decreases. To maximize the potential effects of an explosion in the receiver tanks, the optimum mixture of hydrogen and oxygen (i.e., 2 moles of hydrogen for every mole of oxygen) were obtained by selecting when in
the transfer the explosion would occur. The hydrogen concentration exceeds the lower flammability limit after 2.0 \text{ ft}^3 have transferred from the MCO to the first receiver tank. The hydrogen and oxygen are nearly stoichiometric (15.4\% hydrogen and 7.6\% oxygen) after 10 \text{ ft}^3 have entered the first receiver tank. Assuming 100\% of the hydrogen reacts, the adiabatic combustion pressure is 72 \text{ lb/in}^2. The gas becomes non-flammable due to inadequate oxygen after 17 \text{ ft}^3 have transferred.

In the second receiver tank, the hydrogen concentration exceeds the lower flammability limit after about 13.0 \text{ ft}^3 have transferred. The hydrogen and oxygen produce maximum combustion pressures after 44 \text{ ft}^3 have transferred. At this point the hydrogen concentration is 10.1\% and the oxygen concentration is 5.3\%. Assuming 100\% of the hydrogen reacts, the adiabatic combustion pressure is 56 \text{ lb/in}^2. After 52 \text{ ft}^3 have transferred, the gas in the second receiver tank becomes nonflammable because of inadequate oxygen.

The worst-case situation occurs when between 13 \text{ ft}^3 and 17 \text{ ft}^3 have been transferred to the tanks, because both tanks are then flammable. The flammable mixtures in the receiver tanks are assumed to explode. The combustion pressures are assumed to damage the upper portion of the tank. Particulate matter is resuspended and escapes into the air in the tank room. Normally, the general exhaust system would capture this and no significant release would reach the environment. In the unmitigated case, the general exhaust system has failed, and the unfiltered, contaminated air is released into the environment at ground level.

The MAR for environmental release from the PWC receiver tanks is the contaminated water assumed to be present in the tanks at the time of the explosion. The bounding case water concentration is based on transfer of 10\% the particulate generated in the MCO since the fuel was washed at the K Basins (see Appendix B, Section B8.0). Particulate accumulation in the tanks is considered minimal because of the purification of the PWC water. The mass of \text{UO}_2 in the MCO is assumed to be 1.5 kg, which corresponds to 1.32 kg SNF metal.

Estimates of the activity released to the air during a hydrogen explosion are based on release fractions for a similar situation taken from DOE-HDBK-3010-94. The mechanism for resuspending activity in the water is the immediate effect of the explosion on the liquid surface. Resuspended (wet) particulate is assumed to be vented from the tank by a break in the connection between the tank and the pipes entering the top of the tank.

The release fraction selected to represent aerosolization of a portion of the water in the tank is the release fraction for sudden pressurized liquid releases in which pressures are below 50 \text{ lb/in}^2. The recommended value for the airborne release fraction (ARF) is $5 \times 10^{-5}$, and the recommended value for the respirable fraction is 0.8. The volume of water released is the product of the ARF, the RF, and the total volume of water in the PWC receiver tanks, which is taken to be about 600 L. Higher or lower values will not change the conclusion. The value selected is a reasonable amount for the two tanks.
The actual amount of spent fuel released into the air is the product of the volume of water released and the bounding concentration of fuel particulate in the water. The maximum amount of fuel particulate that could be present in the receiver tanks after draining an MCO is 10% of the bounding loose particulate inventory of the MCO, 1,500 g UO₂ (see Appendix B, Section B8.0). The equivalent amount of spent fuel is 1,320 g. The bounding concentration of fuel particulate in the receiver tank water is the bounding particulate inventory divided by the total volume of water in the PWC receiver tanks. The bounding mass of uranium released to the air is computed as shown below.

\[
\text{Mass}_{\text{Airborne}} = \frac{(0.024 \text{ L released}) \times 1,320 \text{ g U}}{650 \text{ L water}} = 0.049 \text{ g U}.
\]

This accident requires both a failure to purge the PWC receiver tanks with helium (source of oxygen) and an interruption of the drain just prior to breakthrough (source of hydrogen). If the delay lasts long enough, the helium purge is of little effect because diffusion will admit air from the ventilation system and allow helium to escape the receiver tanks.

With the hydrogen concentration in the MCO at 10% at the start of draining, the MCO will contain 7.7 gmoles hydrogen, 14.0 gmoles helium, and 2.3 gmoles water vapor. The difference between this case and the 90% case is small. The predrain purge of the MCO has little effect on the eventual hydrogen concentrations after a 2-hour delay. After the MCO gas transfers to the PWC receiver tanks, the flammable concentrations are similar to the 90% case. Adiabatic combustion pressures are nearly the same, therefore the effect on the PWC receiver tanks is nearly the same. Omission of the predrain purge is not necessary to cause this accident.

Increasing the amount of water in the PWC tanks at the start of draining has the effect of reducing the amount of air in the tanks. This means less hydrogen must enter the tanks to become flammable, and the peak hydrogen concentrations will be greater. This reduces the likelihood that the hydrogen in both tanks could burn at the same time. The first tank becomes flammable after very little gas has transferred. However, it also becomes nonflammable sooner. The range of overlap in which both tanks are flammable is greatly reduced. The adiabatic combustion pressure in the receiver tanks is somewhat increased because of higher hydrogen concentrations. Overall, the accident conditions are not affected by the volume of water in the PWC receiver tanks at the start of draining.

The mixing factor for the first PWC receiver tank is likely greater than 0.8 under all conditions because of the mixing created by the water spray in the tank. With mixing factors greater than 0.8, the flammable conditions in the first receiver tank are little different from those described above.
The mixing factor for the second PWC receiver tank is likely less than 0.5 because of a lack of air movement in the tank. Gases enter at the top and are removed from the top of the tank. With a smaller mixing factor for the second tank, the likelihood that both tanks could burn at the same time decreases. The second tank becomes flammable after more gas has left the MCO, so the overlap is much smaller. Overall, the mixing factors for the PWC receiver tanks do not affect the possibility of flammable concentrations in the PWC receiver tanks.

4.5.3 Consequence Analysis

**Unmitigated Consequences.** The following dose calculation equation is used to calculate the dose to the onsite receptor. The release duration is less than 1 hour.

\[
D_{\text{onsite}} = M \times \frac{K}{Q'} \times BR \times UD
\]

\[
= (0.049 \text{ g})(7.32 \times 10^{-2} \text{ s/m}^3)(3.33 \times 10^{-4} \text{ m}^3/s)(4.38 \times 10^5 \text{ rem/g})
\]

\[
= 0.52 \text{ rem } (5.2 \times 10^{-3} \text{ Sv}).
\]

The unmitigated dose consequences at the remaining receptor sites are calculated in the same manner and are shown in Table 4-3. Because the projected doses do not exceed the guidelines for anticipated releases, there are no safety-significant consequences for this event.

**Mitigated Consequences.** Because the unmitigated consequences do not exceed guidelines, there is no need to analyze the mitigated event.

4.5.4 Comparison with Guidelines

**Unmitigated Doses.** The unmitigated offsite dose for this event is below offsite release limits, and the unmitigated onsite dose is below onsite evaluation guidelines.

4.5.5 Safety Equipment and Controls

Because the unmitigated doses for this event do not exceed guidelines, no additional controls are needed.
Table 4-3. Comparison of Doses with Risk Guidelines for Receptors Downwind from a Bounding Hydrogen Explosion at the Process Water Conditioning Receiver Tank.

<table>
<thead>
<tr>
<th>Receptor location (distance and direction)</th>
<th>Duration (hours)</th>
<th>$\chi/Q^a$ (a/m$^3$) (without stack)</th>
<th>Unmitigated dose$^b$ (rem) (Sv)</th>
<th>Evaluation guideline$^c$/release limits (rem) (Sv), anticipated$^d$</th>
<th>Safety-significant mitigated dose (Sv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>&lt;1</td>
<td>7.32 E-02</td>
<td>0.52</td>
<td>1.0 E+00</td>
<td>Not calculated$^e$</td>
</tr>
<tr>
<td>Columbia River (650 m NW)</td>
<td>&lt;1</td>
<td>2.44 E-03</td>
<td>0.017</td>
<td>--</td>
<td>Not calculated$^e$</td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>&lt;1</td>
<td>1.60 E-04</td>
<td>1.1 E-03</td>
<td>--</td>
<td>Not calculated$^e$</td>
</tr>
<tr>
<td>Hanford Site boundary (10,090 m W)</td>
<td>&lt;1</td>
<td>4.48 E-05</td>
<td>3.2 E-04</td>
<td>5.0 E-01</td>
<td>Not calculated$^e$</td>
</tr>
</tbody>
</table>


$^a$Fifty-year committed effective dose equivalent from inhalation.

$^b$Evaluation guideline for onsite (100 m) receptor only.

$^c$Anticipated event frequency is $>10^{-2}$ to $<10^{-1}$ per year.

$^d$Since the unmitigated accident dose exceeds guidelines/limits, no mitigated doses were calculated.

4.6 HYDROGEN EXPLOSION AFTER INITIATION OF SAFETY-CLASS HELIUM PURGE

4.6.1 Scenario Development

Initiation of a safety-class helium (SCHel) purge of the MCO means that helium enters the MCO through the long axial process tube and exits through the MCO HEPA filter to the local exhaust system. In this accident it is assumed that hydrogen has accumulated in the MCO during the draining operation as a result of a 2-hour delay. Then a power loss occurs, greatly reducing the flow rate in the process bay local exhaust system. Initiation of the SCHel purge causes the accumulated hydrogen to enter the local exhaust system, mix with air, and form a flammable mixture.

Optimally, the local exhaust flow would resume after the hydrogen was transferred into the local exhaust system and be carried to the filters. Combustion of the mixture in the local exhaust filters could lead to the release of enough activity to exceed the onsite risk evaluation guide, making the accident safety-significant.
4.6.2 Source Term Analysis

After the delay, the MCO contains 9.3 gmoles $\text{H}_2$, 19.3 gmoles helium, and 2.3 gmoles water vapor. This is sufficient to produce the particulate release from the local exhaust filter unit. It is assumed that the HEPA filter housing reads 115 mR/h at the time of the explosion. HEPA filters are normally changed when the differential pressure becomes too large, indicating that the filter becoming plugged. An additional administrative criterion is the dose rate on the housing to the side of the filters. Because the filters must be changed by hand, the exposure to personnel during changeout of the filters would be excessive if a dose rate limit were not in place. From Appendix B, Table B-9, the local exhaust filters read 0.88 mR/h when loaded with 1 g SNF. This includes a factor of 10 to account for possible loss of $^{137}\text{Cs}$ due to radioactive decay and greater solubility in water. Thus to read 115 mR/h, the filters must be loaded with a total of 131 g SNF. When the hydrogen, helium, and air mixture ignites in the process bay local exhaust, only a portion of the radioactive particulate on the prefilter and HEPA filter is dislodged and becomes airborne. As discussed in Appendix B, Section B7.0, using the bounding release fraction and respirable fraction for HEPA filter blasts leads to an airborne release of 1.31 g SNF in a period of less than 1 hour.

4.6.3 Consequence Analysis

Unmitigated Consequences. Doses for this unmitigated accident are the same as those shown for the cask venting accident in Table 4-1.

Mitigated Consequences. This accident requires safety-significant controls to prevent it.

4.6.4 Comparison with Guidelines

Comparison of Unmitigated Doses. Event tree sequences indicate that the unmitigated frequency for this external hydrogen explosion event is in the anticipated category (i.e., an unmitigated frequency greater than $10^{-2}$ per year). The unmitigated sequence considered the processing of 200 MCOs per year and sufficient hydrogen accumulation in cask prior to venting. The unmitigated radiological offsite dose for this event is below offsite release limits, while the unmitigated onsite dose for an anticipated event is above onsite risk evaluation guidelines.

Comparison of Mitigated Doses. The mitigated frequency of the event tree sequences that represent this external hydrogen explosion and unfiltered release is less than $10^{-4}$ per year, thus this mitigated event is prevented. The mitigated sequence credits local exhaust running and limited HEPA filter loading.
4.6.5 Safety Equipment and Controls

The safety equipment, controls, and defense-in-depth features designed to prevent and mitigate a hydrogen explosion after initiation of the SCHe purge are found in Section 4.9.

4.7 HYDROGEN EXPLOSION DOWNSTREAM OF VACUUM PUMP DURING VACUUM DRYING

4.7.1 Scenario Development

While the MCO is being vacuum dried, hydrogen is being generated by reactions between uranium and residual water. Since helium is being added, a mixture of hydrogen and helium passes through the vacuum pump to the process bay local exhaust system. The pipe between the vacuum pump and the local exhaust system initially contains air. In preparation for vacuum pumping progresses this is replaced with helium as well as small concentrations of hydrogen. The check valve located near the local exhaust duct minimizes the movement of air from the duct into the discharge pipe.

During normal drying operations, there are periods during which the helium purge is valved out, but the vacuum pump continues to run. Examples of this are the "no purge vacuum check" and the "proof test." During these periods, the hydrogen concentration may increase significantly, leading to flammable mixtures of hydrogen, helium and air in the pipe between the check valve and the Local Exhaust system. If the check valve were to fail open, air from the ventilation duct and hydrogen from the vacuum pump could form flammable mixtures anywhere in the pipe.

Combustion of the flammable mixture is not expected to harm the pipe due to the small volume of flammable gas. Thus there are no environmental releases or injury to personnel as a result of this deflagration. The accident is not safety-significant.

If the process bay local exhaust HVAC and process vent system were disabled, hydrogen could accumulate in this system leading to an explosion that could destroy the ductwork and HEPA filters. The consequences of this accident are similar to those of the first accident, an explosion in the process bay local exhaust HVAC and process vent system during MCO venting.

4.7.2 Source Term Analysis

During drying of the MCO, it is assumed that the fuel temperature is 60 °C, and the average gas temperature is 50 °C. The relative humidity in the MCO is assumed to be 10%. From the discussion in Appendix B, Section B1.1, the hydrogen generation rate is 0.65 gmole H₂ per hour from ordinary corrosion of uranium and 1.52 gmole H₂ per hour from hydride reactions. The total is 2.17 gmole H₂ per hour. The amount of air at 25 °C in the process vent duct is 53.6 gmoles. This is based on a 10-in. diameter duct 10 ft long and a 14-in. by 14-in. section 30 ft
long. Assuming the air flow is interrupted, the rate at which the hydrogen concentration increases is approximately

\[
\frac{2.17 \text{ gmole/h}}{53.6 \text{ gmole}} = 4.0\% \text{ per hour.}
\]

Therefore, the time needed to reach the lower explosive limit (4% hydrogen) is 60 minutes, as shown below.

\[
\frac{4.0\%}{6.9\% \text{ per hour}} = 0.580 \text{ hour} = 35 \text{ minutes.}
\]

The resulting explosion in the process bay local exhaust HVAC and process vent system ductwork could either injure personnel in the process bay or release radioactivity on the HEPA filters to the environment. Since the process bay is not normally occupied during drying operations, the potential for personnel injury is very low. If the hydrogen in the duct were ignited near the local exhaust HEPA filters, the blast wave could damage the HEPA filters and their housing, allowing radioactive contamination on the filters to become airborne and enter the process bay or the environment.

4.7.3 Consequence Analysis

**Unmitigated Consequences.** Doses for this unmitigated accident are the same as those shown for the cask venting accident in Table 4-1.

**Mitigated Consequences.** This accident requires safety-significant controls to prevent it.

4.7.4 Comparison with Guidelines

**Comparison of Unmitigated Doses.** Event tree sequences indicate that the unmitigated frequency for this external hydrogen explosion is in the anticipated category (i.e., an unmitigated frequency greater than \(10^{-2}\) per year). The unmitigated sequence considered the processing of 200 MCOs per year and sufficient hydrogen accumulation in cask prior to venting. The unmitigated radiological offsite dose for this event is below offsite release limits, while the unmitigated onsite dose for an anticipated event is above onsite risk evaluation guidelines.

**Comparison of Mitigated Doses.** The mitigated frequency of the event tree sequences that represent this external hydrogen explosion and unfiltered release is less than \(10^{-6}\) per year, thus this mitigated event is prevented. The mitigated sequence credits the local exhaust running, and limited HEPA filter loading.
4.7.5 Safety Equipment and Controls

The safety equipment, controls, and defense-in-depth features designed to prevent and mitigate a hydrogen explosion during venting are found in Section 4.9.

4.8 FAILURE TO CLOSE MULTI-CANISTER OVERPACK PORT VALVE

4.8.1 Scenario Development

After the MCO is considered to be dry, it is pressurized with helium, the port valves are closed, the process bay local exhaust hood is removed, and the MCO port covers are bolted in place. The MCO is ready to be sealed in the shipping cask and transported to the Canister Storage Building (CSB).

If one or both of the port valves were not closed, the MCO would immediately depressurize when the local exhaust hood is removed. It is assumed that the operators performing this work do not notice, and continue with the MCO and cask closure procedure. During the period prior to sampling at CSB, significant hydrogen may accumulate. The action of removing the port covers at the CSB sampling/weld station would lead to a sudden flammable gas release into the hood. Ignition of the hydrogen-air mixture in the sampling/weld hood could prove fatal to the CSB operator standing in front of the hood removing the cover port.

4.8.2 Source Term Analysis

This accident has been analyzed for the CSB (SNF-3328, Chapter 5.0). Failure to close the port valves at CVDF is one of the initiating events.

4.8.3 Consequence Analysis

The consequences are discussed in SNF-3328, Canister Storage Building Design Basis Accident Analysis Documentation. The conclusion is that this accident requires safety-significant controls to prevent it.

4.8.4 Comparison with Guidelines

Unmitigated Doses. The unmitigated offsite dose for this event is below offsite release limits, while the unmitigated onsite dose is above onsite evaluation guidelines (SNF-3328).

Mitigated Doses. With safety-significant features credited, the accident is prevented, and onsite evaluation guidelines are satisfied (SNF-3328).
4.8.5 Safety Equipment and Controls

The safety equipment, controls, and defense-in-depth features designed to prevent and mitigate a hydrogen explosion at the CSB are found in Section 4.9.

4.9 SUMMARY OF SAFETY-CLASS STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

Under normal operating conditions, there is no external accumulation of flammable concentrations of hydrogen. Under upset or accident conditions, safety-significant equipment is required in order to ensure flammable concentrations of hydrogen external to the MCO and CVDF systems are precluded.

The checklist designators included in the accident bins, other than the accident selected as the DBA, represent additional accident sequences slightly different than the DBA. All of these binned accidents are bounded by the DBA because they have lesser or equivalent worst-case consequences and frequencies.

In addition to the DBA, an accident was identified in the E1 bin representing an external hydrogen explosion caused by elevated hydrogen generations from misloaded fuel in an MCO or a shipping delay to CVDF (HNF-SD-SNF-HIE-004). The controls in the E1 bin provide both prevention and mitigation of an external explosion event, as well as protection of initial condition assumptions made in the analysis. The accident is prevented by directing the hydrogen from the cask to the local exhaust where it is diluted to less than flammable concentrations, and by terminating the vent operation if the dilution airflow is lost in the local exhaust duct. These preventative controls make the accident unlikely (see Appendix A), for which the onsite risk evaluation guideline is 10 rem. The dose consequence of the worst-case external hydrogen explosion is greater than 10 rem, so credit is taken for a limit on the MAR (on the HEPA filters) to provide mitigation of the consequences. With this additional control, the frequency of the accident is reduced to extremely unlikely, and the dose consequence falls within risk evaluation guidelines. One additional control is applied to protect initial cask–MCO conditions that were assumed in the analysis.

The safety-significant equipment is described below.

Safety-significant equipment for dilution:

- Cask venting orifice and jumper

The process bay local exhaust HVAC and process vent system provides a cask venting connection with a flow restricting orifice to keep concentrations of hydrogen below the flammable limit with at least 1,000 ft³/min of flow in the duct work.
The cask vent jumper tool also directs hydrogen from the cask to the local exhaust to provide for worker safety.

- **MCO vent jumper tool**

  The MCO venting tool provides a means to vent an MCO prior to process connections being made (after the cask lid has been removed). This vent tool controls MCO pressures in case of process delays by venting to the local exhaust through the same vent line (including orifice restriction). The vent tool also provides for worker safety by directing the hydrogen from the cask to the local exhaust.

- **Cask venting interlock with process bay local exhaust HVAC and process vent system**

  A shutoff valve interlocked to the local exhaust low-flow alarm is provided because flammable concentrations would be generated almost instantaneously if the cask were vented into a stagnant local exhaust duct.

- **Process bay local exhaust HVAC and process vent system (exhaust fans and plenums, duct work, HEPA filters, and flow switch)**

  The process bay local exhaust HVAC and process vent system mitigates a gaseous release into the process bay by sweeping it through HEPA filters before it is discharged outside the facility. Low flow alarms are set at 1,150 ft³/min to provide an actual flow of greater than 1,000 ft³/min. The flow switch is interlocked with the shutoff valve.

Safety-class equipment (performing a safety-significant function) for confinement:

- **Cask-MCO**

  The cask-MCO is a major part of the pressure boundary for confinement of radioactive materials during processing.

Assumptions made that require protection by technical safety requirements (TSRs) are listed below.

- **Receipt transportation window**

  The transportation cask must be vented to the process bay local exhaust HVAC and process vent system HEPA filters within a specified time from being sealed at the K Basins.
Limitation on the radionuclide inventory on the process bay local exhaust HVAC and process vent system HEPA filters

The HEPA filter and prefilter housing contact dose radiation levels must be maintained equal to or less than 70 mR/h consistent with the source term used in the accident analysis.

The bounding MCO external hydrogen explosion accident (E.1) and the other accidents identified in the CVDF hazard analysis report (HNF-SD-SNF-HIE-004) that may potentially lead to a flammable hydrogen mixture outside the MCO are listed in Table 4-4, along with corresponding checklist designators from the hazard analysis report, safety functions, and structures, systems, and components (SSCs).

The accidents in the remaining bins require the following safety SSCs and TSRs, in addition to the ones identified for the DBA (E.1):

E.2 Hydrogen explosion outside an MCO due to instrumentation failure

The accident scenarios identified in the hazard analysis for the E.2 bin represent external hydrogen explosions caused by elevated bay temperatures (and subsequent potential for elevated fuel temperatures and reaction rates) and actuation of the SCHF system concurrent with a no-flow condition in the local exhaust (HNF-SD-SNF-HIE-004). The controls in the E2 bin prevent the external hydrogen explosion by providing dilution in the local exhaust system and mitigation by limiting the MAR on the local exhaust HEPA filters. In addition, the general exhaust system and SSCs that support process bay confinement are credited because the local exhaust cannot be guaranteed to provide confinement in all cases following the external explosion.

Process bay local exhaust HVAC and process vent system process hood isolation damper and instrument air supply

Isolation dampers in the process bay local exhaust HVAC and process vent system process hood fail closed. If power is lost, dampers will open with electrical power from the standby power system and instrument air supplied by the local dedicated tank. The hood isolation damper and instrument air supply operate in conjunction with the standby power system to facilitate HVAC operating while on standby power.

Process general supply/exhaust HVAC system (exhaust HEPA filter, exhaust duct work, isolation damper)

The process general supply/exhaust HVAC system mitigates a release into the process bay by sweeping it through HEPA filters before discharging it outside the facility. The process general supply/exhaust HVAC system also provides confinement in conjunction with the facility's structure by maintaining a negative building pressure. Fail-closed exhaust dampers from the process bays isolate other flow paths and ensure that differential pressure is maintained.
Reference air system (reference air header, differential pressure alarms)

The reference air system monitors the negative pressure in the process bays and process water tank room by providing differential pressure indication and alarms to the control room for operator response.

Standby electrical power (diesel generator and process bay local exhaust, HVAC and process vent system restart circuit)

The standby power system provides connections to restart the local exhaust fans and supporting equipment. Operation of the local exhaust on standby power will maintain building differential pressure sufficient for confinement during facility power outages.

Process bay recirculation HVAC system isolation dampers (outside inlets)

The process bay recirculation HVAC system provides fail-closed outside air inlet dampers so the local exhaust on standby power can maintain process bay differential pressure.

E.3 Hydrogen explosion outside an MCO due to excessive water in MCO

The accident scenarios identified in the hazard analysis for the E.3 bin represent external hydrogen explosions caused by excessive water remaining in an MCO (instrumentation failure or operator error) (HNF-SD-SNF-HIE-004). The controls in the E3 bin prevent the external hydrogen explosion by providing dilution in the local exhaust system and by preventing excessive free water in an MCO at an unexpected time. Mitigation is provided by a limitation on the MAR on the local exhaust HEPA filters. In addition, the general exhaust system and SSCs that support process bay confinement are credited because the local exhaust cannot be guaranteed to provide confinement in all cases following the external explosion.

All HVAC system equipment identified for accident E.2

Assumptions made that require protection by TSRs are listed below.

Procedure to verify the results of the pressure rebound tests before continuing process steps

An initial pressure rebound test surveillance (pressure rise test) must be met before entry into the proof-of-dryness demonstration is allowed. Similarly, a proof-of-dryness demonstration surveillance must be met before the final pressure rebound test steps can begin. Finally, a final pressure rebound test must be met before shipment preparation steps can begin.
E.4 Hydrogen explosion outside an MCO due to process upset of key parameters

The accident scenarios identified in the hazard analysis for the E.4 bin represent external hydrogen explosions caused by elevated hydrogen generation rates (high temperature tempered water, water ingress into MCO, air ingress into MCO, loss of annulus water), venting of MCO before breakthrough during draining, and venting cask-MCO while preparing for shipping (HNF-SD-SNF-HIE-004). The controls in the E4 bin prevent the external hydrogen explosion by providing dilution in the local exhaust system and mitigation by limiting the MAR on the local exhaust HEPA filters. In addition, the general exhaust system and SSCs that support process bay confinement are credited because the local exhaust cannot be guaranteed to provide confinement in all cases following the external explosion.

- All HVAC system equipment identified for accident E.2

E.5 Hydrogen explosion outside an MCO due to loss of support utilities

The accident scenarios identified in the hazard analysis for the E.5 bin represent external hydrogen explosions caused by a loss of a support system (e.g., instrument air) because of accidents in adjacent bays, crane load drops, and accidents in the spare bay. This bin also includes loss of power events caused by external forces (e.g., vehicle accident), flooding, and lightning strike (HNF-SD-SNF-HIE-004). The controls in the E5 bin prevent an external hydrogen explosion by providing dilution in the local exhaust system and by controlling specific initiators that result in a loss of support utilities (e.g., crane load drop and facility loss of power). In addition, the general exhaust system and SSCs that support process bay confinement are credited because the local exhaust cannot be guaranteed to provide confinement in all cases following the external explosion.

- All HVAC system equipment identified for accident E.2

- SCHe system (vent delay)

The pressure-regulated discharge flow path from the MCO to the local exhaust system ensures a minimum 10-minute delay from SCHe initiation until discharge flow initiation to the local exhaust to allow standby power restart of the local exhaust.

- Lines and valves to isolate and purge the MCO

Lines and valves for isolating the MCO include the isolation valves (and filters on air supply to valve actuators) in the VFS, general-service helium system, PWC system, and SCHe system. Upon demand, all the valves close to isolate the MCO, except the SCHe system valves, which open to allow helium to the MCO. These SSCs ensure the proper functioning of the SCHe system.
The 30 lb/in² gauge check valve on the 30 lb/in² gauge pressure relief line (backup pressure management to the SCHe system) opens, vents a small amount of hydrogen, and then re-seats to limit hydrogen flows into the local exhaust duct. The valve prevents a blowdown of the MCO from 30 lb/in² gauge to atmospheric pressure and the corresponding release of a large volume of hydrogen.

Assumptions made that require protection by TSRs are listed below.

- Administrative procedure for restricting crane movement during MCO processing except as part of an approved recovery plan

Bridge crane movement is not allowed from the time that draining operations begin until the proof-of-dryness demonstration is complete and the MCO isolation valves are closed unless as part of an approved recovery plan. This restriction ensures that key process lines cannot be sheared by crane movement, which could cause failure of features that provide hydrogen control.

E.6 Hydrogen explosion outside an MCO due to facility fire

The accident scenarios identified in the hazard analysis for the E.6 bin represent external hydrogen explosions caused by an internal or external facility fire, including a fire in the transfer corridor caused by maintenance activities (HNF-SD-SNF-HIE-004). The controls in the E.6 bin prevent an external hydrogen explosion by ensuring that control of the MCO and process is not lost in the event of a fire in the process bay. The control on combustibles precludes damage to safety-related SSCs whose malfunction could result in the loss of control of the MCO or process. The control on combustibles necessitates protection of the initial bay temperature, which is an assumption made in the fire hazards analysis.

Safety-class equipment (performing a safety-significant function) to prevent an external hydrogen explosion:

- Safety-class instrumentation and control (SCIC) process bay high temperature trip

The SCIC process bay high temperature trip acts to protect an initial condition assumption in the fire hazards analysis.

Assumptions made that require protection by TSRs are listed below.

- Combustible loadings limited

While an MCO is present in the facility, combustible loadings are limited as determined by the fire hazard analysis (SNF-4268). These limits ensure that any fire
in the CVDF does not result in uncontrolled releases (e.g., fire-caused loss of process control).

- Restore bay temperature following a process bay high temperature trip

On high bay temperature trip alarm, operations must return the process bay temperature to within acceptable limits

E.7 Hydrogen explosion outside an MCO due to contamination of helium supply

The accident scenarios identified in the hazard analysis for the E.7 bin represent external hydrogen explosions caused by contaminants in the helium supply (unexpected fuel reactions) (HNF-SD-SNF-HIE-004). The controls in the E7 bin prevent an external hydrogen explosion by controlling the helium supply.

Assumptions made that require protection by TSRs are listed below:

- Shipment paperwork for gas bottle content during receipt

The manufacturer's paperwork and shipping papers will be checked upon helium cylinder receipt at the CVDF, both the normal and safety-class supply, to verify that the cylinder's contents were sampled by the supplier and that the sample met the required purity specification of >99% helium.

E.8 Hydrogen explosion outside the MCO due to line break caused by a seismic event

The accident scenarios identified in the hazard analysis for the E.8 bin represent external hydrogen explosions in the transfer corridor or process bay caused by a seismic event (HNF-SD-SNF-HIE-004). A seismic event is an unlikely initiating event, therefore no credit is taken for preventative features in the E8 bin. Credit is taken for limiting the MAR on the local exhaust HEPA filters.

No additional requirements result from analysis of this accident.
### Table 4-4: Summary of Safety Features Required to Mitigate or Prevent a Multi-Canister Overpack External Hydrogen Explosion (7 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS</th>
</tr>
</thead>
</table>
| E.1 Hydrogen explosion outside an MCO due to hydrogen generation within the cask | PB-B-13g PB-L-11a | Prevent hydrogen explosion; Dilute the hydrogen in the exhaust system; Direct hydrogen to the exhaust system (worker safety) | Safety-significant equipment for confinement and dilution:  
- Cask venting orifice and jumper  
- MCO vent jumper tool  
- Cask venting interlock with HVAC/PV  
- HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters, and flow switch)  
Safety-class equipment (performing a safety-significant function) for confinement:  
- Cask-MCO  
TSR:  
- Receipt transportation window  
- Limitation on the radionuclide inventory on the HVAC/PV, HEPA filters  
Defence in depth:  
- No leak path below the water line in the MCO  
- Cask vent line enters HVAC/PV piping away from operator | A |
Table 4-4. Summary of Safety Features Required to Mitigate or Prevent a Multi-Canister Overpack External Hydrogen Explosion. (7 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS²</th>
</tr>
</thead>
</table>
| E-2: Hydrogen explosion outside an MCO due to instrumentation failure | PB-B-02a PB-L-11f | Prevent hydrogen explosion; Protect against instrumentation inaccuracy | Safety-significant equipment for confinement and dilution:  
  - HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters, and flow switch)  
  - HVAC/PV process hood isolation damper  
  - HVACD system (exhaust HEPA filter, exhaust duct work, isolation damper)  
  - Standby electrical power (diesel generator and HVAC/PV system restart circuit)  
  - HVACB isolation dampers (outside inlets)  
  Safety-significant equipment for monitoring:  
  - Reference air system (reference air header, differential pressure alarms for process bays)  
  TSR:  
  - Limitation on the radionuclide inventory on the HVAC/PV HEPA filters  
  Defense-in-depth equipment for detection:  
  - SCIC process bay high temperature trip  
  Defense-in-depth equipment for prevention:  
  - Air dryer on the instrument air supply  
  Defense-in-depth equipment for confinement, purge, and pressurize:  
  - Cask-MCO  
  - SCHe system  
  - Lines and valves to isolate and purge the MCO° | B |
Table 4-4. Summary of Safety Features Required to Mitigate or Prevent a Multi-Canister Overpack External Hydrogen Explosion. (7 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designation</th>
<th>Safety function</th>
<th>Safety features</th>
</tr>
</thead>
</table>
| E.3. Hydrogen explosion outside an MCO due to excessive water in MCO | PB-B-03b, PB-B-13d | Prevent hydrogen explosion; Limit the amount of water during (and after) the proof-of-dryness demonstration | Safety-significant equipment for confinement and dilution:  
  - HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters, and flow switches)  
  - HVAC/PV process hood isolation damper  
  - Standby electrical power (Diesel generator and HVAC/PV system restart circuit)  
  - HVAC isolation dampers (outside air inlets)  
  - HVACD system (exhaust HEPA filter, exhaust duct work, isolation damper)  

Safety-significant equipment for monitoring:  
- Reference air system (reference air header, differential pressure alarms for process bays)  

TSR:  
- Procedure to verify the results of the pressure rebound tests before continuing process steps  
- Limitation on the radiouclide inventory on the HVAC/PV HEPA filters  

Defense-in-depth equipment for MCO process testing:  
- Initial pressure rebound test prior to proof-of-dryness demonstration (temperature indicator on the tempered water [annulus] system and pressure on the VPS)  
- Final pressure rebound test following the proof-of-dryness demonstration after all potential water sources are isolated (temperature indicator on the tempered water [annulus] system and pressure on the VPS)  

Defense in depth:  
- The MCS will not allow out-of-sequence operation
### Table 4-4: Summary of Safety Features Required to Mitigate or Prevent a Multi-Canister Overpack External Hydrogen Explosion

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS²</th>
</tr>
</thead>
</table>
| E-4: Hydrogen explosion outside an MCO due to process upset of key parameters | PB-B-03a | Prevent hydrogen accumulation and explosion | Safety-significant equipment for confinement and dilution:  
- HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters, and flow switch)  
- HVAC/PV process hood isolation damper  
- HVACD system (exhaust HEPA filter, exhaust duct work, isolation damper)  
- Standby electrical power (diesel generator and HVAC/PV system restart circuit)  
- HVAC B isolation dampers (outside air inlets)  
Safety-significant equipment for monitoring:  
- Reference air system (reference air header, differential pressure alarms for process bays)  
**TSR:**  
- Limitation on the radionuclide inventory on the HVAC/PV HEPA filters | B |
|                  | PB-B-13a              |                |                |         |
|                  | PB-B-13b              |                |                |         |
|                  | PB-B-13c              |                |                |         |
|                  | PB-H-06f              | Protect against instrument inaccuracy |                |         |
|                  | PB-H-06g              |                |                |         |
|                  | PB-H-11d              |                |                |         |
|                  | PB-L-11e              |                |                |         |
|                  | PB-L-11g              |                |                |         |
Table 4-4. Summary of Safety Features Required to Mitigate or Prevent a Multi-Canister Overpack External Hydrogen Explosion. (7 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designatora</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5: Hydrogen explosion outside an MCO due to loss of support utilities</td>
<td>PB-F-02a</td>
<td>Prevent hydrogen explosion</td>
<td>Safety-significant equipment for confinement and dilution:</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>PB-F-05</td>
<td></td>
<td>• VPS components (pressure management)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SB-F-01b, SB-F-02b</td>
<td></td>
<td>• HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters, and flow switch)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OU-F-04, OU-R-02, OU-R-03, OU-R-04</td>
<td></td>
<td>• HVAC/PV process hood isolation damper</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Standby electrical power (diesel generator and HVAC/PV system restart circuit)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• HVACB isolation dampers (outside air inlets)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• HVACD system (exhaust HEPA filter, exhaust duct work, isolation damper)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Safety-significant equipment for monitoring:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Reference air system (reference air header, differential pressure alarms for process bays)</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TSR:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Receipt transportation window</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Limitation on the radionuclide inventory on the HVAC/PV HEPA filters</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Administrative procedure for restricting crane movement during MCO processing except as part of an approved recovery plan</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Safety-class equipment (providing a safety-significant function) for confinement and dilution:</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Cask-MCO</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• SCE system (including vent delay)</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Lines and valves to isolate and purge the MCO</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Defense-in-depth equipment for detection of process upset:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Safety-class detection of process upset and safety-class equipment (performing a safety-significant function) for shutdown designed to fail to a safe position</td>
<td>B</td>
</tr>
<tr>
<td>Candidate accident</td>
<td>Checklist designator</td>
<td>Safety function</td>
<td>Safety features</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------</td>
<td>----------------</td>
<td>----------------</td>
<td></td>
</tr>
</tbody>
</table>
| E.6 Hydrogen explosion outside an MCO due to facility fire | TC-I-12, PB-L-01, PB-L-02, PB-L-03, PB-L-04, PB-L-05, PB-L-06, PB-L-07, PB-L-08, PB-L-09, PB-L-10, PB-L-13, EB-L-14, EB-L-15, EB-L-16, PB-P-02, OU-P-02a | Protect a processing process bay against external fire | Safety-class equipment (performing a safety-significant function) for detection:  
  * SCIC process bay high temperature trip |
|                   |                     | (administrative area, transfer corridor, other nonprocessing process bay) and limit the fire risk inside a processing process bay | TSR:  
  * Combustible loadings limited  
  * Limitations on the radionuclide inventory on the HVAC/PV/HEPA filters  
  * Restore bay temperatures following process bay high temperature trip |
|                   |                     |                | Defense-in-depth equipment for detection:  
  * SCIC process bay temperature detection |
|                   |                     |                | Defense-in-depth equipment for prevention:  
  * Air dryer on the instrument air supply |
|                   |                     |                | Defense-in-depth equipment for confinement, purge, and pressurize:  
  * Cask-MCO  
  * SCHe system  
  * Lines and valves to isolate and purge the MCO |
|                   |                     |                | Defense-in-depth fire equipment  
  * Programmatic controls for fire prevention  
  * Fire protection system present in each bay |

| E.7 Hydrogen explosion outside an MCO due to contamination of helium supply | PB-H-06k | Prevent contamination of helium supply | TSR:  
  * Shipment paperwork verified for helium supply gas content during receipt |
Table 4-1. Summary of Safety Features Required to Mitigate or Prevent a
Multi-Canister Overpack External Hydrogen Explosion. (7 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
</tr>
</thead>
<tbody>
<tr>
<td>E.S. Hydrogen explosion outside an MCO due to line break caused by a seismic event</td>
<td>TC-R-01 PB-R-01a OU-R-01a</td>
<td>Control material at risk</td>
<td>No SSCs required</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TSR:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Limitation on the radionuclide inventory on the HVAC/PV HEPA filters</td>
</tr>
</tbody>
</table>


**U.S. Nuclear Regulatory Commission important-to-safety classifications: Category A = critical to safe operation, Category B = major impact on safety, Category C = minor impact on safety.

Lines and valves to isolate the MCO include the isolation valves (and filters on air supply to valve actuators) in the VPS, general-service helium system, PWC system, and SChE system.

HEPA = high-efficiency particulate air (filter)
HVAC = heating, ventilation, and air conditioning
HVACB = process bay recirculation HVAC system
HVAC/PV = process bay local exhaust HVAC and process vent system
HVACD = process general supply/exhaust HVAC system
ITS = important to safety
MCO = multi-canister overpack
MCS = monitoring and control system
NRC = U.S. Nuclear Regulatory Commission
PWC = process water conditioning
SChE = safety-class helium
SCIC = safety-class instrumentation and control
SSC = structure, system, and component
TSR = technical safety requirement
VPS = vacuum purge system
8:4-4 = 8-hour initial vacuum cycle, 4-hour subsequent vacuum cycles, 4-hour return to pressure between vacuum cycles
4.10 REFERENCES


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Figure 4-1. General Sequence for External Hydrogen Explosions.
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5.0 CALCULATIONS FOR HYDROGEN GENERATION AND EXPLOSION WITHIN A MULTI-CANISTER OVERPACK

5.1 PURPOSE AND OBJECTIVES

The calculations in this chapter address hydrogen generation and combustion within a multi-canister overpack (MCO) during the time the MCO is inside the Cold Vacuum Drying Facility (CVDF). The quantity of radioactive material released following a deflagration or detonation in an MCO and the resulting doses to onsite and offsite receptors are computed. Dose consequences are compared with guidelines to help ascertain the need for appropriate preventive and/or mitigative controls.

Three accident scenarios involving flammable gas mixtures inside the MCO are described and evaluated in this chapter:

- A hydrogen explosion shortly after arrival at the CVDF caused by failure to purge the MCO void space while at the K Basins
- A hydrogen explosion caused by oxygen in the helium system
- A hydrogen explosion caused by air ingress while the MCO is under vacuum.

Each accident scenario is described, the mechanics of producing a flammable mixture are developed, the consequences of the combustion inside the MCO are evaluated, and appropriate preventive and/or mitigative controls are discussed.

The design basis internal hydrogen explosion is the air ingress while under vacuum. This accident has the bounding dose consequences (bounding airborne release fraction [ARF] and material at risk [MAR]) for internal hydrogen explosions and higher probability than the others.

In all postulated accident sequences, hydrogen is allowed to accumulate 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. To read the figure begin at the bottom and move upward. The sequence of events begins when enough hydrogen has accumulated in the MCO. Three conditions are necessary for this accumulation to occur within a reasonable time frame: uranium metal, water, and elevated temperatures. The uranium and water are reactants, and the elevated temperature speeds the reaction. In the next step, the accumulated hydrogen mixes with oxygen (usually air) to form a combustible mixture. In the final step, this mixture is ignited. Since it takes very little energy to begin the hydrogen–oxygen combustion, it will be assumed that ignition sources are present where needed. The combustion could be initiated, for example, by a small particle of uranium hydride.
5.2 HYDROGEN EXPLOSION UPON ARRIVAL AT THE COLD VACUUM DRYING FACILITY

5.2.1 Scenario Development

Before the MCO leaves the K Basins, the void spaces in the shipping cask and the MCO are inerted with helium. The helium displaces the air to prevent flammable mixtures of air and hydrogen from forming in the void space. If the helium inerting were omitted before the MCO was shipped to the CVDF, a flammable mixture could form in the void space. The likely presence of hydride particles could serve as an available ignition source. Depending on the various combinations of MCO temperatures, shipping times, and exposed uranium areas, the mixture could become flammable at any time between departure of the cask-MCO from the K Basins and venting of the cask at the CVDF. If the mixture were ignited, the resulting pressures could exceed the 150 lb/in² gauge design limit of the shipping cask, causing the cask to rupture and release excess pressure to the environment. Another possible consequence of an explosion inside the MCO is release of particulate from the MCO. Since the radioactive particulate at risk is the particulate associated with residual contamination on the upper portion of the MCO rather than the particulate associated with the spent nuclear fuel (SNF) itself, the amount of radioactive material that could become airborne is greatly reduced.

A related accident could occur between removing the cask lid and attaching the local exhaust hood. If the MCO port valve were not closed after the cask lid was removed, air could diffuse into the MCO to produce a flammable mixture. Ignition at this point would vent any particulate matter associated with residual contamination on the upper portion of the MCO into the process bay and eventually the outdoor environment.

5.2.2 Source Term Analysis

5.2.2.1 Pressure Buildup Inside the Cask–Multi-Canister Overpack. Appendix B, Table B-1, estimates that 8.29 gmoles of hydrogen are generated during shipment from the K Basins to the CVDF. A small portion of this hydrogen would remain dissolved in the water present in the MCO and the cask. If the MCO were not inerted with helium before leaving the K Basins, the remaining hydrogen could form a flammable mixture with the air in the void space.

The void space in the cask–MCO during shipment is estimated to be 41.2 L. This is based on a void layer 4.25 in. thick and 20 in. in diameter at the top of the MCO. In addition, a void layer 0.6 in. thick between the outside of the MCO and the inside of the cask is treated as a circular cylindrical shell 16 in. tall with a diameter of 24 in. The space at the top of the cask and the top of the MCO is represented as a cylinder 1 in. tall with a diameter of 24 in. (The dimensions and volume of the void space are not critical to the conclusions below.) The ideal gas law can be used to calculate the number of moles of gas in the void space. Assuming a 41.2-L volume of air at a pressure of 1 atm and an initial temperature of 15 °C, the amount of air in the void space is 1.73 gmoles, of which 0.36 gmoles are oxygen and 1.37 gmoles are nitrogen.
When the cask-MCO arrives at the CVDF, the temperature is assumed to be 35 °C. If the void space was not inerted with helium at the K Basins, it would contain 8.29 gmoles hydrogen, 0.09 gmoles water vapor (100% relative humidity), 1.37 gmoles nitrogen, and 0.36 gmoles oxygen, for a total of 10.11 gmoles. The pressure in the cask-MCO can be calculated using the ideal gas law, as shown below.

\[ P = (n)(R)(T / V) \]

where

- \( P \) = pressure in the MCO cask (atm)
- \( n \) = number of moles of gas (10.11 moles)
- \( R \) = ideal gas constant (0.082058 L-atm/mole/K)
- \( T \) = temperature of gas (308.15 K [35 °C])
- \( V \) = volume of gas (41.2 L).

\[ P = (10.11 \text{ moles})(0.082058 \text{ L-atm/mole/K})(308.15 \text{ K})/(41.2 \text{ L}) \]

\[ P = 6.21 \text{ atm} \]

Assuming the mixture of hydrogen and air is flammable and that 100% of the oxygen is consumed, the heat of combustion is 41,900 cal due to the formation of 0.72 gmoles water vapor. The post-combustion gas mixture is 7.57 gmoles hydrogen, 1.37 gmoles nitrogen, and 0.81 gmoles water vapor. Allowing an adiabatic temperature rise, the final temperature is 1,120 K. From the ideal gas law, the final pressure is 21.8 atm, or 305 lb/in² gauge.

5.2.2.2 Particulate Available for Release from the Multi-Canister Overpack. To estimate the potential surface contamination and subsequent release from the MCO, consider first how the guard plate becomes contaminated. A clean MCO shield plug assembly is placed on the MCO at the K Basins. As the MCO is transported to CVDF, the water inside the MCO will slosh and carry particulate from one surface to another. The ratio of guard plate surface area to the entire surface area in the MCO is 0.34% (Appendix B, Section B6.0).

An additional consideration is the small gas volume inside the MCO. The baskets and their contents act as baffles that greatly reduce the velocity of the water, leading to less movement of particulate and less resulting relocation of particulate to the guard plate. Also, because of the moist conditions, resuspension of the particulate is reduced. A factor of 10 is used to account for these two effects (baffling, moist conditions). Thus, the fraction of the loose particulate in the MCO that is attached to the underside of the MCO guard plate is assumed to be 0.034%, or 4.44 g SNF metal. This is the MAR. Using the airborne release fraction (0.005) and respirable fraction (0.4) for venting of pressurized gases (DOE-HDBK-3010-94), which would bound the potential emissions, the mass released as respirable particles is calculated as shown:

\[ M = \text{MAR} \times \text{ARF} \times \text{RF} \]
where

\[
M = \text{mass (g)}
\]

\[
MAR = \text{material at risk (4.44 g SNF)}
\]

\[
ARF = \text{airborne release fraction (0.005)}
\]

\[
RF = \text{respirable fraction (0.4)}.
\]

\[
M = (4.44 \text{ g SNF})(0.005)(0.4) = 0.0089 \text{ g SNF}.
\]

### 5.2.3 Consequence Analysis

The predicted pressure in the cask–MCO is well in excess of the design pressure limit of the cask. The high-pressure gas will breach the confinement boundary represented by the cask. A gas mixture still rich in hydrogen will exit the cask, carrying with it a portion of any loose particulate attached to the underside of the cask lid as well as a portion of the loose particulate attached to the underside of the MCO guard plate.

#### 5.2.3.1 High-Pressure Release from the Cask–Multi-Canister Overpack

To evaluate the injury potential of the hydrogen gas release, it is assumed that all of the post-combustion gas is expelled from the MCO and forms a stoichiometric mixture with air. From the ideal gas law, 0.45 g moles of gas at atmospheric pressure are left in the MCO. The other 9.30 g moles have mixed with 17.28 g moles of air, forming a 1,300 L mixture that is 27.2% hydrogen and 13.6% oxygen. The temperature of the MCO gas is assumed to be 800 K after leaving the MCO. The gas mixes with air at 25 °C to form the final mixture, which is at a temperature of 593.9 K. The flammable gas is assumed to form a roughly spherical cloud above the MCO. The cloud has a radius of about 0.7 m. When it burns, 417,000 cal are liberated. With a trinitrotoluene (TNT) effectiveness of 20%, this corresponds to 74 g of TNT.

Using the injury estimation method presented in Appendix B, Section B4.0, an individual located 0.4 m from the outer edge of this sphere (1.1 m from the center) would experience an overpressure of 14.9 lb/in². This pressure would be fatal (by lung hemorrhage) in about 1% of the individuals exposed to it. Eardrums would be ruptured in 95% of the exposed individuals. Eardrum ruptures occur out to 4 m from the center of the puff with greater than 1% probability. It is therefore possible for a worker standing next to the top of the MCO to be seriously injured or killed if the rupture disk gives way. This is a rather narrow time window, since the interval between installation of the mezzanine bridge and venting the cask–MCO is about 90 minutes, and workers are not in close proximity to the MCO the entire time. Therefore, serious injury is not expected.
5.2.3.2 Release of Particulate from Multi-Canister Overpack. The potential downwind impacts of a high-pressure release from the cask-MCO are calculated 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)
- \( \chi/Q' \) = time-integrated atmospheric transport factor (s/m²)
- \( BR \) = breathing rate (m³/s)
- \( UD \) = dose per unit respirable radioactive material inhaled (rem/g).

The following assumptions have been used to determine the radiological consequences to the onsite and offsite receptors.

- The values for the air transport factors, \( \chi/Q \), for the selected receptor location are those given for acute ground-level releases in Table 1-4.
- The light activity breathing rate is \( 3.33 \times 10^4 \) m³/s (HNF-SD-SNF-TI-059).
- The dose per unit of respirable radioactive material inhaled is \( 4.38 \times 10^5 \) rem/g SNF (see Table 1-2).

**Unmitigated Consequences.** Using dose calculation equation and the mass of 0.0089 g calculated in Section 5.2.2.2, the dose to the onsite receptor is calculated as follows.

\[ D_{\text{onsite}} = (0.0089) \left( 7.32 \times 10^{-2} \text{ s/m}^3 \right) \left( 3.33 \times 10^4 \text{ m}^3/\text{s} \right) \left( 4.38 \times 10^5 \text{ rem/g SNF} \right) \]

\[ = 0.095 \text{ rem}. \]

The dose consequences at the remaining receptor sites are calculated in the same manner and are shown in Table 5-1.

**Mitigated Consequences.** Table 5-1 shows that the unmitigated dose consequences do not exceed onsite risk evaluation guidelines or offsite limits, therefore no mitigated consequences were calculated.
Table 5-1. Dose Calculation Summary: Failure to Purge at K Basins.

<table>
<thead>
<tr>
<th>Receptor location (distance, direction)</th>
<th>Duration (hours)</th>
<th>( \chi/Q^a ) (s/m(^2))</th>
<th>Unmitigated dose(^b) (rem (Sv))</th>
<th>Evaluation guideline(^c)/release limits (rem (Sv), anticipated(^d))</th>
<th>Safety-significant mitigated dose (rem (Sv))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>&lt;1</td>
<td>7.32 E-02</td>
<td>0.095 (9.5 E-04)</td>
<td>1.0 (1.0 E-02)</td>
<td>Not calculated(^*)</td>
</tr>
<tr>
<td>Columbia River, near bank (650 m W)</td>
<td>&lt;1</td>
<td>2.44 E-03</td>
<td>3.2 E-03 (3.2 E-05)</td>
<td></td>
<td>Not calculated(^*)</td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>&lt;1</td>
<td>1.60 E-04</td>
<td>2.1 E-04 (2.1 E-06)</td>
<td></td>
<td>Not calculated(^*)</td>
</tr>
<tr>
<td>Hanford Site boundary (10,090 m W)</td>
<td>&lt;1</td>
<td>4.48 E-05</td>
<td>5.8 E-05 (5.8 E-07)</td>
<td>0.5 (5.0 E-03)</td>
<td>Not calculated(^*)</td>
</tr>
</tbody>
</table>


\(^b\) Fifty-year committed effective dose equivalent.

\(^c\) Evaluation guideline for onsite (100 m) receptor only.

\(^d\) Anticipated event frequency is >10\(^{-5}\) to ≤10\(^{-3}\) per year.

\(^*\) Since the unmitigated accident does not exceed release limits, no mitigated consequences were calculated.

5.2.4 Comparison to Guidelines

From Table 5-1, the unmitigated dose consequences of failing to perform the helium purge of the cask–MCO at the K Basins do not exceed the risk evaluation guidelines or release limits for anticipated events.

5.2.5 Safety Equipment and Controls

Since the consequences of this accident do not exceed the risk evaluation guidelines for anticipated events, no safety equipment of controls are necessary.

5.3 HYDROGEN EXPLOSION CAUSED BY OXYGEN IN THE HELIUM SYSTEM

5.3.1 Scenario Development

Helium is supplied by two main sources, the safety-class helium (SCHe) supply tanks and the general service helium tank trailer. During maintenance with the helium supply open to the air, the helium will diffuse away and air will take its place. If the helium supply lines are not purged with helium prior to use, air in the lines will be forced into the MCO, leading to flammable...
mixtures. However, the limited volume of the process piping makes it is unlikely that there will be enough oxygen to make the MCO gas flammable.

The helium system is used in various purges from the very beginning of processing at the CVDF. These purges would eliminate most, if not all, of the air in the lines before MCO purging takes place. The presence of air in the helium system is not an explosion hazard because the required air volume cannot be obtained. For example, in the purge of the vent line, a 4-minute purge at 1 ft³/min uses 4 ft³ of gas. For pipe with an inside diameter of 1 in., 4 ft³ is found in 730 ft of pipe. Since the length of potentially affected helium system pipe is much less than 730 ft, any residual air will be flushed out before the MCO is connected to the helium system.

Oxygen could also be inadvertently forced into an MCO if the supplier provided oxygen rather than helium. This substitution would require multiple failures to accomplish because the helium and oxygen are kept in different color tanks and the fittings for the helium and oxygen tanks are different sizes and types. However, the supplier has adaptors which would permit any gas to be added to any tank. If pure oxygen (rather than helium) were added to the MCO during initial processing activities at the CVDF, a flammable mixture could be formed during draining. The bounding MCO produces enough hydrogen to form a flammable mixture. Were this mixture to ignite, the pressure inside the MCO would exceed the 30 lb/in² gauge pressure rupture disk setting. The excess pressure and some particulate would be discharged to the process bay local exhaust ventilation system. The environmental releases would be insignificant because of the high-efficiency particulate air (HEPA) filtration and elevated release from the 48-ft heating, ventilation, and air conditioning (HVAC) stack.

Delay during draining or failure to purge prior to draining would result in higher hydrogen concentrations. A delay during draining could occur as a result of the following failures:

- The process water conditioning (PWC) receiver tank is not drained before MCO draining begins, resulting in the high-level alarm shutting down the transfer from the MCO
- The PWC receiver tank high-level indicator shows a false overfilled condition.
- A power outage occurs during draining.

After several hours of delay, enough hydrogen has formed that an explosion would exceed the 150 lb/in² gauge rupture disk design pressure.

Another way to accumulate excessive hydrogen is to fail to purge the MCO at the start of draining. Because of the long heatup time, considerable hydrogen accumulates before the water is drained from the MCO. Normally, this hydrogen is purged using the helium system. If the purge step were omitted, the drain cycle would begin with excessive hydrogen. An explosion early in the drain operation would exceed the 150 lb/in² gauge rupture disk design pressure.
5.3.2 Source Term Analysis

When an MCO arrives at the CVDF, the first use of helium is to purge the vent line before venting. If the purge gas were oxygen rather than helium, a flammable mixture could form in the vent line. Ignition of the mixture is not expected to damage the line because of the small volume of gas: the line diameter is 0.5 in., and the flammable mixture would be present in a length of just a few feet.

Immediately after venting, the cask-MCO is pressure-purged to reduce hydrogen concentrations. An explosion during the first pressurization could exceed the cask design pressure and release radioactive material into the process bay. Normally, the air in the bay is filtered by the general exhaust system before being released to the environment. However, for the unmitigated analysis, the airborne activity is assumed to be discharged to the environment. The MAR in this case is approximately the same as that calculated in Section 5.2.3.2 for the high-pressure release. Therefore, the doses are bounded by those shown on Table 5-1, and the doses do not exceed onsite evaluation guidelines or offsite release limits.

The MCO is purged again after the cask lid is removed and the MCO is connected to the CVDF process lines. About 3.5 hours have elapsed since the first purge, which allows enough hydrogen to have accumulated to support combustion. However, the MAR has not increased, so the accident consequences are no worse.

The next purge occurs after heating the MCO with the tempered water system. About 6 hours have passed, so enough hydrogen has accumulated to damage the MCO, but the MAR is still small. The MCO is still filled with water, and only the underside of the lid offers resuspensible particulate.

The drain operation offers enough MAR that the particulate released from the MCO can exceed the onsite dose guidelines. This accident will be analyzed in more detail.

The hydrogen concentration in the bounding MCO rises to about 90% during the 6 hour heatup period before draining. The helium purge preceding the drain operation lowers this to about 50%. This purge is not very effective because the volume of the helium lines is comparable to the gas volume of the MCO, the pressure variation is small, and the hydrogen generation is for oxygen-free water.

As the MCO drains, two phenomena affect the hydrogen concentration. The first is dilution by the added gas (oxygen). The second is a reduction in the hydrogen generation rate from 1.50 gmoles/h to 0.0015 gmoles/h (see Appendix B, Section B1.2). In effect, the generation of hydrogen ceases as the water is removed.

The drain operation is assumed to begin normally and then be interrupted. Hydrogen accumulates in the MCO during the subsequent delay. Then the flammable mixture of oxygen, hydrogen, and water vapor explodes. Pressures great enough to be vented by the 30 lb/in² pressure relief or the 150 lb/in² rupture disk are readily attainable.
The largest pressure would be at near-stoichiometric conditions, where the hydrogen concentration was 59%, the oxygen concentration 29%, and the water vapor concentration is 12% corresponding to 100% relative humidity at 50 °C. The adiabatic combustion pressure is about 5,000 °C and the corresponding pressure is at 190 lb/in². However, water undergoes significant dissociation at temperatures above 2,500 °C (Perry 1963). This dissociation means the reaction between hydrogen and oxygen to form water will proceed at a slower rate or be incomplete. The projected adiabatic temperature and pressure will not be reached. Nevertheless, shock waves could potentially form during combustion leading to pressures in excess of the 39 atm (562 lb/in² gauge) limiting pressure of the MCO (see HNF-SD-SNFRARR-005 Revision 1, Section 2.2.6.2.2). This accident could potentially fail the MCO pressure boundary. Note that if the drain interruption occurs with a void space in the MCO of 100 L, then a hydrogen concentration of 59% could be reached in 4 hours. The hydrogen concentration at the start of draining is assumed to be 50%.

5.3.3 Consequence Analysis

The explosion in the MCO resuspends particulate matter and forces it from the MCO through the 30 lb/in² gauge rupture disk line and, if the pressures are high enough, through the 150 lb/in² gauge MCO rupture disk. Gases discharged through the 30 lb/in² gauge rupture disk travel to the local exhaust system. Gases discharged through the 150 lb/in² gauge MCO rupture disk are directed toward the face of the local exhaust air intake. In both cases, the environmental releases are minimal because of the presence of HEPA filters on the local exhaust effluent, as well as the elevated discharge point.

If the air flow in the local exhaust system were stopped, the gaseous release from the MCO could enter the process bay. In this case, the general exhaust system would filter and release the airborne particulate. Thus the environmental releases would again be insignificant.

If the air flow in both the local and general exhaust systems failed, the airborne particulate would gradually leak from the building. The maximum amount of radioactive material that could become airborne in the process bay is the bounding pressurized release amount for blowdowns prior to vacuum drying operations. This type of release is discussed in Appendix B, Section B5.0, and is estimated to be 26 g SNF.

Unmitigated Consequences. Using dose calculation equation and the mass of 26 g of SNF calculated in Appendix B, Section B5.0, the dose to the onsite receptor is calculated as follows.

\[
D_{\text{onsite}} = (26 \text{ g SNF}) (7.32 \times 10^{-2} \text{ s/m}^3) (3.33 \times 10^4 \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g SNF})
\]

\[
= \sim 280 \text{ rem}.
\]

The dose consequences at the remaining receptor sites are calculated in the same manner and are shown in Table 5-2.
Table 5-2. Dose Calculation Summary: Oxygen in Helium System.

<table>
<thead>
<tr>
<th>Receptor location (distance, direction)</th>
<th>Duration (hours)</th>
<th>χ/Q(^a) (s/m(^2))</th>
<th>Unmitigated dose(^b) rem (Sv)</th>
<th>Evaluation guideline(^c) release limits rem (Sv), anticipated(^d)</th>
<th>Safety-significant mitigated dose rem (Sv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hanford Site boundary (10,090 m W)</td>
<td>&lt;1</td>
<td>4.48 E-05</td>
<td>1.7 E-01 (1.7 E-03)</td>
<td>0.5</td>
<td>Prevented</td>
</tr>
<tr>
<td>Columbia River, near bank (650 m W)</td>
<td>&lt;1</td>
<td>2.44 E-03</td>
<td>9.2 (9.2 E-02)</td>
<td>–</td>
<td>Prevented</td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>&lt;1</td>
<td>1.60 E-04</td>
<td>6.1 E-01 (6.1 E-03)</td>
<td>–</td>
<td>Prevented</td>
</tr>
<tr>
<td>Onsite (100 m E)</td>
<td>&lt;1</td>
<td>7.32 E-02</td>
<td>280 (2.8)</td>
<td>1.0</td>
<td>Prevented</td>
</tr>
</tbody>
</table>


\(^b\)Fifty-year committed effective dose equivalent.

\(^c\)Evaluation guideline for onsite (100 m) receptor only.

\(^d\)Anticipated event frequency is >10\(^{-2}\) to ≤10\(^{-1}\) per year.

**Mitigated Consequences.** Table 5-2 shows that the unmitigated dose consequences exceed onsite risk evaluation guidelines, but they do not exceed offsite release limits. The dose consequences to the onsite receptor are mitigated by ensuring that helium purity is as specified, that a purge of the MCO is initiated if the drain cycle is interrupted, and that ventilation flow is maintained in the process bay local exhaust and general exhaust, thus ensuring that any release is HEPA filtered before being discharged to the environment. Several failures must occur before an onsite receptor could receive a dose from this event in excess of the evaluation guideline. The probability of this entire sequence of failures occurring is less than 10\(^{-6}\) per year, so no mitigated consequences have been calculated.

**5.3.4 Comparison to Guidelines**

**Unmitigated Consequences.** The unmitigated dose consequences for this event are below the offsite release limits but exceed the onsite evaluation guidelines.

**Mitigated Consequences.** The probability of this event is not credible, so the event is prevented and no mitigated consequences have been calculated.
5.3.5 Safety Equipment and Controls

The safety equipment, controls, and defense-in-depth features designed to prevent and mitigate the dose consequences of a hydrogen explosion caused by oxygen in the helium system are found in Section 5.5.

5.4 HYDROGEN EXPLOSION CAUSED BY AIR INGRESS

5.4.1 Scenario Development

During the MCO drying process, the MCO is under varying vacuum pressures. Hydrogen gas is still being generated by reactions of water and water vapor with the uranium metal. The generated hydrogen is normally swept from the MCO by the helium purge. If this flow were interrupted long enough that the hydrogen concentration exceeded 8.7% (see Appendix B, Section B2.0), an air ingress would lead to flammable mixtures. The flexible lines connected to the MCO are made of nonmetallic substances, such as Teflon\(^1\), that can melt at relatively low temperatures. A fire in the process bay could lead to a leak in one or more of these flexible lines. Such a leak while the MCO was under vacuum would allow air to be drawn into the MCO.

In addition, high temperatures in the process bay could lead to abnormal operation of the logic circuits controlling certain valves. Failure of the control system could lead to valve line-ups that would facilitate an air ingress accident. The high temperatures could be the result of hot weather, HVAC failure, or fires in the process bay.

Either process line, the one connected to the long axial process tube or the one connected to the filtered process exit port, could fail and provide the source of the air ingress. Since a motive force is needed to draw the air into the MCO, the event is postulated to occur under worst-case vacuum conditions (e.g., early in the drying process).

The worst-case consequences of a hydrogen explosion within an MCO do not lead to pressures that exceed the MCO design limits. Rather, the explosion produces a short pressure pulse below the design pressure limit, and the high-temperature gas in the MCO is then vented to the process bay or the local exhaust system through the same openings that allowed the air to enter.

5.4.2 Source Term Analysis

During drying operations, the MCO contains varying amounts of helium, water vapor, and hydrogen. The water vapor reacts with exposed uranium metal to produce the hydrogen.

\(^{1}\text{Teflon is a trademark of E.I. du Pont de Nemours & Company.}\)
The purpose of the drying operation is to remove the water vapor. As the MCO becomes drier, the hydrogen production rate decreases. Additional effects are temperature related. At high vacuum, the heat transfer is poor, so the fuel temperature tends to increase. During helium purges, the fuel cools. The associated expansion and contraction of fuel and cladding defects can trap or release small amounts of water.

For this accident to occur, there must be a delay during processing during which the helium purge is not operating. This allows hydrogen to build up in the MCO to higher than normal amounts. Once the hydrogen concentration exceeds 8.7% of the helium, a burn is possible if the right amount of air is added to the helium–hydrogen mixture (see Appendix B, Section B2.0).

The adiabatic combustion pressure associated with a hydrogen concentration of 8.7% in helium is 42 lb/in² gauge. For the minimum flammable case, the hydrogen concentration is 6.07% and the oxygen concentration is 6.28% prior to combustion (see Appendix B, Section B2.0). Using greater hydrogen concentrations leads to higher pressures. For example, if the hydrogen and helium are present in equal concentrations, the optimal mixture with air gives a hydrogen concentration of 22.8% and an oxygen concentration of 11.4% prior to combustion. The adiabatic combustion pressure is 100 lb/in² gauge. The limiting case is pure hydrogen (no helium). For this bounding situation, the adiabatic combustion pressure (after optimal mixing with air) is 110 lb/in² gauge. The hydrogen concentration is 29.4% and the oxygen concentration is half that. These last two cases can produce shock waves caused by the high concentration of hydrogen. The main effect of these shock waves is to increase the eventual flow rate from the MCO by widening existing leak paths or creating new ones, for example, if the rupture disk were to break open. Shock wave pressures are around twice that of the adiabatic pressure. When the shock wave reflects from a flat surface, the pressure can be doubled again. The estimated peak pressure for a stoichiometric mixture of hydrogen in air at atmospheric pressure before combustion is 37 atm (NUREG/CR-2726), or 530 lb/in² gauge. The MCO is not considered to be damaged by the shock waves for two reasons. First, MCOs have received static pressure tests at 39 atm without failure (see HNF-SD-SNF-SARR-005 Revision 1, Section 2.2.6.2.2). Second, the high pressures only exist for several milliseconds, a time period too short to impart significant momentum to any portion of the MCO pressure boundary.

5.4.3 Consequence Analysis

In the bounding pressurized release, about 44 g SNF are released to the process bay (see Appendix B, Section B5.0). In the unmitigated analysis, the airborne activity not filtered, and it is released at ground level.

Unmitigated Consequences. Using the dose calculation equation and the mass of 44 g of SNF calculated in Appendix B, Section B5.0, the dose to the onsite receptor is calculated as follows.

\[ D_{\text{onsite}} = (44 \text{ g SNF}) \left( 7.32 \times 10^{-2} \text{ s/m}^3 \right) \left( 3.33 \times 10^4 \text{ m}^3/\text{s} \right) \left( 4.38 \times 10^4 \text{ rem/g} \right) \]
\[ = 470 \text{ rem} \]
The dose consequences at the remaining receptor sites are calculated in the same manner and are shown in Table 5-3.

**Table 5-3. Dose Calculation Summary: Air Ingress During Vacuum.**

<table>
<thead>
<tr>
<th>Receptor location (distance, direction)</th>
<th>Duration (hours)</th>
<th>$\chi/Q$</th>
<th>Unmitigated dose$^b$ (rem (Sv))</th>
<th>Evaluation guideline$^c$/release limits (rem (Sv), anticipated$^d$)</th>
<th>Safety-significant mitigated dose (rem (Sv))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>&lt;1</td>
<td>7.32 E-02</td>
<td>470 (4.7)</td>
<td>1.0 (1.0 E-02)</td>
<td>Prevented</td>
</tr>
<tr>
<td>Columbia River, near bank (650 m W)</td>
<td>&lt;1</td>
<td>2.44 E-03</td>
<td>160 (1.6 E-01)</td>
<td>--</td>
<td>Prevented</td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>&lt;1</td>
<td>1.60 E-04</td>
<td>1.0 (1.0 E-02)</td>
<td>--</td>
<td>Prevented</td>
</tr>
<tr>
<td>Hanford Site boundary (10,090 m W)</td>
<td>&lt;1</td>
<td>4.48 E-05</td>
<td>2.9 E-01 (2.9 E-03)</td>
<td>0.5 (5.0 E-03)</td>
<td>Prevented</td>
</tr>
</tbody>
</table>


$^b$Fifty-year committed effective dose equivalent.

$^c$Evaluation guideline for onsite (100 m) receptor only.

$^d$Anticipated event frequency is $>10^{-4}$ to $\leq 10^{-1}$ per year.

**Mitigated Consequences.** Mitigation of the internal hydrogen explosion accident takes credit for the integrity of selected isolation valves and lines to isolate the MCO, the safety-class instrumentation and control (SCIC) system and related instrumentation in other systems, the SCHe system, the tempered water (annulus) system, and the cask–MCO. The isolation valves and lines inside the safety-class portion of the VPS and PWC systems ensure that there is no air ingress into the MCO. The SCIC system provides control functions to initiate isolation and purge of the MCO (isolation and purge trip) if the process upsets exceed trip setpoints. The SCHe system provides the positive means of providing a minimum dedicated helium purge to the MCO to sweep hydrogen or air (if an air ingress were to occur) from the MCO in the event that general service helium were not available. The tempered water (annulus) system ensures that MCO temperatures, and subsequent hydrogen generation rates, remain within analyzed bounds.

Since the unmitigated accident does not exceed the offsite dose limits, no mitigated consequences were calculated for the offsite receptor. The unmitigated accident leads to onsite doses that are greater than the risk evaluation guideline for anticipated events. With the credited controls, the accident is prevented to beyond extremely unlikely. In addition, the presence of HEPA filters further reduces the onsite dose for the boundary failure postulated in the scenario.
5.4.4 Comparison to Guidelines

Comparison of Unmitigated Doses. Event tree sequences indicate that the unmitigated frequency for the internal hydrogen explosion design basis accident (DBA) is in the anticipated category (i.e., an unmitigated frequency greater than $10^{-2}$ per year) (see Appendix A). The unmitigated sequence considered the processing of 200 MCOs per year. The unmitigated radiological offsite dose for this event is below offsite release limits, while the unmitigated onsite dose for an anticipated event is above onsite risk evaluation guidelines.

Comparison of Mitigated Doses. The mitigated frequency of the event tree sequence that represents this DBA as an internal hydrogen explosion is $3 \times 10^{-7}$ per year, thus this mitigated DBA is beyond extremely unlikely (see Appendix A). With safety-class and safety-significant features credited (performing a safety-significant function), the mitigated internal hydrogen explosion is both prevented and mitigated.

5.4.5 Safety Equipment and Controls

The safety equipment, controls, and defense-in-depth features designed to prevent and mitigate the dose consequences of internal combustion accidents are found in Section 5.5.

5.5 SUMMARY OF SAFETY-CLASS STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

Under normal operating conditions, helium flow through the MCO precludes the accumulation of flammable concentrations of hydrogen in the MCO. Under upset or accident conditions, safety-significant equipment is required in order to ensure this capability is not lost. The function of precluding flammable concentrations could be compromised by a loss of helium flow or an air ingress.

The checklist designators included in the accident bins, other than the accident selected as the DBA, represent additional accident sequences slightly different than the DBA. All of these binned accidents are bounded by the DBA because they have lesser or equivalent worst-case consequences and frequencies.

The accident scenarios identified in the hazard analysis for the I 1 bin represent internal hydrogen explosions caused by elevated fuel corrosion rates (high temperature tempered water), water ingress into MCO, and air ingress into MCO (HNF-SD-SNF-HIE-004). The controls in the I 1 bin prevent an internal hydrogen explosion by controlling the hydrogen concentration in the MCO and by preventing air ingress into the MCO. The normal hydrogen concentrations inside the MCO are controlled to ensure that if the MCO gas contents were to be mixed with air, the resulting gas mixture would not be flammable. The likelihood of an internal explosion is further reduced by crediting features that prevent air ingress so that onsite risk evaluation guidelines and
Offsite release limits are satisfied. The structures, systems, and components (SSCs) that limit fuel temperature also are credited to protect the analysis assumption pertaining to hydrogen generation rates. In addition, because the scenario postulates a process line break that is tantamount to a gaseous release, confinement systems are credited with controlling that release. Note that the confinement systems are not credited with mitigation of the internal explosion release but only with mitigation of the gaseous release associated with the line break.

The safety-significant equipment and controls designated to prevent the dose consequences of the MCO internal hydrogen combustion accident are described below.

Safety-class equipment (performing a safety-significant function) for detection of process upset:

- **SCIC system, including vacuum cycle timer (8-4-4 logic)**
  
  The SCIC system uses programmable logic controllers, wiring to process instrumentation, vacuum limit timer, signals from seismic detectors and temperature monitors, system controls, and output relays to perform an isolation and purge trip and a tempered water trip.

- **General-service helium system: safety-class flow instrumentation**

  The general-service helium system provides helium flow information to the SCIC system to initiate MCO isolation and SCHe actuation during process upset conditions.

- **Vacuum purge system pressure instrumentation**

  Pressure indicators on the vacuum purge system provide MCO internal pressure information to the SCIC system, which initiates MCO isolation and SCHe actuation during process upset conditions.

- **Tempered water (annulus) system temperature trip**

  The tempered water (annulus) system includes antisiphon valves, low water level indication and alarm, and manual refill capability to ensure a minimum water level is maintained above the elevation of the fuel within the MCO. The system detects high water temperature and signals the SCIC system to actuate the tempered water trip.

- **Tempered water (annulus) system low level alarm**

  Redundant liquid level indicators are used by the tempered water (annulus) system to detect a low water level in the cask-MCO annulus and to provide a signal to the SCIC system to actuate the low-level alarm.
• Tempered water (annulus) system level check petcocks

The level check petcocks provide a manual means of verifying the presence of water in the annulus. The petcocks are located in and above the double-walled portion of the tempered water (annulus) piping and are connected to the outer and inner pipes above the height of the fuel in the MCO. If a low-level alarm is received, the petcocks can be used to verify the presence of water in the inner or outer pipe, thus indicating the presence of water in the annulus.

Safety-class equipment (performing a safety-significant function) for confinement, purge, and pressurization:

• Cask–MCO

The cask–MCO is a major part of the pressure boundary for confinement of radioactive materials during processing and provides connections for the process piping to the SCHHe system. The MCO also acts as the vessel for helium dilution of hydrogen.

• SCHHe system

The SCHHe system provides two redundant and independent paths for purging and pressurizing the MCO and venting to the process vent. The SCHHe purging and pressurizing functions prevent flammable concentrations of hydrogen and oxygen from forming within the MCO.

• Tempered water (annulus) system piping and antisiphon valves

The tempered water system provides for sufficient heat transfer from the MCO so that excessive corrosion rates and related hydrogen generation rates are not experienced.

• Lines and valves to isolate and purge the MCO

Lines and valves to isolate the MCO include the isolation valves (and filters on air supply to valve actuators) in the VPS, general-service helium system, PWC system, and SCHHe system. Upon demand, all the valves close to isolate the MCO, except the SCHHe system valves, which open to allow helium to the MCO. These SSCs ensure the proper functioning of the SCHHe system.

Safety-significant equipment for confinement:

• Process bay local exhaust HVAC and process vent system (exhaust fans and plenums, duct work, HEPA filters)
The process bay local exhaust HVAC and process vent system mitigates a gaseous release (that would occur subsequent to the line break postulated in this event) into the process bay by sweeping it through HEPA filters before it is discharged outside the facility.

- **Process bay local exhaust HVAC and process vent system process hood isolation damper and instrument air supply**

  Isolation dampers in the process bay local exhaust HVAC and process vent system process hood fail closed. If power is lost, dampers will open with electrical power from the standby power system and instrument air supplied by the local dedicated tank. The hood isolation damper and instrument air supply operate in conjunction with the standby power system to facilitate HVAC operating while on standby power.

- **Process general supply/exhaust HVAC system (exhaust HEPA filter, exhaust duct work, isolation damper)**

  The process general supply/exhaust HVAC system mitigates a release into the process bay or process water tank room by filtering it before discharging it outside the facility. The process general supply/exhaust HVAC system also provides confinement in conjunction with the facility’s structure by maintaining a negative building pressure. Fail-closed exhaust dampers from the process bays and process water tank room isolate other flow paths and ensure that differential pressure is maintained.

- **Reference air system (reference air header, differential pressure alarms)**

  The reference air system monitors the negative pressure in the process bays and process water tank room by providing differential pressure indication and alarms to the control room for operator response.

- **Standby electrical power (diesel generator and process bay local exhaust HVAC and process vent system restart circuit)**

  The standby power system provides connections to restart the local exhaust fans and supporting equipment. Operation of the local exhaust on standby power will maintain building differential pressure sufficient for confinement during facility power outages.

- **Process bay recirculation HVAC system isolation dampers (outside air inlets)**

  The process bay recirculation HVAC system provides fail-closed outside air inlet dampers so the local exhaust on standby power can maintain process bay differential pressure.
Assumptions made that require protection by technical safety requirements (TSRs) are listed below:

- Perform process connector leak test before processing
  
  The VPS process connectors must be verified to be leak-tight to protect analysis assumptions in relation to air inleakage into the MCO and process systems. In the frequency analysis, credit is taken for a reduced likelihood of an air inleakage upon a leak test of the process connectors.

- Close long axial process tube port before closing filtered process exit port at the end of processing
  
  When isolating the MCO at the end of processing, the long axial process tube port must be closed at least 5 minutes before closing the filtered process exit port. This ensures that an SCIC trip will occur if the procedure to isolate the MCO is inadvertently conducted on an MCO still to be processed. Under some conditions, if the filtered process exit port is closed first on an MCO still being processed, it is possible to bypass SCIC trips.

The bounding MCO internal hydrogen explosion accident (I.1) and the other accidents identified in the CVDF hazard analysis report (HNF-SD-SNF-HIE-004) that can potentially involve hydrogen combustion in an MCO are itemized in Table 5-4, along with corresponding checklist designators from the hazard analysis report, safety functions, and SSCs.

The other accidents within the remaining bins require the following safety SSCs and TSRs in addition to the ones identified for the DBA (I.1):

I.2 Hydrogen explosion within an MCO due to instrumentation failure (significant air ingress into the MCO)

The accident scenario identified in the hazard analysis for the I.2 bin represents an internal hydrogen explosion caused by elevated fuel corrosion rates (high bay temperature) (HNF-SD-SNF-HIE-004). The controls in the I2 bin prevent an internal hydrogen explosion by protecting against the malfunction of SSCs. Upon detection of elevated temperatures in the process bay, the MCO is placed into a safe and stable configuration to remove reliance on non-safety related SSCs. For an internal explosion to be possible, a line leak must have occurred to allow an air ingress. To mitigate the gaseous release associated with a line leak, credit is taken for confinement systems to control that release. Note that the confinement systems are not credited with mitigation of the internal explosion release but only with mitigation of the gaseous release associated with the line leak.
Safety-class equipment (performing a safety-significant function) for detection:

- SCIC process bay high temperature detection

The SCIC high bay temperature trip isolates the MCO and actuates the SCHe system so excessive temperatures in the bay cannot cause instrument inaccuracies or malfunctions that might result in MCO overpressurization.

I.3 Hydrogen explosion within an MCO due to loss of MCO control caused by facility fire (significant air ingress into the MCO)

The accident scenarios identified in the hazard analysis for the I.3 bin represent internal hydrogen explosions caused by process upsets during fire in the bay (HNF-SD-SNF-HIE-004). The controls in the I.3 bin prevent an internal hydrogen explosion by protecting safety-related SSCs from damage during a fire in the process bay. Controlling the combustibles in the bay prevents such damage. In addition, credit is taken for controls to protect a bay temperature assumption made in the fire hazards analysis.

Safety-class equipment (performing a safety-significant function) to prevent an internal hydrogen explosion:

- SCIC process bay high temperature trip

The SCIC process bay high temperature trip acts to protect an initial condition assumption in the fire hazards analysis.

Assumptions made that require protection by TSRs are listed below:

- Combustible loadings limited

While an MCO is present in the facility, combustible loadings are limited as determined by the fire hazard analysis (SNF-4268). These limits ensure that any fire in the CVDF does not result in uncontrolled releases (e.g., fire-caused loss of process control).

- Restore bay temperature following a process bay high temperature trip

On high bay temperature trip alarm, operations must return the process bay temperature to within acceptable limits.

I.4 Hydrogen explosion within an MCO due to hydride reaction

The accident scenarios identified in the hazard analysis for the I.4 bin represent internal hydrogen explosions caused by hydride reactions (HNF-SD-SNF-HIE-004). The uranium hydride reaction, in and of itself, has been shown to produce insufficient quantities of hydrogen to cause
an internal hydrogen explosion. Thus, no controls are necessary for this bin. Hydrides have been accounted for as a contributor to other internal hydrogen explosion bins and other DBAs by an increase in the effective corrosion reaction rate.

No additional requirements result from analysis of this accident.

1.5 Hydrogen explosion within an MCO due to loss of support utilities (significant air ingress)

The accident scenarios identified in the hazard analysis for the 1.5 bin represent internal hydrogen explosions caused by loss of support systems resulting from accidents in adjacent bays, crane load drops, and accidents in the spare bay. This bin also includes loss-of-power events caused by external forces (e.g., vehicle accident), flooding, and lightning strike. The controls in the 1.5 bin prevent an internal hydrogen explosion by protecting against the malfunction of SSCs and by controlling specific initiators that would result in a loss of support utilities. For an internal explosion to be possible, a line leak must have occurred to allow an air ingress. To mitigate the gaseous release associated with a line leak, credit is taken for confinement systems to control that release. Note that the confinement systems are not credited with mitigation of the internal explosion release but only with mitigation of the gaseous release associated with the line leak.

Assumptions made that require protection by TSRs are listed below:

- Crane movement restricted during MCO processing except as part of an approved recovery procedure

Bridge crane movement is not allowed from the time that draining operations begin until the proof-of-dryness demonstration is complete and the MCO isolation valves are closed, except as part of an approved recovery procedure. This restriction ensures that key process lines cannot be sheared by crane movement, which could result in damage to systems relied upon to preclude an internal hydrogen explosion.

1.6 Hydrogen explosion within an MCO due to line break caused by a seismic event

The accident scenarios identified in the hazard analysis for the 1.6 bin represent internal hydrogen explosions caused by process upsets following a seismic event (HNF-SD-SNF-HIE-004). The controls in the 1.6 bin prevent an internal hydrogen explosion by removing reliance on nonqualified SSCs (piping and valves) whose failure could allow air ingress into the MCO. The MCO will be vented and confinement SSCs are credited with controlling the potential gaseous release. Note that the confinement systems are not credited with mitigation of the internal explosion release but only with mitigation of the gaseous release.
The manufacturer’s paperwork and shipping papers should be checked upon helium cylinder receipt at the CVDF, both the normal and safety-class supply, to verify that the cylinder’s contents were sampled by the supplier and that the sample met the required purity specification of > 99% helium.
Table 5-4. Summary of Safety Features Required to Mitigate or Prevent a Multi-Canister Overpack Internal Hydrogen Explosion (6 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITSa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen explosion within an MCO due to process upset of key parameters (bounding accident, PB-B-13a)</td>
<td>PB-B-03a PB-B-13a PB-B-13b PB-H-11d PB-H-11e PB-L-11d</td>
<td>Prevent hydrogen explosion:</td>
<td>Safety-class equipment (performing a safety-significant function) for detection of process upset:</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Prevent accumulation of flammable concentrations of hydrogen</td>
<td>+ SCIC, including vacuum limit timer</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>+ Protection against air ingress</td>
<td>+ General-service helium system: safety-class flow instrumentation</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>+ VPS pressure instrumentation</td>
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<td></td>
<td></td>
<td></td>
<td>+ Tempered water (annulus) system temperature trip</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>+ Tempered water (annulus) low level</td>
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<td></td>
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<td></td>
<td>+ Tempered water (annulus) level check petcocks</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Safety-class equipment (performing a safety-significant function) for confinement, purge, and pressurize:</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ Cask-MCO</td>
<td>B</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>+ SCHe system</td>
<td>A</td>
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<td></td>
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<td></td>
<td>+ Lines and valves to isolate and purge the MCO</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ Tempered water (annulus) piping and antisiphon valves</td>
<td>B</td>
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<td></td>
<td></td>
<td></td>
<td>Safety-significant equipment for confinement:</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>+ HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters)</td>
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<td></td>
<td></td>
<td></td>
<td>+ HVAC/PV process hood isolation damper</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>+ HVACD system (exhaust HEPA filter, exhaust duct work, isolation damper)</td>
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<td></td>
<td></td>
<td></td>
<td>+ Standby electrical power (diesel generator and HVAC/PV system restart circuit)</td>
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<td></td>
<td></td>
<td></td>
<td>+ HVACB isolation dampers (outside air inlets)</td>
<td></td>
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<td></td>
<td>Safety-significant equipment for monitoring:</td>
<td>B</td>
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<td></td>
<td></td>
<td></td>
<td>+ Reference air system (reference air header, differential pressure alarms for process bays)</td>
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<td></td>
<td>TSR:</td>
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<td></td>
<td></td>
<td></td>
<td>+ Perform process connector leak test before processing</td>
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<td></td>
<td></td>
<td></td>
<td>+ Close long axial process tube port before closing filtered process exit port at the end of processing</td>
<td></td>
</tr>
<tr>
<td>Candidate accident</td>
<td>Checklist designator</td>
<td>Safety function</td>
<td>Safety features</td>
<td>NRC FITS</td>
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<tr>
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</tr>
<tr>
<td>I.2. Hydrogen explosion within an MCO due to instrumentation failure</td>
<td>PD-B-02a</td>
<td>Prevent hydrogen explosion; Protect against instrumentation inaccuracy</td>
<td>Safety-class equipment (performing a safety-significant function) for detection; SCIC process bay high temperature trip</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Safety-class equipment (performing a safety-significant function) for confinement, purge, and pressurize:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Cask-MCO</td>
<td>A</td>
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<td></td>
<td></td>
<td></td>
<td>• SCDH system</td>
<td>B</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>• Lines and valves to isolate and purge the MO</td>
<td>B</td>
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<td></td>
<td>Safety-significant equipment for confinement:</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• HYACC/PV system (exhaust fans and plenums, duct work, HEPA filters)</td>
<td>A</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• HYACC/PV process hood isolation damper</td>
<td>B</td>
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<td></td>
<td></td>
<td></td>
<td>• HVACD system (exhaust HEPA filter, exhaust duct work, isolation damper)</td>
<td>B</td>
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<td></td>
<td></td>
<td></td>
<td>• Standby electrical power (diesel generator and HYACC/PV system restart circuit)</td>
<td>B</td>
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<td></td>
<td></td>
<td></td>
<td>• HVACB isolation dampers (outside air inlets)</td>
<td>B</td>
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<td></td>
<td>Safety-significant equipment for monitoring:</td>
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<td></td>
<td></td>
<td></td>
<td>• Reference air system (reference air header, differential pressure alarms)</td>
<td>B</td>
</tr>
<tr>
<td>Candidate accident</td>
<td>Checklist designator*</td>
<td>Safety function</td>
<td>Safety features</td>
<td>NRC ITS&lt;sup&gt;8&lt;/sup&gt;</td>
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</tr>
<tr>
<td>I.3. Hydrogen explosion within an MCO due to loss of MCO control caused by facility fire</td>
<td>PB-L-01, PB-L-02, PB-L-03, PB-L-04, PB-L-05, PB-L-06, PB-L-07, PB-L-08, PB-L-09, PB-L-10, PB-L-13, PB-L-14, PB-L-15, PB-L-16</td>
<td>Prevent hydrogen explosion, Protect a processing process bay against external fire (administrative area, transfer corridor, other nonprocessing process bay) and limit the fire risk inside a processing process bay</td>
<td>Safety-class equipment (performing a safety-significant function) for detection: SCIC process bay high temperature trip</td>
<td>B</td>
</tr>
<tr>
<td>I.4. Hydrogen explosion within an MCO due to hydride reaction</td>
<td>PB-I-12</td>
<td>The hydride reaction cannot create enough hydrogen to generate an explosion</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>
### Table 5-4: Summary of Safety Features Required to Mitigate or Prevent a Multi-Canister Overpack Internal Hydrogen Explosion (6 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator</th>
<th>Safety function</th>
<th>Safety features</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.5: Hydrogen explosion within an MCO due to loss of support utilities</td>
<td>PB-F-02a</td>
<td>Prevent hydrogen explosion;</td>
<td>Safety-class (performing a safety-significant function) equipment for detection;</td>
</tr>
<tr>
<td></td>
<td>PB-F-05</td>
<td>+ Place the MCO in a safe configuration during a loss of support utilities</td>
<td>+ SCIC process bay high temperature trip</td>
</tr>
<tr>
<td></td>
<td>SB-F-01b</td>
<td></td>
<td>Safety-class (performing a safety-significant function) equipment for confinement, purge, and pressurize:</td>
</tr>
<tr>
<td></td>
<td>SB-F-02b</td>
<td></td>
<td>+ Cask-MCO</td>
</tr>
<tr>
<td></td>
<td>OU-P-04</td>
<td></td>
<td>+ SCHe system</td>
</tr>
<tr>
<td></td>
<td>OU-R-02</td>
<td></td>
<td>+ Lines and valves to isolate and purge the MCO^4</td>
</tr>
<tr>
<td></td>
<td>OU-R-03</td>
<td></td>
<td>Safety-significant equipment for confinement:</td>
</tr>
<tr>
<td></td>
<td>OU-R-04</td>
<td></td>
<td>+ HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters)</td>
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<td>+ HVAC/PV process hood isolation damper</td>
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<td></td>
<td>+ HVACD system (exhaust HEPA filter, exhaust duct work, isolation damper)</td>
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<td>+ Standby electrical power (diesel generator and HVAC/PV system restart circuit)</td>
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<td>+ HVACB isolation dampers (outside air inlets)</td>
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<td></td>
<td>Safety-significant equipment for monitoring:</td>
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<td></td>
<td></td>
<td></td>
<td>+ Reference air system (reference air header, differential pressure alarms for process bays)</td>
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<td></td>
<td>TSR:</td>
</tr>
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<td></td>
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<td></td>
<td>+ Crane movement restricted during MCO processing except as part of an approved recovery plan</td>
</tr>
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<td></td>
<td>NRC ITS^5</td>
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<td>B</td>
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<td>A</td>
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<td></td>
<td></td>
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<td>B</td>
</tr>
<tr>
<td>Safety function</td>
<td>Checklist designation</td>
<td>Candidate event</td>
<td>NRC ITS</td>
</tr>
<tr>
<td>-----------------</td>
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<td>---------</td>
</tr>
<tr>
<td>Safety-class (performing a safety-significant function) equipment for detection</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>A</td>
</tr>
<tr>
<td>Safety-class (performing a safety-significant function) equipment for shutdown</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>B</td>
</tr>
<tr>
<td>Safety-significant equipment for containment</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>B</td>
</tr>
<tr>
<td>HVAC/CV system (exhaust fans and plenums, duct work, HEPA filters)</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>B</td>
</tr>
<tr>
<td>HVAC/CV system (recess downwind)</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>B</td>
</tr>
<tr>
<td>HVAC/CV system (recess downwind)</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>B</td>
</tr>
<tr>
<td>Safety-significant equipment for monitoring</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>B</td>
</tr>
<tr>
<td>Safety-significant equipment for monitoring</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>B</td>
</tr>
<tr>
<td>Safety-significant equipment for monitoring</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>B</td>
</tr>
<tr>
<td>To address event controlled such that movement from seismic events will not impact key shutdown systems</td>
<td>TRA-01A</td>
<td>1.6: Hydrogen explosion within an MCO due to the break caused by a seismic event</td>
<td>B</td>
</tr>
</tbody>
</table>

Table 5-4: Summary of Safety Features Required to Minimize or Prevent a Multi-Cluster Overpack Internal Hydrogen Explosion (6 sheets)
Table 5-4. Summary of Safety Features Required to Mitigate or Prevent a Multi-Canister Overpack Internal Hydrogen Explosion. (6 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
</tr>
</thead>
<tbody>
<tr>
<td>L7: Hydrogen explosion within an MCO due to contamination of helium supply</td>
<td>FB-H-06k</td>
<td>Prevent a contamination of helium supply</td>
<td>TSR:</td>
</tr>
</tbody>
</table>

  - Shipment paperwork verified for helium supply gas content during receipt

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*U.S. Nuclear Regulatory Commission important-to-safety classifications; Category A = critical to safe operation, Category B = major impact on safety, Category C = minor impact to safety.

Lines and valves to isolate the MCO include the isolation valves (and filters on air supply to valve actuators) in the VPS, general-service helium system, PWC system, and SCHe system.


HEPA = high-efficiency particulate air (filter).
HVAC = process bay recirculation HVAC system.
HVAC/PV = process bay local exhaust HVAC and process vent system.
HVACD = process general supply/exhaust HVAC system.
ITS = important to safety.
MCO = multi-canister overpack.
NRC = U.S. Nuclear Regulatory Commission.
SCHe = safety-class helium.
SCIC = safety-class instrumentation and control.
TSR = technical safety requirement.
VPS = vacuum purge system.
5.6 REFERENCES


Figure 5-1. Logic Diagram for Hydrogen Generation and Combustion inside a Multi-Canister Overpack.
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6.0 CALCULATIONS FOR MULTI-CANISTER OVERPACK THERMAL RUNAWAY REACTION SCENARIOS

6.1 PURPOSE AND OBJECTIVES

The calculations in this chapter address unmitigated and mitigated thermal runaway accident scenarios for a multi-canister overpack (MCO) in the Cold Vacuum Drying Facility (CVDF). Thermal runaway reaction accidents occur when heat removal from the MCO is not sufficient to prevent fuel elements and scrap fuel from heating up as a result of decay heat and chemical reaction heat. As the temperature increases, the chemical reaction rate increases, producing more gases (primarily hydrogen) and heat. The thermal runaway reaction will continue until all of the water is consumed by the uranium-water and uranium hydride-water chemical reactions.

Based on the CVDF hazard analysis report (HNF-SD-SNF-HIE-004), many potential accidents include a thermal or fuel reaction runaway. The accidents involving a thermal runaway reaction have been examined and event-tree analyses performed. Detailed descriptions with the event-tree analyses are presented in Appendix A. From all of the potential thermal runaway reaction accidents, one design basis accident (DBA) has been chosen that is credible for the unmitigated consequence analysis. There are two consequences of interest: (1) temperature and (2) dose. The frequencies are examined in Appendix A, which shows that the DBA is prevented with safety features and equipment. In addition to examining the DBA in the unmitigated analysis, several mitigated scenarios are examined to show the importance of various safety features and equipment.

The HANSF code, version 1.3.2 (SNF-3650), was used to simulate all thermal runaway reaction scenarios. The HANSF code calculates temperatures for the fuel elements and scrap fuel and particulate production by using the reaction rates from HNF-SD-SNF-TI-015. The quality assurance for HANSF is documented in Appendix E of SNF-5226, Comparison Cases Simulated with HANSF 1.3.2 to Supplement Thermal Analyses Documented in HNF-SD-SNF-CN-023.

6.2 SCENARIO DEVELOPMENT

Maximum consequences are expected when there is a thermal runaway reaction accident with high-pressure conditions. However, the frequency of low-pressure thermal runaway is higher than the frequency of a high-pressure thermal runaway simply because a closed (isolated) MCO, which happens for only short time periods under normal conditions, is not required for the low-pressure thermal runaway scenario. Furthermore, the high pressure MCO is analyzed to better evaluate pressure management controls versus temperature management controls (see Chapter 7.0). Hence, the low-pressure thermal runaway scenario was chosen as the high-temperature DBA.
Of all the scenarios evaluated, a loss of annulus water was selected as the DBA because it represents the bounding consequences (highest temperatures and doses).

All of the thermal runaway scenarios require an insufficient rate of heat removal from the inside of the MCO. The amount of heat removal capability needed depends on the heat generation rate from radioactive decay and the fuel–water reaction rate in the MCO. Under normal conditions, the main heat sink or cooling mechanism for the MCO is the flowing tempered annulus water. Because of the high thermal conductivity of water, heat removal from the MCO is still adequate under conditions of stationary annulus water and off-center MCO in cask. Any metal-to-metal contact would improve thermal conductivity. Hotter tempered annulus water has less heat removal capability than cooler annulus water. The temperature capability of the annulus water cooling system ranges from 10 °C to 100 °C with an operating value of 50 °C used in the safety calculations. If the annulus water were lost and air takes the place of the tempered water, then heat removal from the MCO is degraded since the air thermal conductivity is much lower than the water thermal conductivity. With the postulated loss of tempered annulus water, heat generation inside the bounding MCO exceeds the heat removal capability. In the thermal runaway DBA scenario, the annulus water is lost and not restored. The lost annulus water causes the fuel temperatures inside the MCO to slowly increase at first, but after 10 hours, the rate of temperature rise increases significantly. About 11.5 hours after the loss of annulus water, some fuel temperatures exceed 725 °C, the eutectic temperature of uranium and iron (steel).

The high fuel temperatures result in the continuous release of particulate from the MCO, driven by the hot gases generated from the uranium-fuel reaction within the MCO. This release would continue as long as unreacted uranium is in contact with water vapor.

The fuel temperatures reached in localized regions inside the MCO could exceed the uranium-steel eutectic temperature and allow the formation of some eutectic. This could cause spalling and limited structural damage to MCO components such as the scrap and fuel baskets. The thermal calculations with the HANSP code (SNF-3650) predict that about 700 kg of fuel in a Mark IV MCO (all in the bottom scrap basket) will reach a temperature in excess of 700 °C, with a maximum center post temperature less than 1,000 °C. The maximum wall temperature for the Mark IV MCO during the loss of annulus water is 500 °C. For the Mark IA MCO, no fuel reaches temperatures in excess of 710 °C, with a maximum center post temperature of 640 °C. The maximum Mark IA MCO wall temperature is less than 520 °C. These calculations show that no temperatures are reached during the thermal runaway sufficient to cause structural damage to the MCO walls for either fuel type or to the Mark IA baskets and center post. Only limited damage to the bottom Mark IV scrap basket and bottom part of center post is predicted. Thus, the safety-class confinement and criticality contingency function of the MCO and the criticality contingency function of the Mark IA basket center post is not challenged during the thermal runaway. Because the Mark IV baskets are not safety class, limited structural damage would be tolerable.
6.2.1 Unmitigated Initiating Events

The MCO thermal runaway reaction scenario is assumed to begin after the water draining process is finished when some undrained, residual water is still present in the MCO to react with the fuel. The calculation in this chapter assumes the MCO contains a bounding value of 26.5 kg (HNF-SD-SNF-CN-023) of free residual water when the accident is initiated.

To assess the consequences of a thermal runaway accident that is truly unmitigated, the CVDF operators are assumed to not interact with the unmitigated accident. The unmitigated accident scenario assumes an open bounding MCO with uranium hydrides and with no tempered water system, no safety-class helium (SChE) or general service helium system, no 30 lb/in² vent path, no local exhaust system with filter, no general exhaust system with filter, and no operator intervention. Hence, the unmitigated thermal runaway scenario is very hypothetical, but could actually be initiated by the following events (see Appendix A for event tree with frequencies):

- MCO processing without helium flow (the flow of helium does not prevent the thermal runaway, but lengthens the time required to reach high temperatures)
- Loss of tempered water in the annulus between the MCO and the cask (i.e., tempered water system failure); thus, degrading heat removal from MCO
- Continuous release through a failed process line (the release continues as long as unreacted uranium is in contact with water vapor or oxygen).

The unmitigated thermal runaway reaction accident event tree is shown in Appendix A. The unmitigated frequency of MCO that experience a loss of tempered water in the annulus with no restoration is shown on the event tree to be $5 \times 10^4$. Some external event such as a power failure or earthquake could be the common cause failure for the unmitigated thermal runaway scenario, or operator error could be the common cause failure. For the unmitigated accident, the frequencies for the lack of helium flow, the continuous release through a process line, lack of filters, etc. is not explicitly calculated since the accident is unmitigated.

The following assumptions are used in the analyses.

- The MCO thermal runaway reaction scenario is assumed to begin when the water draining process is finished but some undrained (residual) water is still present in the MCO to react with the fuel. It is assumed that 26.5 kg of free undrained (residual) water (1.5 kg in the top scrap basket, 6 kg in the bottom scrap basket, 18 kg in three fuel baskets, and 1 kg in the gap between the bottom fuel basket and the MCO bottom plate) are present when the thermal runaway accident is initiated (SNF-5226).
- Uranium hydrate contains 1.19 kg of water (HNF-SD-SNF-TI-015).
The MCO is at bounding configuration with two scrap baskets.

- Enhancement factor or rate multiplier fuel–water reaction equals 10 (HNF-SD-SNF-TI-015)
- Surface area equals 12 m² (HNF-SD-SNF-TI-015)
- Decay heat rate equals 705 W for three fuel baskets and two scrap baskets (HNF-SD-SNF-TI-015).

Uranium hydride is included using an enhancement factor or rate multiplier of 12 to account for the mass fraction of hydride and its surface area (HNF-SD-SNF-TI-015). This factor is multiplied by the reaction rate from literature in order to conservatively enhance the oxidation rate. The rate multipliers of 12 for hydride–water reactions and 10 for uranium–water reactions are kept separate in the model because each reaction produces different amounts of heat and hydrogen. Hence, the rate multiplier of 22 is just a convenient way to say that both reactions are modeled.

The effects of fuel crumbling at high temperatures were not explicitly included in the analysis but were included in the rate multiplier of 22. Increased reaction rates were not observed experimentally in fuel samples that crumbled over time (HNF-4206), although other samples that did not crumble had lower rates by a factor of 2 to 4. The analysis assumes that the reaction rate multiplier of 10 for uranium and 12 for uranium hydride for a combined rate multiplier of 22 bounds any effects of increased surface area caused by fuel crumbling. For comparison, the crumbled samples had rate multipliers less than 4 (HNF-4206).

No hydrogen gettering takes place because of the presence of water at the beginning of the scenario and air at the end of the scenario. Hydrogen gettering or uranium–hydrogen reaction \( (U + 1.5 \text{H}_2 \rightarrow \text{UH}_3) \) has been shown not to occur to any significant degree in the presence of water or oxygen (SNF-3650).

About 15 kg of particulate are generated between the time the MCO leaves the K Basins and the time it is drained at the CVDF. This newly generated particulate is available to be entrained by exiting gases during a release.

With the high temperatures produced by the thermal runaway conditions, the uranium hydrates will decompose and produce more water (up to 1.19 kg) for the fuel–water reactions.

The quantity of water contained in the aluminum hydroxide, a maximum of about 3.3 kg (HNF-SD-SNF-TI-015), is used in this analysis to account for aluminum hydroxide decomposition at elevated temperatures. This quantity of water is small compared to the 26.5 kg of free water assumed in the analysis and does not
impact the results. Only three baskets have temperatures in excess of 150 °C where some aluminum hydroxide could decompose (ALCOA 1987, Figure 4-4). A total of about 0.74 kg of hydroxide water is released for this scenario.

Additional details regarding input can be found in SNF-5226, Appendix C.

6.2.2 Unmitigated Multi-Canister Overpack Temperature Increase

With no water in the cask–MCO annulus (i.e., loss of coolant) and no helium flow, the fuel decay heat and fuel–water reaction heat will increase the gas temperature in the MCO above 50 °C with or without high pressures (i.e., MCO isolation is not required for a thermal runaway reaction). The uranium–water chemical reaction \(U + 2H_2O \rightarrow UO_2 + 2H_2 + \text{heat}\) and the uranium hydride-water chemical reaction \(\text{UH}_3 + 2H_2O \rightarrow UO_2 + 3.5H_2 + \text{heat}\) will generate hydrogen gas and heat. The steam or water vapor from the heated liquid water will provide an oxidant for the exposed fuel in the scrap basket and fuel baskets.

The key assumption in this unmitigated scenario, with no helium flow, is that enough free residual water exists in the draining or drained MCO to keep reacting with the fuel until temperatures get above 600 °C. Calculations show that less than 10 kg of water is required for a thermal excursion if the annulus water is lost and not restored.

Not all of the water for the fuel reactions needs to be free water because water decomposes from the uranium hydrates at slightly elevated temperatures (>65 °C) and provides additional water for the fuel reactions. Furthermore, even aluminum hydroxide, which may be present on some of the fuel cladding, starts to thermally decompose and free its chemically-bound water at temperatures above 150 °C (ALCOA 1987, Figure 4.4). The aluminum hydroxide water, which can be as high as 3.3 kg (HNF-SD-SNF-TI-015), is included in this analysis as a source term of water vapor because the HANSF code does not have aluminum hydroxide thermal decomposition capability. Only three baskets are hot enough (>150 °C) to have thermal decomposition, which causes about 0.74 kg of chemically bound water to be freed for reaction with fuel. Most of this water is freed in the hot bottom basket. The 0.74 kg of freed water is small compared to the initial 26.5 kg of free residual water and causes only a small effect on the fuel temperatures.

For the unmitigated thermal runaway scenario, the bottom scrap basket innermost fine fuel gets slightly hotter than 1,000 °C in about 11.5 to 12 hours (see details of analysis in SNF-5226, case OVLOCXAL). The HANSF code does not incorporate fuel damage; hence, the code may not predict realistic temperatures if uranium fuel rises above 650 °C, which is its eutectic temperature with aluminum (aluminum liner is placed in fuel basket on bottom plate below the wire mesh), or rises above 725 °C, which is its eutectic temperature with iron or steel (HNF-SD-SNF-SARR-05). If there is no fuel damage, then HANSF is expected to calculate realistic conservative temperatures (SNF-5226). If there were no eutectic interface between the fuel and aluminum (only present in fuel baskets) or steel (more pertinent for scrap baskets), the fuel would melt at around 1,125 °C.
6.2.3 Unmitigated Continuous Release

The fuel–water reactions continue. Even with no air ingress into the MCO, the exposed fuel continues to be oxidized by the water remaining in the MCO, causing a continuous stream of gases and entrained particulate to flow out of the MCO. Both the scrap fuel and exposed fuel elements react with the water vapor that is flowing upwards through the MCO and exiting out the orifice. The water vapor continues to react with uranium and uranium hydride until the water is completely consumed or released; all water (both free and hydrated water) is gone from the two scrap baskets in about 2 hours after high temperatures are reached or about 14 hours after the loss of annulus water. Some water exists in the fuel baskets 24 hours after the loss of annulus water. Since the fuel does not get as hot as the scrap fuel, because the surface area to volume ratio is smaller, water is not consumed as fast in the fuel baskets and some water remains 24 hours after the loss of annulus water.

Some air ingress is expected, primarily after the water is consumed, assuming that air is available outside of the orifice. Because air outside the MCO is cooler and more dense than the hot MCO gases, air will flow counter to the exiting light gases if there is not much flow resistance between the line break/opening and the MCO. After all of the free water and most of the hydrated water is depleted, the MCO will start to cool and draw in more air. The air will continue to react with the exposed fuel, primarily in the upper scrap basket, which is located near the rupture disk orifice at the top of the MCO. However, the upper scrap basket does not have a thermal runaway reaction with incoming air (oxygen). The incoming air rate is not high enough to feed a scrap basket thermal runaway above about 140 °C, meaning that the chemical reaction is oxidant limited at hot temperatures.

6.3 SOURCE TERM ANALYSIS

The respirable source term is based on the material at risk (MAR), the airborne (particulate) release fraction (ARF), and the respirable fraction (RF). These terms are explained and calculated in the following sections.

6.3.1 Unmitigated Material at Risk

When water draining starts in the CVDF, the bounding amount of particulate on the fuel elements and scrap fuel was calculated to be about 20 kg (HNF-SD-SNF-TI-015). This initial particulate is assumed not to be available for airborne release because the initial particulate must be strongly adherent to the fuel and cladding in order to have survived a comprehensive wash at the K Basins.

Under bounding conditions and an off-normal draining process, an additional 15 kg of particulate could be generated between the time the MCO leaves the K Basin area and the time it is drained at the CVDF (HNF-SD-SNF-TI-015). This newly generated particulate would be potentially available to be entrained by exiting gases from the MCO.
For the unmitigated low-pressure thermal runaway accident, the generated particulate was calculated by the HANSF code (SNF-3650) to be about 37 kg of UO₂, which is generated the first 12 hours after the loss of annulus water. This particulate is added to the 15 kg generated before draining is complete for a total of 52 kg UO₂, which is equivalent to about 46 kg spent nuclear fuel (SNF).

The water vapor and liquid water will continue to react with the fuel until all of the water is gone (consumed or released). With the high temperatures (>65 °C) produced by the thermal runaway reactions, the uranium hydrates also will decompose and produce more water for the fuel–water reactions. There is bounding value of 1.19 kg of water in the uranium hydrates (HNF-SD-SNF-TI-015), and the thermal decomposition of the hydrates, which can become significant at temperatures above 65 °C, was calculated using the HANSF code (SNF-3650). The results of the thermal runaway reaction are not sensitive to the amount of hydrate water since it is much smaller (1.19 kg) than the amount of residual free water left after draining (26.5 kg).

The HANSF code was used to calculate particulate generation of UO₂ over the 24-hour time period after the loss of annulus water. About 163 kg of particulate is generated 24 hours after the loss of annulus water. This particulate is added to the 15 kg of particulate generated before draining is finished to get the total newly generated particulate value of 178 kg, which is equivalent to 161.3 kg SNF, generated 24 hours after the loss of annulus water.

Some of the particulate generated will become entrained by the exiting gases (hydrogen and water vapor) and be released to the environment.

In summary, the total particulate MAR consists of the following values:

- \( \text{MAR}_1 = 13.2 \text{ kg SNF (15 kg UO}_2\text{) oxidized between K Basin cleaning and completion of the draining process (HNF-SD-SNF-TI-015).} \)

  This value was not calculated by HANSF code and is only used as part of the following MARs.

- \( \text{MAR}_2 = 46 \text{ kg SNF (52 kg UO}_2\text{) for the 12-hour continuous release (includes MAR}_1\text{).} \)

- \( \text{MAR}_3 = 157 \text{ kg SNF (178 kg UO}_2\text{) for the 24-hour continuous release (includes MAR}_1\text{).} \)

The release fractions are described in the following section.

### 6.3.2 Airborne Release Fraction and Respirable Fraction

In the following sections, the product of ARF and RF is estimated for the continuous releases that follow the loss of annulus water (applied to \( \text{MAR}_2 \) and \( \text{MAR}_3 \)).
6.3.2.1 Continuous Releases. Some of the new particulate is continuously released with the hydrogen through the line opening or break (unmitigated scenario). Under very high temperature conditions, the ARF of all radionuclides in the fuel, such as the fission products (e.g., cesium) and transuranics (e.g., plutonium), will not be the same as the uranium particulate release. For example, the cesium and other semi-volatiles in the fuel could vaporize at temperatures in excess of 600 °C, increasing the rate at which it becomes airborne (DOE-STD-1027-92). However, cesium and other nontransuranic radionuclides contribute less than 0.5% of the SNF dose factor (total rem per gram of the SNF). Hence, any increase of release fraction for this group of radionuclides will not significantly affect the total dose.

The bounding value of the respirable release fraction, ARF x RF, for particulate release for rapid uranium oxidation (thermal stress: uranium, > 500 °C) is 1.0 x 10⁻³, as reported in DOE-HDBK-3010-94, Airborne Release Fraction/Rates and Respirable Fractions/Rates for Nonreactor Nuclear Facilities (page 4-3). The bounding respirable release fraction for falling molten uranium droplets (temperature > 1,100 °C) is 1.0 x 10⁻² (DOE-HDBK-3010-94). Since falling molten droplets with high surrounding gas velocities are not the physical situation in the high-temperature MCO, 1.0 x 10⁻² is considered overly conservative. On the other hand, since some MCO fuel temperatures exceed 1,000 °C and may approach 1,125 °C, the 1.0 x 10⁻³ release fraction for fuel with temperature > 500 °C may not be bounding. Hence, an intermediate respirable release fraction of 5 x 10⁻³ was selected for this analysis, which is considered conservative.

Additional analyses using the HANSF version 1.3.2 code (SNF-3650) may adequately demonstrate that fuel melting does not occur. The implications of a revised thermal runaway DBA with reduced consequences (as a result of not incorporating a molten fuel ARF) are being evaluated further to assess impact on selected controls. The ARF used in this analysis is conservative.

The source term, \( M_2 \), for the continuous release is calculated by multiplying \( MAR_2 \), the MAR for the 12-hour continuous release, by the product of ARF and RF as follows:

\[
M_2 = (MAR_2)(ARF \times RF) \\
= (46 \text{ kg SNF})(1,000 \text{ g/kg})(5.0 \times 10^{-3}) \\
= 230 \text{ g SNF}.
\]

The source term, \( M_3 \), for the 24-hour continuous release (offsite) is calculated by multiplying \( MAR_3 \), the MAR for the 24-hour continuous release, by the product of ARF and RF as follows:

\[
M_3 = (MAR_3)(ARF \times RF) \\
= (157 \text{ kg SNF})(1,000 \text{ g/kg})(5.0 \times 10^{-3}) \\
= 785 \text{ g SNF}.
\]
In summary, the total bounding source term for environmental doses consists of two numbers, one for each continuous release:

- \( M_2 = 230 \text{ g SNF} \) for the 12-hour continuous release
- \( M_3 = 785 \text{ g SNF} \) for the 24-hour continuous release.

### 6.4 CONSEQUENCE ANALYSIS

The radiological dose is calculated using the following equation:

\[
DE = M \times \frac{x}{Q'} \times BR \times UD
\]

where

- \( D \) = effective dose equivalent based on inhalation exposure only (rem)
- \( M \) = respirable quantity released into the air (g)
  - \( M_2 \) for 12-hour (onsite) continuous release (230 g SNF)
  - \( M_3 \) for 24-hour (offsite) continuous release (785 g SNF)
- \( x/Q' \) = air transport factor (s/m³) from Table 1-4
- \( BR \) = average inhalation rate during the blowdown and 12-hour release (m³/s)
- \( UD \) = committed effective dose equivalent per unit gram inhaled (438,000 rem/g SNF).

Unmitigated Consequences. The dose calculation equation and data from Chapter 1.0 are used to calculate the dose to the offsite receptor.

\[
D_{\text{offsite}} = M_3 \times \frac{x}{Q'} \times BR \times UD
\]

\[
= (785 \text{ g SNF})(6.50 \times 10^{-6} \text{ s/m}^3)(2.64 \times 10^{-4} \text{ m}^3/\text{s})(4.38 \times 10^5 \text{ rem/g SNF})
\]

\[
= 0.59 \text{ rem (0.0059 Sv)} \text{ for 24-hour continuous release.}
\]

The 24-hour continuous release yields a total offsite dose of 0.59 rem (0.0059 Sv).

The dose consequences at the remaining receptor sites are calculated in the same manner and are shown in Table 6-1 for the 12-hour and 24-hour continuous releases. The mitigated doses are actually prevented, as shown in Appendix A, but the onsite doses are shown here for completeness.
Table 6-1. Dose Calculation Summary for Unmitigated and Mitigated Thermal Runaway Reaction.

<table>
<thead>
<tr>
<th>Receptor location (distance, direction)</th>
<th>Duration (hours)</th>
<th>$\chi/Q^a$ (s/m³) (without stack or plume meander)</th>
<th>Unmitigated dose$^b$ (rem (Sv))</th>
<th>Evaluation guideline/release limits rem (Sv), unlikely$^c$</th>
<th>Safety-significant mitigated dose rem (Sv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>12 (continuous)</td>
<td>6.28 E-03</td>
<td>210 (2.1)</td>
<td>10$^d$ (1.0 E-01)</td>
<td>0.21 (2.1 E-03) prevented</td>
</tr>
<tr>
<td>Columbia River (650 m W)</td>
<td>12 (continuous)</td>
<td>1.99 E-04</td>
<td>6.7 (0.067)</td>
<td></td>
<td>0.0067 (6.7 E-05) prevented</td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>12 (continuous)</td>
<td>2.73 E-05</td>
<td>0.92 (0.009)</td>
<td></td>
<td>9.2 E-04 (9.2 E-06) prevented</td>
</tr>
<tr>
<td>Hanford Site Boundary (10,090 m W)</td>
<td>24 (continuous)</td>
<td>6.50 E-06</td>
<td>0.59 (0.0059)</td>
<td>5.0$^*$ (5.0 E-01)</td>
<td>5.9 E-04 (5.9 E-06) prevented</td>
</tr>
</tbody>
</table>


$^a$Fifty-year committed effective dose equivalent.

$^b$Unlikely event frequency is $>10^4$ to $10^5$.

$^c$Evaluation guideline for onsite (100 m) receptor for unmitigated accidents in the unlikely frequency category.

$^d$Release limit for unmitigated accidents in the unlikely frequency category.

6.4.1 Other Mitigated Thermal Runaway Scenarios

6.4.1.1 Air Ingress. If the vacuum pump is functioning when a line break exists, an air ingress accident could occur, which could lead to hydrogen deflagration inside the MCO (see Section 5.0). Hence, the most stable shut down mode is to close the main isolation valves of the MCO and turn on the SCHe system, and restore the annulus water if it were lost. Air ingress will not result in a thermal runaway reaction unless the fuel is very hot (> 125 °C), which doesn't happen under normal processing. More discussion on air ingress scenarios can be found in HNF-3553, Spent Nuclear Fuel Project Final Safety Analysis Report, Annex A, “Canister Storage Building Final Safety Analysis Report.”

6.4.1.2 Degraded Vacuum. This scenario assumes a severely degraded vacuum pumping rate of 13 ft³/min instead of 35 ft³/min with no helium flow and has a high unmitigated frequency of $3.4 \times 10^2$ (Appendix A). This scenario results in high fuel temperatures for some of the fuel even with circulating 50 °C annulus water if no helium purge is present (see details in SNF-5226, case VXDG). Since this scenario has a high unmitigated frequency, and maximum fuel temperatures exceeding the eutectic temperatures, it must be prevented or mitigated. If the vacuum pumping rate does not stay at 30 ft³/min or more, the vacuum is considered to be degraded or off-normal.
This can be caused by air ingress between the MCO and vacuum pump, a partially blocked process line, or a degraded vacuum pump itself. This scenario has numerous causes, and therefore, has a high frequency of $3.4 \times 10^{-2}$ (Appendix A). The SCHe system, the general-service helium system with safety-class flow meter and alarm, and the 8-4-4 cycle are all designed to prevent the degraded vacuum high-temperature accident.

The 8-4-4 cycle refers to the starting the vacuum drying procedure with 8 hours of vacuuming with helium purge, followed by 4 hours of helium purge only, and then continuing with 4 hours of vacuuming with helium purge. The 4 hours of vacuum+helium purge and 4 hours of just helium purge alternate until the MCO is dry enough for the proof test. The 8-4-4 cycle is very stable and is stable for annulus water temperatures 10 °C higher than 50 °C. The safety-class instrumentation and control (SCIC) system monitors the cycle times of the 8-4-4 cycle and initiates the SCHe system if the cycle times aren't right. The SCHe system provides a stable shut down mode even if the general service helium does not feed the SCHe supply line, resulting in only one hour of helium supply (SCHe supply bottle). Just having the helium there initially at 10 lb/in² gauge pressure is enough to provide stable temperatures if the annulus water is 50 °C or less. The frequency of the mitigated scenario with the SCHe system and the 8-4-4 cycle functional is $3.38 \times 10^{-10}$ (Appendix A), which shows that the degraded vacuum, high-temperature scenario (no helium purge) is prevented.

6.4.1.3 Helium Flow or Purge. Helium flow or purge with a degraded vacuum will keep the fuel temperatures stable even if the vacuum pumping is degraded down to 13 ft³/min, as long as the annulus water is maintained (see SNF-5226 for detailed results, case VPDG1P4). If the annulus water is lost, as in the DBA, then helium flow will not prevent localized hot spots in the top scrap basket. However, if the annulus water is lost, the helium flow will not only minimize the amount of fuel that gets hot (> 700°C) but will also delay the start of rapid fuel temperature rise to 16 hours. As mentioned previously, if the annulus water is maintained (stagnant annulus requires the process bay temperature to be < 115 °F), stagnant helium (supplied by the system) is sufficient to maintain stable fuel temperatures. The loss of annulus water and failure to restore it has been shown to have a frequency of $6.6 \times 10^{-7}$, which is beyond extremely unlikely (Appendix A).

6.5 COMPARISON TO GUIDELINES

Comparison of Unmitigated Doses. The unmitigated frequency of the event tree sequences that represent this DBA, including an unfiltered release, is $5 \times 10^{-4}$ per year, thus this unmitigated DBA is unlikely (see Appendix A). The unmitigated sequence considered the processing of 200 MCOs per year, failure of single-walled tempered water system inlet piping, and a leak in the vacuum line. The unmitigated radiological offsite dose for this event is above offsite release limits.

Comparison of Mitigated Doses. The mitigated frequency of the event tree sequences that represent this DBA as a thermal runaway excursion is $1 \times 10^{-8}$ per year without release. Thus, this mitigated DBA is beyond extremely unlikely (see Appendix A). The accident is prevented
with safety-class features (i.e., tempered water double-walled pipe and the ability to detect low annulus water and refill the system). Failure of prevention features is beyond extremely unlikely. Thus, the offsite release limits and onsite evaluation guidelines are met.

6.6 SUMMARY OF SAFETY-CLASS STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

Under normal operating conditions, annulus water levels and helium in the MCO provide adequate heat transfer to prevent thermal runaway reactions. Under upset or accident conditions, safety-class equipment is required in order to ensure this capability is not lost. The heat transfer from the MCO could be compromised by a loss of water level or high tempered water temperatures. The heat transfer within the MCO could be compromised by a loss of helium.

The checklist designators included in the accident bins, other than the accident selected as the DBA, represent additional accident sequences slightly different than the DBA. All of these binned accidents are bounded by the DBA because they have lesser or equivalent worst-case consequences and frequencies.

The accident scenarios identified in the hazard analysis for the T.1 bin represent thermal runaway accidents caused by failure of the proof-of-dryness demonstration (instrumentation failure or operator error) and degraded vacuum pump and subsequent possible elevated fuel temperatures. This bin also includes thermal runaways in a loss-of-power event caused by external forces (e.g., vehicle accident), flooding, and lightning strikes (HNF-SD-SNF-HIE-004). The controls in the T.1 bin prevent a thermal runaway by ensuring that an adequate heat sink is available. In addition, credit is taken for controls that prevent bypass of safety features by incorrectly proceeding with the cold vacuum drying process or by operator error.

The safety-class equipment designated to prevent the dose consequences of thermal runaway reaction accidents are described below.

Safety-class equipment for detection of process upset:

- **Tempered water (annulus) system level alarm**

  Redundant liquid level indicators are used by the tempered water (annulus) system to detect a low water level in the cask-MCO annulus and to provide a signal to the SCIC system to actuate the low-level alarm.

- **Tempered water (annulus) system level check petcocks**

  The level check petcocks provide a manual means of verifying the presence of water in the annulus. The petcocks are located in and above the double-walled portion of the tempered water (annulus) piping and are connected to the outer and
inner pipes above the height of the fuel in the MCO. If a low-level alarm is received, the petcocks can be used to verify the presence of water in the inner or outer pipe, thus indicating the presence of water in the annulus.

Safety-class equipment for heat removal:

- Tempered water (annulus) system piping and antisiphon valves

A portion of the tempered water (annulus) system contains double-walled safety-class piping and antisiphon valves to ensure retention of a minimum water level above the elevation of the SNF inside the MCO.

- Manual refill piping and vent port

The tempered water (annulus system) provides manual refill capability, which could be required if a low annulus water level were detected.

- Cask-MCO

The cask-MCO is a major part of the pressure boundary for tempered water (annulus) and a confinement of radioactive materials during processing and provides connections for the process piping to the SCHe system.

Assumptions made that require protection by technical safety requirements (TSRs) are listed below:

- Administrative procedure for restricting crane movement during MCO processing except as part of an approved recovery procedure

Bridge crane movement is not allowed from the time that draining operations begin until the proof-of-dryness demonstration is complete and the MCO isolation valves are closed except as part of an approved recovery procedure. This restriction ensures that key process lines cannot be sheared by crane movement, which could result in loss of annulus water if the lower tempered water (annulus) line were damaged.

- Procedure to verify the results of the pressure rebound tests before continuing process steps

An initial pressure rebound test surveillance (pressure rise test) must be met before entry into the proof-of-dryness demonstration is allowed. Similarly, a proof-of-dryness demonstration surveillance must be met before the final pressure rebound test steps can begin. Finally, a final pressure rebound test must be met before shipment preparation steps can begin.
Close long axial process tube port before closing filtered process exit port at the end of processing.

When isolating the MCO at the end of processing, the long axial process tube port must be closed at least 5 minutes before closing the filtered process exit port. This ensures that an SCIC trip will occur if the procedure to isolate the MCO is inadvertently conducted on an MCO still to be processed.

The bounding thermal runaway accident (T.1) and the other accidents identified in the CVDF hazard analysis report (HNF-SD-SNF-HIE-004) that can potentially involve a thermal runaway reaction in an MCO are itemized in Table 6-2, along with corresponding checklist designators from the hazard analysis report, safety functions, and structures, systems, and components (SSCs).

The accidents within the remaining bins require the following safety SSCs and TSRs, in addition to those identified for the DBA (T.1):

**T.2 Thermal runaway reaction in MCO due to instrumentation failure**

The accident scenarios identified in the hazard analysis for the T.2 bin represent thermal runaway accidents caused by elevated fuel temperatures resulting from a high bay temperature and high annulus water temperature (HNF-SD-SNF-HIE-004). The controls in the T2 bin prevent a thermal runaway by monitoring key process parameters and by protecting safety-related SSCs from damage. SCHe actuation is credited, therefore confinement and dilution provided by the local exhaust system also are credited.

Safety-class equipment for detection of process upset or instrumentation failure:

- Vacuum purge system (VPS) instrumentation (pressure)

  Pressure indicators on the VPS provide MCO internal pressure information to the SCIC system, which initiates MCO isolation and SCHe actuation during process upset conditions.

- SCIC vacuum cycle timer (8-4-4 logic)

  The SCIC system uses programmable logic controllers, wiring to process instrumentation, vacuum limit timer, signals from seismic detectors and temperature monitors, system controls, and output relays to perform an MCO isolation and purge trip and a tempered water trip.
Tempered water (annulus) system temperature trip

The system has temperature indicators and transmitters to detect high tempered water (annulus) water temperature and signals the SCIC system to actuate the tempered water trip.

SCIC process bay high temperature trip

The SCIC high bay temperature trip isolates the MCO and actuates the SChE system. A safety-class alarm alerts operations to the bay condition.

Safety-class equipment for confinement, purge, and pressurization:

- Cask-MCO

The cask-MCO is a major part of the pressure boundary for confinement of radioactive materials during processing and provides connections for the process piping to the SChE system.

- SChE system

The SChE system provides two redundant and independent paths for purging and pressurizing the MCO and venting to the process vent. The SChE purging and pressurizing functions help to prevent elevated temperatures inside the MCO.

- Lines and valves to isolate and purge the MCO

Lines and valves to isolate the MCO include the isolation valves (and filters on air supply to valve actuators) in the VPS, general-service helium system, process water conditioning (PWC) system, and SChE system. Upon demand, all the valves close to isolate the MCO, except the SChE system valves, which open to allow helium to the MCO.

Safety-significant equipment for dilution and filtration to support SChE operation:

- Process bay local exhaust heating, ventilation, and air conditioning (HVAC) and process vent system (exhaust fans and plenums, duct work, high-efficiency particulate air [HEPA] filters)

The process bay local exhaust HVAC and process vent system mitigates a gaseous release into the process bay by sweeping it through HEPA filters before it is discharged outside the facility. This ensures that SChE flows are filtered and diluted.
Process bay local exhaust HVAC and process vent system process hood isolation damper and instrument air supply

Isolation dampers in the process bay local exhaust HVAC and process vent system process hood fail closed. If power is lost, dampers will open with electrical power from the standby power system and instrument air supplied by the local dedicated tank. The hood isolation damper and instrument air supply operate in conjunction with the standby power system to facilitate HVAC operating while on standby power. This supports operation of the local exhaust to filter and dilute SCHe flows.

Standby electrical power (diesel generator and process bay local exhaust HVAC and process vent system restart circuit)

The standby power system provides connections to restart the local exhaust fans and supporting equipment. Operation of the local exhaust on standby power will maintain building differential pressure sufficient for confinement during facility power outages. This supports operation of the local exhaust to filter and dilute SCHe flows.

Assumptions made that require protection by TSRs are listed below.

- Restore bay temperatures following process bay high temperature trip

On high bay temperature trip alarm, operations must return the process bay temperatures to within acceptable limits.

T3 Thermal runaway reaction in MCO due to loss of MCO control caused by facility fire

The accident scenarios identified in the hazard analysis for the T3 bin represent thermal runaway accidents caused by process upsets from internal and external facility fires (HNF-SD-SNF-HIE-004). The controls in the T3 bin prevent a thermal runaway by protecting safety-related SSCs from damage during a fire event in the bay. Credit also is taken for controls on the bay temperature to protect an assumption made in the fire hazards analysis.

Safety-class equipment for detection:

- SCIC process bay high temperature trip

The SCIC process bay high temperature trip acts to protect an initial condition assumption in the fire hazards analysis.
Assumptions made that require protection by TSRs are listed below.

- **Combustible loadings limited**
  
  While an MCO is present in the facility, combustible loadings are limited as determined by the fire hazard analysis (SNF-4268).

- **Restore bay temperature following a process bay high temperature trip**
  
  On high bay temperature trip alarm, operations must return the process bay temperature to within acceptable limits.

**T.4 Thermal runaway reaction in MCO due to loss of support utilities**

The accident scenarios identified in the hazard analysis for the T.4 bin represent thermal runaway accidents caused by a loss of a support system because of accidents in adjacent bays, crane load drops, and accidents in the spare bay (HNF-SD-SNF-HIE-004). The controls in the T4 bin prevent a thermal runaway by monitoring key process parameters, precluding water addition to the MCO, and placing the MCO into a safe and stable configuration. SCHe actuation is credited, therefore confinement and dilution provided by the local exhaust system also are credited.

**Safety-class equipment to prevent process upsets:**

- Deionized water and PWC drain line isolation valves interlocked closed after being used in the process

  The VPS isolation valves (on the deionized water supply line) and the PWC drain line isolation valves prevent water from entering the MCO. After these lines are used in the process, they are closed and interlocked to the SCIC system so they cannot be inadvertently opened later in the process.

**T.5 Thermal runaway reaction in MCO due to contamination of helium supply**

The accident scenario identified in the hazard analysis for the T.5 bin represents a thermal runaway accident caused by fuel reactions with contaminants in the helium supply (HNF-SD-SNF-HIE-004). The controls in the T5 bin prevent a thermal runaway by controlling the helium supply to the MCO.

Assumptions made that require protection by TSRs are listed below.

- **Shipment paperwork verified for gas bottle content during receipt**

  The manufacturer's paperwork and shipping papers shall be checked upon helium cylinder receipt at the CVDF, both the normal and safety-class supply, to verify that
the cylinder's contents were sampled by the supplier and that the sample met the required purity specification of >99% helium.

T.6 Thermal runaway reaction in MCO due to line break caused by a seismic event

The accident scenarios identified in the hazard analysis for the T.6 bin represent thermal runaway accidents caused by process upsets following a seismic event (HNF-SD-SNF-HIE-004). The controls in the T6 bin prevent a thermal runaway by removing reliance on nonqualified SSCs and placing the MCO into a safe and stable configuration.

Safety equipment for detection of seismic event

- SCIC seismic trip

On detecting a seismic event, the SCIC system seismic trip isolates the MCO and actuates the SCHe system and de-energizes the tempered water (annulus) system to ensure the seismic event will not initiate thermal runaway.

Assumptions made that require protection by TSRs are listed below:

- Trailer placement controlled such that movement from seismic events will not impact key shutdown systems

Before connecting CVDF systems to the MCO, the cask, which is located upon the trailer, must be positioned such that the cask is no greater than an established safe distance from the ideal horizontal placement. This control protects the MCO and safety-class components during seismic events.
<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS^b</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.1 Runaway reaction due to loss of process control parameter (including presence of heat sink) (bounding accident PB-B-13g)</td>
<td>PB-B-13c</td>
<td>Prevent runaway reaction</td>
<td>Safety-class equipment for detection:</td>
<td>B</td>
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<tr>
<td></td>
<td>PB-B-13d</td>
<td>Maintain parameters within limits</td>
<td>Tempered water (annulus) system level alarm</td>
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<td>PB-H-08</td>
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<td>Tempered water (annulus) system level check petcocks</td>
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<td>OU-P-04</td>
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<td>Safety-class equipment for heat removal:</td>
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<td>OU-R-02</td>
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<td>Tempered water (annulus) system piping and antisiphon valves</td>
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<td></td>
<td>OU-R-03</td>
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<td>Manual refill piping and vent port</td>
<td>B</td>
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<td>OU-R-04</td>
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<td>Cask-MCO</td>
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<td>TSIR:</td>
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<td>Administrative procedure for restricting crane movement during MCO processing except as part of an approved recovery procedure</td>
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<td>Close long axial process tube port before closing filtered process exit port at the end of processing</td>
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<td>Procedure to verify the results of the pressure rebound tests before continuing process steps</td>
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<td>Defense-in-depth equipment for confinement, purge, and pressurize:</td>
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<td>General-service helium system, safety-class flow instrumentation</td>
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<td>SCHe system</td>
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<td>Lines and valves to isolate and purge the MCO^4</td>
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<td>Candidate accident</td>
<td>Checklist designator</td>
<td>Safety function</td>
<td>Safety features</td>
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<tr>
<td>T.2. Runaway reaction in MCO due to instrumentation failure</td>
<td>PB-B-026</td>
<td>Protect instrumentation</td>
<td>Safety-class equipment for detection:</td>
<td>B</td>
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<td></td>
<td>PB-B-03a</td>
<td>operability and analysis assumption</td>
<td>• VPS instrumentation (pressure)</td>
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<td>• SCIC vacuum cycle timer (8-4-4 logic)</td>
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<td>• SCIC process bay high temperature trip</td>
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<td>• Tempered water (annulus) system: temperature trip</td>
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<td>Safety-class equipment for confinement, purge, and pressurization:</td>
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<td>• Cask-MCO</td>
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<td>• SCHe system</td>
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<td>• Lines and valves to isolate and purge the MCO</td>
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<td>Safety-significant equipment for dilution and filtration to support SCHe operation:</td>
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<td>• HVAC/PV system (exhaust fans and plenums; duct work, HEPA filters)</td>
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<td>• HVAC/PV process hood isolation damper</td>
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<td>• Standby electrical power (diesel generator and HVAC/PV system restart circuit)</td>
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<td>TSR:</td>
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<td>• Administrative procedure for restricting crane movement during MCO processing except as part of an approved recovery procedure</td>
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<td>• Restore bay temperatures following process bay high temperature trip</td>
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<td>Defense in depth:</td>
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<td>• HVAC maintains operating bay temperature</td>
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Table 6-2. Summary of Safety Features Required to Mitigate or Prevent a Thermal Runaway Reaction. (6 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS*</th>
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</thead>
<tbody>
<tr>
<td>T:3 Runaway reaction in MCO due to loss of MCO control caused by facility fire</td>
<td>PB-L-01, PB-L-02, PB-L-03, PB-L-04, PB-L-05, PB-L-06, PB-L-07, PB-L-08, PB-L-09, PB-L-10, PB-L-13, PB-L-14, PB-L-15, PB-L-16, PB-P-02, OU-P-02a</td>
<td>Protect a processing process bay against external fire, administrative area, transfer corridor, other nonprocessing process bay, and limit the fire risk inside a processing process bay</td>
<td>Safety-class equipment (performing a safety-significant function) for detection: SCIC process bay high temperature trip</td>
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<td>TSR:</td>
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<td>- Combustible loadings limited</td>
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<td>- Restore bay temperatures following process bay high temperature trip</td>
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<td>Defense-in-depth equipment for process upset conditions and process bay temperature detection:</td>
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<td>- VPS instrumentation (pressure)</td>
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<td>- SCIC vacuum cycle timer (8-4-4-4 logic)</td>
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<td>- Tempered water (annulus) system temperature trip</td>
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<td>- Tempered water (annulus) system level alarm</td>
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<td>- General-service helium system: safety-class flow instrumentation</td>
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<td>Defense-in-depth equipment for heat removal:</td>
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<td>- Tempered water (annulus) system piping and antisyphon valves</td>
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<td>- Manual refill piping and vent port</td>
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<td>- Cask-MCO</td>
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<td>Defense-in-depth equipment for shutdown:</td>
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<td>- SCHe system</td>
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<td>- Lines and valves to isolate and purge the MCO*</td>
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<td>Defense in depth:</td>
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<td>- Procedure to limit combustible loading</td>
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<td>- Fire protection system present in each bay</td>
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<td>- SCHe system</td>
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<td>- Lines and valves to isolate and purge the MCO*</td>
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<tr>
<td>Candidate accident</td>
<td>Checklist designator</td>
<td>Safety function</td>
<td>Safety features</td>
<td>NRC ITS*</td>
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<tr>
<td>T.4: Runaway reaction due to loss of support utilities</td>
<td>PB-F-02a, PB-F-05, SB-F-01b, SB-F-02b</td>
<td>Prevent runaway reaction: Place the MCO in a safe configuration during a loss of support utilities</td>
<td>Safety-class equipment for detection: VPS instrumentation (pressure), SCIC (pressure/vacuum cycle timer) (B-4-4-logic), SCIC process bay high temperature trip</td>
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<td>Safety-class equipment for heat removal: Tempered water (annulus) system piping and antisuiph valves</td>
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<td>Manual refill piping and vent port</td>
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<td>Cask-MCO</td>
<td>A</td>
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<td>Safety-class equipment for confinement, purge, and pressurization: SCHe system</td>
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<td>Lines and valves to isolate and purge the MCO*</td>
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<td>Safety-class equipment for prevention of process upset: Deionized water and PWC drain line isolation valves interlocked closed after</td>
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<td>being used in the process</td>
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<td>Safety-significant equipment for dilution and filtration to support SCHe operation: HVAC/C/V system (exhaust fans and plenums, duct work, HEPA filters)</td>
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<td>HVAC/C/V process hood isolation damper</td>
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<td>Standby electrical power (diesel generator and HVAC/C/V system restart circuit)</td>
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<td>TSR: Administrative procedure for restricting crane movement during MCO processing except as part of</td>
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<td>an approved recovery procedure</td>
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<td>Defense-in-depth equipment for confinement, purge, and pressurize: General-service helium system:</td>
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<td>safety-class flow instrumentation</td>
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</table>
Table 6-2: Summary of Safety Features Required to Mitigate or Prevent a Thermal Runaway Reaction (6 sheets)

<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist desig.</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS*</th>
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</thead>
</table>
| T.4: Runaway reaction due to loss of support utilities (continued) | | | Defense-in-depth equipment for MCO process testing:  
   + Initial pressure rebound test prior to proof-of-dryness demonstration (temperature indicator on the tempered water [annulus] system and pressure on the VPS)  
   + Final pressure rebound test following the proof-of-dryness demonstration after all potential water sources are isolated (temperature indicator on the tempered water [annulus] system and pressure on the VPS) | | |
| T.5: Runaway reaction due to a contamination of the helium supply | PB-H-06k | Prevent using a contaminated helium supply | TSR:  
   + Shipment paperwork verified for helium receipt | |
| T.6: Runaway reaction due to line break caused by a seismic event | PB-R-01a OU-R-01a | Prevent the runaway reaction:  
   + Place the MCO is a safe configuration following a seismic event | Safety-class equipment for tempered water annulus level  
   + Tempered water (annulus) system piping and anti-siphon valves  
   + Refill piping and vent port  
   Safety equipment for detection of seismic event  
   + SCIC seismic trip  
   Safety-class equipment for confinement, purge, and pressurization:  
   + Cask–MCO  
   + SCHN system  
   + Lines and valves to isolate and purge the MCO* | B |
<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
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</thead>
</table>

*Checklist designators are from HNF-SD-SNF-HIE-004, 1999, Cold Vacuum Drying Facility Hazard Analysis, Rev. 4, Fluor Daniel Hanford, Incorporated, Richland, Washington.

*U.S. Nuclear Regulatory Commission important-to-safety classifications: Category A = critical to safe operation, Category B = major impact on safety, Category C = minor impact to safety.

*Lines and valves to isolate the MCO include the isolation valves (and filters on air supply to valve actuators) in the VPS, general-service helium system, PWC system, and SCHe system.

HEPA = high-efficiency particulate air (filter)
HYAC = heating, ventilation, and air conditioning
HYAC/PV = process bay local exhaust HVAC and process vent system
ITS = important to safety
MCO = multi-cask overpack
NRC = U.S. Nuclear Regulatory Commission
PWC = process water conditioning
SCHe = safety-class helium
SCIC = safety-class instrumentation and control
TSR = technical safety requirement
VPS = vacuum purge system
8-4-4 = 8-hour initial vacuum cycle, 4-hour subsequent vacuum cycles, 4-hour return to pressure between vacuum cycles.
6.7 REFERENCES


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7.0 CALCULATIONS FOR MULTI-CANISTER OVERPACK OVERPRESSURIZATION

7.1 PURPOSE AND OBJECTIVES

The calculations in this chapter address overpressurization accidents for a multi-canister overpack (MCO) in the Cold Vacuum Drying Facility (CVDF). Overpressurization of an MCO occurs when the MCO gas pressure increases faster than a vent path or gaseous release path lowers it. The main concern is for an isolated MCO with no vent path or relief path. With water in the MCO, even after it is drained, the fuel-water reactions produce hydrogen gas, which increases the MCO pressure. Without proper venting or relieving while the fuel-water reaction continues (i.e., water remains), the pressure will increase until the MCO containment fails (vessel failure or rupture disk opening).

There are two consequences of interest: (1) MCO pressure and (2) dose. The frequencies are examined in Appendix A, which shows that the design basis accident (DBA) is prevented with safety features and equipment. In addition to examining the DBA in the unmitigated analysis, several mitigated scenarios are examined to show the importance of several safety features and equipment.

Safety-class features that prevent an MCO overpressurization accident include the safety-class instrumentation and control (SCIC) system and instrumentation to detect process upsets and activate the safety-class helium (SCHe) system, the SCHe system to provide the MCO purge and vent function, the 30 lb/in² gauge pressure vent path, the 150 lb/in² gauge rupture disk, and the safety-class portions of the tempered water system. These preventive features reduce the estimated overpressurization accident frequency into the beyond extremely unlikely range. Since the unmitigated offsite dose is well below the release limit of 5 rem for an extremely unlikely event, no additional safety-class mitigation features are required. However, success of some of the credited prevention features (e.g., the 30 lb/in² gauge rupture disk) might result in dose consequences that exceed onsite guidelines. Thus, safety-significant mitigation features provided for the MCO overpressurization accident include components of the process bay local exhaust heating, ventilation, and air conditioning (HVAC) system, process general exhaust HVAC system, associated high-efficiency particulate air (HEPA) filtration, process bay differential pressure alarms, and electrical standby power.

The HANSF code, version 1.3.2 (SNF-3650), was used to simulate the MCO overpressurization scenario. The HANSF code calculates fuel temperatures, and hydrogen and particulate production for an oxygen free environment by using the reaction rates from HNF-SD-SNF-TI-015. The quality assurance for HANSF at Hanford is documented in Appendix E of SNF-5226, Comparison Cases Simulated with HANSF 1.3.2 to Supplement Thermal Analyses Documented in HNF-SD-SNF-CN-023. The results of overpressurization DBA, including its thermal behavior, are also presented in SNF-5226.
7.2 MULTI-CANISTER OVERPACK OVERPRESSURIZATION SCENARIO DEVELOPMENT

Based on the CVDF hazard analysis report (HNF-SD-SNF-HIE-004), several potential accidents have been identified that would lead to MCO overpressurization. From all of the potential overpressurization reaction accidents, a bounding accident was chosen for the unmitigated consequence analysis. The most credible high-pressure scenario consists of an isolated MCO with stationary annulus water. Without the safety features identified in this section, a loss of power would close the isolation valves and shut off the tempered water pump leaving the MCO isolated and without flowing annulus water. This scenario is selected as the DBA because it represents the bounding dose consequences (highest material at risk [MAR] and pressure) and has a high likelihood.

The overpressurization DBA is assumed to begin after the water draining process is finished with some undrained, residual water still present in the MCO to react with the fuel. As little as 5 kg of residual water can pressurize the MCO vessel to 300 lb/in² gauge by reacting with the fuel and producing hydrogen. The greatest consequences are expected for the overpressurization accident with the highest pressure conditions. High internal gas pressure is required to cause a breach of MCO confinement and a blowdown release.

With uranium-water reaction rates producing hydrogen gas at all MCO temperatures, the overpressurization accident scenario will eventually lead to an increase in pressure sufficient to breach the MCO. An isolated MCO will reach unacceptable pressures given enough time (more than a week for cool tempered water annulus cases). The key aspect of high-pressure overpressurization accidents is the amount of time required to breach the MCO.

The MCO overpressurization scenario consists of the following events and processes:

- MCO pressurization until the isolated MCO is breached
- Blowdown release of particulate through an opening equivalent to 1-in.-diameter circle
- Continuous release of gases and particulate from uranium-water reactions (the release continues as long as unreacted uranium is in contact with water vapor or oxygen).

The following assumptions are used in the analyses.

- The MCO overpressurization reaction scenario is assumed to begin when the water draining process is finished but some undrained (residual) water is still present in the MCO to react with the fuel. It is assumed that 26.5 kg of free undrained (residual) water (1.5 kg in the top scrap basket, 6 kg in the bottom scrap basket, 18 kg in three fuel baskets, and 1 kg in the gap between the bottom fuel basket and the MCO bottom plate) are present when the high-pressure overpressurization accident is
initiated (HNF-SD-SNF-CN-023). As little as 5 kg of residual water can pressurize the MCO vessel to 300 lb/in² gauge by reacting with the fuel and producing hydrogen.

- Uranium hydrate contains 1.19 kg of water (HNF-SD-SNF-TI-015).

- The MCO is at bounding configuration with two scrap baskets
  - Enhancement factor or rate multiplier fuel-water reaction equals 10 (HNF-SD-SNF-TI-015)
  - Surface area equals 12 m² (HNF-SD-SNF-TI-015)
  - Decay heat rate equals 776 W for five fuel baskets and 705 W for three fuel baskets and two scrap baskets (HNF-SD-SNF-TI-015).

- Uranium hydrides are included using an enhancement factor or rate multiplier of 12 to account for the mass fraction of hydride and its surface area (HNF-SD-SNF-TI-015).

- No hydrogen gettering takes place because of the presence of water during the entire scenario. Hydrogen gettering or uranium-hydrogen reaction (U + 1.5 H₂ → UH₃) has been shown not to occur to any significant degree in the presence of water or oxygen (SNF-5226).

- About 15 kg of particulate is generated between the time the MCO leaves the K Basins area and the time it is drained at the CVDF (HNF-SD-SNF-TI-015). This newly generated particulate is available to be entrained by exiting gases during a blowdown release and the subsequent long continuous release.

- Unmitigated blowdown release pressure is assumed to be 345 lb/in² gauge.

- The bay temperature is assumed to be 90 °F.

Additional details regarding input can be found in SNF-5226, Appendix C.

For the unmitigated MCO overpressurization accident sequence, the MCO vents or port valves are postulated to be closed or blocked. Thus the uranium–water chemical reaction generates hydrogen gas, which pressurizes the MCO. The steam or water vapor from the heated liquid water also increases the MCO pressure (for an isolated MCO) and, more importantly, provides an oxidant for the exposed fuel in the scrap and fuel baskets. The increasing gas temperature in the MCO also helps pressurize the MCO. In the unmitigated scenario, the blowdown at a pressure of 345 lb/in² gauge occurs about 96 hours after MCO isolation. This pressure would cause the rupture disk (rated at 150 lb/in² gauge) to burst and could also fail the
MCO. However, to be conservative, the MCO is assumed to retain confinement until the 345 lb/in² gauge pressure is reached.

If the MCO were to be breached from high pressure, most of the gas and some suspended particulate would be carried out of the MCO in a very short time (<10 seconds). In addition to the particulate, hydrogen also would be released during the blowdown. Hydrogen deflagrations, external to the MCO, are also discussed in Chapter 4.0. The features and controls that prevent or mitigate the particulate release also prevent or mitigate the hydrogen consequence.

After the MCO is breached, the fuel-water reactions continue without the high pressure. Even with no air ingress into the MCO, the remaining water in the MCO keeps reacting with the exposed fuel, causing a continuous stream of gases and entrained particulate to flow out of the MCO. Both the scrap fuel and exposed fuel elements will react with the water vapor that is flowing upwards through the MCO and exiting out the orifice. The water vapor continues to react with uranium and uranium hydride until the water is completely consumed, which is more than 24 hours after the blowdown.

### 7.2.1 Multi-Canister Overpack Pressurization

The uranium–water chemical reaction \( U + 2H_2O \rightarrow UO_2 + 2H_2 + \text{heat} \) and the uranium hydride-water chemical reaction \( UH_3 + 2H_2O \rightarrow UO_2 + 3.5H_2 + \text{heat} \) will generate hydrogen gas and pressurize the MCO if the MCO ports are closed or blocked. The steam or water vapor from the heated liquid water also will increase the MCO pressure for an isolated MCO and, more importantly, will provide an oxidant for the exposed fuel in the scrap basket and fuel baskets. In the high-pressure thermal runaway DBA, the uranium hydrides are assumed not to be present which slows down the rate of pressurization (hydrides are 75% more effective in producing hydrogen than uranium), but increases the radiological dose when a release occurs. In other words, uranium hydride increases the rate of pressurization and decreases the radiological dose from quick releases.

For an isolated MCO, the MCO gas pressure keeps increasing as long as water is available to keep reacting with the fuel. For example, if 26.5 kg of free water were present at the time of MCO isolation, then the MCO pressure eventually would reach a maximum pressure of about 3,380 lb/in² (230 atm). This high pressure is not only large enough to easily breach the MCO seals and threads, but probably large enough to breach even the MCO containment shell itself. For the unmitigated release, the pressure is assumed to be relieved around 345 lb/in² gauge (26.5 atm absolute), which produces a dose above both offsite and onsite guidelines (see Section 7.6).

### 7.2.2 High-Pressure Blowdown Release through Breached Multi-Canister Overpack

The MCO in this analysis is assumed to leak at 345 lb/in² gauge, which happens about 96 hours after the MCO is isolated if uranium hydrides are present. Since the hydride-water
reaction produces 75% more hydrogen than the uranium-water reaction, the time required to reach this pressure will be more than 96 hours if little or no uranium hydride is on the fuel. The MCO is not expected to leak under 560 lb/in² gauge pressure, but this analysis assumes an earlier breach, which will be shown to exceed off-site guidelines in Section 7.6. The MCO Topical Report (HNF-SD-SNF-SARR-005) states that based on the codes used in the MCO design, the mechanically closed MCO (before welding at the Canister Storage Building) would not suffer any damage at internal pressures up to 340 lb/in² gauge. At some pressure in excess of 340 lb/in² gauge, the thread root of the collar would begin to yield, and at some pressure very much larger than 340 lb/in² gauge, leakage around the Helicoflex seal would result. An MCO was built and tested to an internal pressure of 562.5 lb/in² gauge to match the test requirement to be placed on MCO procurements. In that test, no leakage and no permanent damage were observed. Credit is not taken for the pressure test, however, because the data is in draft form and the ramifications on selected controls have not been fully evaluated. Therefore, the MCO is assumed to be susceptible to failure at any pressure greater than 340 lb/in² gauge.

During the quick release after the MCO is breached, most of the gas, along with some particulate, will be blown out of the MCO in a very short time (< 10 s) if the leak path has an equivalent opening of a 1-in. diameter circle and a longer time if the opening is smaller. The gas blown out of the breached MCO is assumed to entrain some of the suspended particulate in the MCO at the time of the blowdown and to entrain some particulate that was adhered to the fuel just before the blowdown. The amount of particulate released during the blowdown is estimated later in Section 7.3.

Hydrogen is released during the blowdown in addition to the particulate that is released. Consequences of the hydrogen release are described in Section 7.2.4. The hydrogen release consequence is not analyzed in detail in order to focus on the particulate release, which is large enough to require that the overpressurization accident be mitigated or prevented. Furthermore, the features and controls that mitigate or prevent the particulate release also will mitigate or prevent the consequences of the hydrogen release.

7.2.3 Unmitigated Continuous Release after Blowdown

After the MCO is breached, the fuel–water reactions continue without the high pressure. Even with no air ingress into the MCO, the exposed fuel continues to be oxidized by the water remaining in the MCO, causing a continuous stream of gases and entrained particulate to flow out of the MCO. Both the scrap fuel and exposed fuel elements react with the water vapor that is flowing upwards through the MCO and exiting out the orifice. The water vapor continues to react with uranium until the water is completely consumed or released.

Some air ingress is expected, assuming that air is available outside of the orifice. Because air outside the MCO is cooler and more dense than the hot MCO gases, air will flow counter to the exiting light gases.
7.2.4 Unmitigated Hydrogen Deflagration Outside the Multi-Canister Overpack Caused by Thermal Runaway

The blowdown release (from 345 lb/in² gauge pressure) described in Section 7.2.2 will expel almost 900 g of hydrogen gas in the first 10 seconds. The 12-hour continuous release after the blowdown will expel only another 75 g for a total of about 1,000 g of hydrogen gas over a 12-hour period starting with the blowdown release at 96 hours. The hydrogen release after the blowdown release is much smaller than the blowdown release, the hydrogen from the blowdown release is the only concern. The mass of this release was calculated by the HANSF code. At a pressure of 1 atm and a temperature of 26.7 ºC (80 ºF), the 900 g of hydrogen gas will occupy 11.5 m³. Diluting this volume to 20% hydrogen (a concentration that is high enough to produce destructive shock waves when it burns) requires it to mix with a volume of air that is four times greater. Thus, the 900 g release needs to mix with about 46 m³ of air. For comparison, the CVDF process bays each have a volume of about 1,600 m³, with enough fresh air added (> 1 m³/s due to local and general exhaust systems) to give more than two complete air changes per hour. Hence, flammable mixtures are possible, depending on the circumstances.

Actual events following the discharge of a large volume of hydrogen are difficult to predict. For the unmitigated overpressurization DBA, the local exhaust system is assumed not to exist or is not functioning, such that all of the hydrogen enters the process bay. The most bounding consequence of this hydrogen in the process bay is described below.

Ignition is delayed until a detonable mixture of hydrogen and air forms near the cask. The resulting shock waves could certainly damage the roof of the bay and possibly the walls. For perspective, if 100% of the 900 g of hydrogen burns, it releases the same thermal energy as 23 kg of trinitrotoluene (TNT). However, the energy of the hydrogen and air mixture is spread over a much larger volume, so the blast effects are not as severe as those from TNT. Furthermore, even a stoichiometric mixture of hydrogen and oxygen burns more slowly than exploding TNT. With very good mixing, the 900 g of hydrogen forms a flammable volume of about 58 m³. Using the method for estimating injury probabilities described in Appendix B, Section B4.0, death by lung hemorrhage has greater than 1% chance at a distance of 4.3 m (14 ft) from the center of the free-air explosion. Anyone located on the mezzanine near the MCO could be fatally injured. Averaging the energy release over all of the air in the process bay leads to an average pressure of 3.8 lb/in² gauge (550 lb/ft² gauge). This pressure is large enough to cause considerable structural damage, such as creating openings in the roof which would provide a path to the environment for radioactive particulate.

The continuous release, after the first 10 seconds of blowdown release, is slow enough (< 80 L/hr, or 0.02 L/s, on the average) that the hydrogen concentrations are quickly diluted below the lower flammability limit by natural infiltration.
7.3 SOURCE TERM ANALYSIS

The respirable source term is based on the MAR, the airborne (particulate) release fraction (ARF), and the respirable fraction (RF). These terms are explained and calculated in the following sections.

7.3.1 Unmitigated Material at Risk

When water draining starts in the CVDF, the bounding amount of adhering particulate on the fuel elements and scrap fuel was calculated to be about 20 kg (HNF-SD-SNF-TI-015). This initial particulate is assumed not to be available for release during the blowdown because the initial particulate must be strongly attached to the fuel and cladding in order to have survived a comprehensive wash at the K Basins (HNF-SD-SNF-TI-015).

Under bounding conditions and an off-normal draining process, an additional 15 kg of particulate could be generated between the time the MCO leaves the K Basin area and the time it is drained at the CVDF (HNF-SD-SNF-TI-015). This newly generated particulate would be potentially available to be entrained by exiting gases during a blowdown release.

For the unmitigated high-pressure accident, the generated particulate was calculated by the HANSF code (SNF-3650) to be about 45 kg of UO₂, which is generated from the time draining is completed until the MCO gas pressure reaches about 345 lb/in² gauge pressure, which is about 96 hours. At this pressure, the MCO is assumed to be breached.

The particulate for the blowdown release is the new particulate (15 kg) that is generated after the K Basin wash but before the MCO is completely drained at the CVDF plus the additional new particulate (45 kg) that is generated during the overpressurization DBA up until the time the MCO is assumed to be breached at 345 lb/in² gauge pressure. Hence, the total particulate is the sum of 15 kg and 45 kg for a total of 60 kg of UO₂ for the blowdown release. The equivalent MAR, in terms of spent nuclear fuel (SNF), is 52.9 kg SNF.

About 4 kg of UO₂ are generated over the 12-hour time period after the blowdown. About 9 kg of particulate are generated in about 24 hours after the blowdown.

Some of the particulate generated after the blowdown release will become entrained by the exiting gases (hydrogen and water vapor) and be released to the environment (see Section 7.3.2.1). The particulate MAR for the continuous release is the sum of the new particulate generated before the blowdown and after the K Basin wash but not released during the blowdown (a large fraction remains in MCO) plus the particulate generated after the blowdown. In other words, the particulate MAR for continuous release after the blowdown is about 60 kg of UO₂ (particulate expected to remain after blowdown) plus 4 kg of UO₂ (particulate generated 12 hours after blowdown) for a total of 64 kg of UO₂ (< 57 kg SNF) for the 12-hour continuous release. In like manner, about 69 kg of UO₂ (61 kg SNF) are available for the 24-hour continuous release after the blowdown.
In summary, the total particulate MAR consists of two distinct groups of SNF based on the two different types of releases (blowdown and continuous):

- **MAR₁ = 52.9 kg SNF (60 kg UO₂)** for the blowdown release, which is based on all of the particulate generated between K Basin cleaning and blowdown release.

- **MAR₂ = 57 kg SNF (64 kg UO₂)** for the 12-hour continuous release, which is based on all of the particulate newly generated after blowdown plus the new particulate created before blowdown and not released during blowdown (this amount is approximately equal to MAR₁, as only a small percentage is released during initial blowdown; see Section 7.3.2.1).

- **MAR₃ = 61 kg SNF (69 kg UO₂)** for the 24-hour continuous release, which is based on all of the particulate newly generated after blowdown plus the new particulate created before blowdown and not released during blowdown.

The ARFs are different for each type of release and are described in the following section.

### 7.3.2 Airborne Release Fraction and Respirable Fraction

In the following sections, the product of ARF and RF is estimated for the blowdown release (applied to MAR₁) and for the continuous release that follows the blowdown (applied to MAR₂ and MAR₃).

#### 7.3.2.1 Blowdown Release

For the "venting of pressurized powders" with pressures less than 25 lb/in² gauge, the bounding ARF x RF is $2 \times 10^{-3}$ as reported by DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions/Rates for Nonreactor Nuclear Facilities* (Section 4.4.2.3.2, page 4-73) with an ARF of $5 \times 10^{-3}$ and an RF of 0.4. The product is multiplied by the MAR for the blowdown, MAR₁, in order to obtain a particulate source term for the environmental doses due to the blowdown release. The lower pressure values were used rather than the values listed for pressures greater than 25 lb/in² gauge in order to avoid being overly conservative, as discussed below.

The very large release fractions associated with high-pressure venting (pressures > 25 lb/in² gauge) are overly conservative for the MCO blowdown release and are not used. They are overly conservative because the high-velocity (initially sonic) gases in the MCO blowdown occur over and above the particulate (rupture disk orifice), not underneath the particulate as was the case in the high-pressure vented gas experiments described in DOE-HDBK-3010-94. Furthermore, the gas velocities inside the MCO baskets are small. At the time of blowdown, the gas velocities (averaged velocities inside of baskets, not at base plate) ranges from 0.01 m/s near the MCO bottom, 0.3 m/s at the lower part of bottom fuel basket (or upper part of bottom scrap basket) to 1 m/s at lower part of top scrap basket. These velocities were calculated by using upstream gas density and mass flow rates calculated by the HANSF code. The velocities are higher in the holes of the basket base plates, ranging from 1.5 m/sec to 15 m/sec (from bottom to top baskets), but
the particulate is not located in these holes. The particulate is located above the base plate where the gas velocities are lower due to the larger flow area in the basket. All of these velocities are very low compared to the actual mixed gas sonic velocity (~1024 m/s) in the orifice during the blowdown and compared to the sonic air velocity (~330 m/s) encountered in the high-pressure gas experiments in DOE-HDBK-3010-94 (Section 4.4.2.3.2, page 4-73).

In fact, as a result of the low velocities in the MCO during the blowdown, much lower ARFs could be applied. For example, in Section 3.3 "Gaseous Release," an ARF rate (airborne release rate) of $4 \times 10^5$/h is used for gaseous release under debris, and DOE-HDBK-3010-94 (Section 4.4.4.1.2, page 4-100) gives a bounding ARF rate of $4 \times 10^5$/h for powder on a horizontal surface (not under debris) exposed to air velocities less than 2 m/s with occasional gusts up to 20 m/s. Hence, one of these two rates, each being much lower than the chosen ARF of $5 \times 10^3$, has justification (based on low velocities) for the blowdown release that lasts for about 10 seconds. However, these lower release rates are not used in the analysis because the blowdown will shake loose some particulate, causing it to be suspended and not lying on a horizontal surface when the blowdown occurs. Hence, the much higher ARF of $5 \times 10^3$ is used for the blowdown release, which is conservative due to the gas velocities being much lower than the sonic air velocities realized below the UO2 powder in the experiment. Even though the bounding experiment had an RF of only 0.4 for UO2, and not the maximum possible value of 1.0, the data are considered bounding for the ARF x RF product. If the RF were 1.0 in some other experiment, then evidently the ARF was smaller than $5 \times 10^3$. In other words, the ARF x RF product is considered bounding, even though the RF factor does not have its maximum possible value.

In addition, the leak flow path is very tortuous in the MCO, especially in the scrap basket, and some particulate is located out of the gas flow path. Both of these items will reduce the ARF for the blowdown release out of the MCO but are not included in the source term analysis because of their calculational difficulty, and were not part of the experiments (DOE-HDBK-3010-94, Section 4.4.2.3.2).

The source term, $M_i$, from the blowdown release is calculated by multiplying $MAR_i$ (see Section 7.3.1) with the product of ARF and RF as follows:

$$M_i = (MAR_i)(ARF \times RF)$$

$$= (52.9 \text{ kg SNF})(1,000 \text{ g/kg})(2.0 \times 10^{-3})$$

$$< 106 \text{ g SNF}.$$

7.3.2.2 Continuous Releases. After the blowdown release, the fuel–water reactions create hydrogen and heat in addition to the new particulate. Some of the new particulate is continuously released with the hydrogen through the rupture disk orifice. The bounding value of ARF x RF for particulate release for gaseous releases under debris for 12 hours (DOE-HDBK-3010-94, Section 4.4.4.1.2, page 4-100) is $4.8 \times 10^{-5}$ and twice that ($9.6 \times 10^{-5}$) for 24 hours.
The source term, \( M_2 \), for the continuous release is calculated by multiplying \( \text{MAR}_2 \), the MAR for the 12-hour continuous release, by the product of ARF and RF and as follows:

\[
M_2 = (\text{MAR}_2)(\text{ARF} \times \text{RF})
\]
\[
= (57 \text{ kg SNF})(1,000 \text{ g/kg})(4.8 \times 10^{-3})
\]
\[
< 3 \text{ g SNF}.
\]

The source term, \( M_3 \), for the 24-hour continuous release (offsite) is calculated by multiplying \( \text{MAR}_3 \), the MAR for the 24-hour continuous release, by the respirable release fraction as follows:

\[
M_3 = (\text{MAR}_3)(\text{ARF} \times \text{RF})
\]
\[
= (61 \text{ kg SNF})(1,000 \text{ g/kg})(9.6 \times 10^{-3})
\]
\[
< 6 \text{ g SNF}.
\]

The releases of other radionuclides in the fuel, such as the fission products (some are semi-volatile; e.g., cesium), and transuranics (e.g., plutonium), are assumed to be congruent (at the same rate) with the uranium particulate release. This is a simplifying assumption and is justified for the overpressurization DBA because high temperatures are not realized in the DBA, and, hence, the semi-volatiles should not be released faster than the uranium particulate.

In summary, the total bounding source term for environmental doses consists of three distinct groups based on the two different types of releases (blowdown and continuous):

- \( M_1 = 106 \text{ g SNF} \) for the blowdown release
- \( M_2 = 3 \text{ g SNF} \) for the 12-hour continuous release.
- \( M_3 = 6 \text{ g SNF} \) for the 24-hour continuous release.

### 7.4 CONSEQUENCE ANALYSIS

The radiological dose is calculated using the following equation:

\[
D = M \times \frac{X}{Q'} \times \text{BR} \times \text{UD}
\]

where

- \( D \) = effective dose equivalent based on inhalation exposure only (rem)
- \( M \) = respirable quantity released into the air (g)
\[ M_1 \text{ for blowdown release (106 g SNF)} \]
\[ M_2 \text{ for 12-hour (onsite) continuous release (3 g SNF)} \]
\[ M_3 \text{ for 24-hour (offsite) continuous release (6 g SNF)} \]

\[ \chi/Q' = \text{air transport factor (s/m}) \]
\[ BR = \text{average inhalation rate during the blowdown and 12-hour release (m}^3/\text{s}) \]
\[ UD = \text{committed effective dose equivalent per unit gram inhaled (438,000 rem/g SNF).} \]

**Unmitigated Consequences.** The dose calculation equation and data from Chapter 1.0 are used to calculate the dose to the offsite receptor.

\[ D_{\text{offsite}} = M_1 \times \chi/Q' \times BR \times UD \]
\[ = (106 \text{ g SNF})(4.48 \times 10^{-3} \text{ s/m}) (3.33 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g SNF}) \]
\[ = 0.69 \text{ rem (0.0069 Sv) for blowdown release.} \]

\[ D_{\text{offsite}} = M_3 \times \chi/Q' \times BR \times UD \]
\[ = (6 \text{ g SNF})(6.50 \times 10^{-6} \text{ s/m}) (2.64 \times 10^{-4} \text{ m}^3/\text{s}) (4.38 \times 10^5 \text{ rem/g SNF}) \]
\[ = 0.0045 \text{ rem (4.5 \times 10^{-5} Sv) for 24-hour continuous release.} \]

Adding the doses for the blowdown and continuous releases yields a total offsite dose of 0.70 rem (0.007 Sv) with almost all of the dose coming from the blowdown release.

The dose consequences at the remaining receptor sites are calculated in the same manner and are shown in Table 7-1 for the blowdown and continuous release.

### 7.5 MITIGATION OF OVERPRESSURIZATION DESIGN BASIS ACCIDENT

The chief mitigators of all overpressurization scenarios are the SCHe purge system, the tempered water system, the 30 lb/in² vent path, the local and general exhaust HEPA filters, and the 150 lb/in² rupture disk as backup. With all of the safety equipment (see Section 7.6) and procedures, the unmitigated overpressurization scenario is mitigated below guidelines. The effects of the of some of the individual safety features and equipment were analyzed in detail.
Table 7-1. Dose Calculation Summary for Overpressurization Design Basis Accident
(release at 345 lb/in² gauge pressure).

<table>
<thead>
<tr>
<th>Receptor location (distance, direction)</th>
<th>Duration (hours)</th>
<th>( \chi/Q^* ) (s/m³) (without stack or plume meander)</th>
<th>Unmitigated dose ( \text{rem (Sv)} )</th>
<th>Evaluation guideline/ release limits ( \text{rem (Sv)}, \text{anticipated}^d )</th>
<th>Mitigated dose ( \text{rem (Sv)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>&lt;1 (blowdown)</td>
<td>7.32 E-02</td>
<td>1100 (11)</td>
<td>1.0 (1.0 E-02)</td>
<td></td>
</tr>
<tr>
<td>(100 m E)</td>
<td>12 (continuous)</td>
<td>6.28 E-03</td>
<td>2.7 (0.027)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>1100 (11.0)</td>
<td></td>
<td>1.0 (1.0 E-02)</td>
</tr>
<tr>
<td>Columbia River (650 m W)</td>
<td>&lt;1 (blowdown)</td>
<td>2.44 E-03</td>
<td>38 (0.38)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(650 m W)</td>
<td>12 (continuous)</td>
<td>1.99 E-04</td>
<td>0.09 (0.0009)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>38 (0.38)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>&lt;1 (blowdown)</td>
<td>1.60 E-04</td>
<td>2.5 (0.025)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3,750 m ESE)</td>
<td>12 (continuous)</td>
<td>2.73 E-05</td>
<td>0.012 (1.2 E-04)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>2.5 (0.025)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanford Site boundary (10,090 m W)</td>
<td>&lt;1 (blowdown)</td>
<td>4.48 E-05</td>
<td>0.69 (0.0069)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10,090 m W)</td>
<td>24 (continuous)</td>
<td>6.50 E-06</td>
<td>0.0045 (4.5 E-05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>0.70 (0.007)</td>
<td>0.5 (0.005)</td>
<td></td>
</tr>
</tbody>
</table>


\( \text{Mitigated dose} \) release limits \( \text{rem (Sv)}, \text{anticipated}^d \).

\( ^d \text{Evaluation guideline for onsite (100 m) receptor only.} \)

\( ^* \text{Atmospheric dispersion coefficient from HNF-SD-SNF-TI-059, 1999, A Discussion on the Methodology for Calculating Radiological and Toxicological Consequences for the Spent Nuclear Fuel Project at the Hanford Site, Rev. 2, Fluor Daniel Hanford, Incorporated, Richland, Washington.} \)

\( ^c \text{Fifty-year committed effective dose equivalent.} \)

\( ^d \text{Anticipated event frequency is} >10^2 \text{ to} \leq 10^1. \)
The tempered annulus water affects the heat removal from the MCO and, hence, the rate of pressurization. The separate scenarios that were analyzed include the following:

1. **SCHe system**, circulating 50 °C annulus water (or stationary water), local exhaust system with and without HEPA filters, MCO isolated except for 10 lb/in² SCHe system

2. 30 lb/in² vent path; stationary annulus water and process bay temperature of 32.2 °C (90 °F); local exhaust system with and without HEPA filters, MCO isolated except for 30 lb/in² vent path

3. 150 lb/in² rupture disk; stationary annulus water; local exhaust system with and without HEPA filters.

The totally unmitigated overpressurization scenario is described in Section 7.2.

The SCHe system and the 30 lb/in² vent path are expected to prevent the MCO from reaching high pressures. The following subsections describe the scenarios, source terms, and consequences for the overpressurization mitigated by the safety device(s) that head each subsection.

### 7.5.1 Safety Class Helium System

The SCHe system prevents the high-pressure part of the overpressurization scenario by providing a vent path for the MCO, thus preventing the MCO from pressurizing above 10 lb/in² gauge. It is also redundant to the 30 lb/in² vent path and the 150 lb/in² rupture disk. However, the SCHe system also vents the gas and entrained particulate without hydrogen deflagration concerns and at lower velocities than a blowdown release, thus mitigating the consequences of all overpressurization scenarios. Since the SCHe system is activated by the SCIC if the pressure reaches 11.5 lb/in² gauge (before the 30 lb/in² vent path and the 150 lb/in² rupture disk), the SCHe system is the primary safety feature for preventing high MCO pressures. The doses are bounded by the gaseous release doses calculated in Chapter 2.0.

Furthermore, the helium purge gas, flowing at a rate > 0.7 standard ft³/min (actually the helium flow rate is expected to be around 1.4 standard ft³/min [Chapter B4.0, HNF-3553, Annex B]) will help cool the fuel. The helium purge procedure cools the fuel by not only providing a high gas thermal conductivity inside the MCO, but also carries out some of the heat generated inside the MCO. The results of a vacuum drying case with helium purge rate at 0.7 standard ft³/min are presented in SNF-5226.

If the general service helium supply is lost or cannot feed the SCHe system, then the SCHe bottle supply would only last for about an hour. This fact indicates that the annulus water level must be maintained at CVDF for normal and off-normal events for a bounding MCO, unless the 8-4-4 cycle is taking place. The 8-4-4 vacuum purge cycle (assuming no degradation in vacuum)
prevents a thermal runaway if the annulus water were lost and not restored (see Section 6.2). A helium purge without vacuum, on the other hand, does not remove residual water from the MCO rapidly enough to prevent a thermal runaway if the annulus water were lost and not restored.

The dose consequence for the SCHe system scenario (isolated MCO except for SCHe system) is bounded by the gaseous release in Chapter 2.0, Gaseous Release. The dose is very small, even if no credit is given to the HEPA filters in the local exhaust system, because the bounding ARF rate is only $4.0 \times 10^8$/hr for this gaseous release.

The total loose particulate is 25 kg UO, which equates to an MAR of 22 kg SNF, and the source terms are about 2.2 g SNF and 1.1 g SNF for the unfiltered 24-hour and 12-hour releases, respectively. If the local exhaust HEPA filters are functional (respirable release fraction < 0.001), then the source terms are 0.0022 g SNF and 0.0011 g SNF for the 24-hour and 12-hour releases, respectively. The filtered onsite dose is about 0.001 rem ($1.0 \times 10^4$ Sv), whereas the onsite dose without functional HEPA filters is about 1 rem (0.01 Sv), which is below the onsite dose guidelines for unlikely or extremely unlikely events.

7.5.2 30 lb/in² Vent Path

The SCHe system is backed up by the 30 lb/in² vent path in regard to MCO overpressurization. The consequence of an MCO overpressurization accident with no SCHe system present is calculated in the following sections. The frequency of the 30 lb/in² vent path being activated is estimated to be $2 \times 10^4$, which makes it unlikely (see Appendix A).

7.5.2.1 30 lb/in² Vent Path and Stationary Annulus Water Scenario. Even if the water in the cask-MCO annulus is only stationary, the thermal conductivity and heat capacity of the water are large enough to keep the MCO at stable temperatures for process bay temperatures below 46 °C (115 °F). Basically, the stationary annulus water will maintain stable fuel temperatures if the process bay is not too hot (< 115 °C). This is because (1) the stationary water conducts heat from the MCO to the cask better than air does (as in the loss of annulus water cases), and (2) the stationary water becomes cooler than the normal 50 °C annulus water at early times because of the cooling effects of the process bay temperature if the process bay temperature is less than 46 °C (115 °F). If the process bay temperature reaches 35 °C (95 °C), the SCIC system turns on the SCHe system (Chapter B4.0, HNF-3553, Annex B).

The 30 lb/in² vent path with annulus water scenario assumes the process bay temperature is high normal at 32.2 °C (90 °F). This scenario is the same as the unmitigated scenario except that the cask-MCO annulus contains stationary water and the 30 lb/in² vent path is functional. The 30 lb/in² check valve is modeled to relieve at 35 lb/in² gauge pressure and close again at 20 lb/in² gauge pressure, which is expected to include some margin. Also, the orifice size of the check valve was taken to be 0.2 in. in the model, which is smaller than the real size of 0.25 in. such that some margin was included in the model. The actual check valve is expected to open and close in a smaller range than 35 to 20 lb/in² gauge, but a smaller range is expected to produce the
same source term over 12 and 24 hour time periods. The initial blowdown release, however, will have a smaller source term if the valve pressure range is smaller.

### 7.5.2.2 30 lb/in² Vent Path Scenario Source Term

#### 7.5.2.2.1 Material at Risk

Since the derivation of the MAR is the same as the unmitigated thermal runaway (i.e., using HANSF code), the values are summarized here. Since the MCO gas pressure goes from 35 lb/in² gauge to 20 lb/in² during each blowdown through the 30 lb/in² vent path (due to check valve opening and closing), about 1/4 of the MCO gas volume is released \((1/4 \times \Delta P/P_{atm} = 15/(35 + 14.7))\) for each partial blowdown. Hence, the MAR is calculated for the 30 lb/in² vent path blowdown by multiplying the total particulate in MCO at the time of blowdown by 1/4. For example, the first blowdown occurs about 9.5 hours after the MCO is isolated, with a total particulate mass of 19 kg UO₂ (4 kg generated after draining, and 15 kg generated before and during draining). Thus, the 19 kg is multiplied by 1/4 to get 4.75 kg for the first blowdown release. There are 3 more blowdowns after the first one during the next 12 hours, and 7 more after the first one during the next 24 hours. The last blowdown occurs when the total particulate is approaching 34 kg, which gives 8.5 kg \((34 \times 0.25)\) UO₂ for the last and largest blowdown release within 24 hours after the first blowdown release. The MAR is divided into three distinct groups based on the sum of partial blowdown releases for a given time period:

- \(\text{MAR}_1 = 4.2 \text{ kg SNF (4.75 kg UO}_2\) for the first blowdown release, which is based on 25% of all of the particulate generated between K Basin cleaning and blowdown at 35 lb/in² gauge
- \(\text{MAR}_2 = 15 \text{ kg SNF (17 kg UO}_2\) for three blowdown releases during 12-hour period after the initial one
- \(\text{MAR}_3 = 42 \text{ kg SNF (48 kg UO}_2\) for eight blowdown releases during 24-hour period after the initial one.

#### 7.5.2.2.2 Release Fraction and Respirable Fraction

In the following sections, the product of ARF and RF is estimated for the blowdown release (applied to \(\text{MAR}_1\)) and for the 12-hour and 24-hour releases that follow the first blowdown (applied to \(\text{MAR}_2\) and \(\text{MAR}_3\)). Since each release is a blowdown release or a sum of blowdown releases, the ARFs and RFs are the same. The effects of the local exhaust HEPA filters are also included separately.

**First Blowdown Release.** The ARF x RF product is the same as the one used for the unmitigated blowdown, which is \(2 \times 10^3\).
The source term, $M_1$, from the blowdown release is calculated by multiplying $\text{MAR}_1$ (see Section 7.3.1) with the product of $\text{ARF}$ and $\text{RF}$ as follows (assuming no filters):

$$M_1 = (\text{MAR}_1)(\text{ARF} \times \text{RF}) = (4.2 \text{ kg SNF})(1,000 \text{ g/kg})(2.0 \times 10^3) = 8.4 \text{ g SNF}.$$ 

**Releases Over 12 and 24 Hours.** The ARF and RF product is the same ($2.0 \times 10^3$) for the sum of blowdown releases as for a single blowdown release. The 12-hour and 24-hour releases consist of 3 and 7 separate blowdown releases, respectively, each of which removes about 1/4 of the gas in the MCO. The 1/4 factor was included in the $\text{MAR}$ calculation. The source term, $M_2$, for the 12-hour release is calculated by multiplying $\text{MAR}_2$, the $\text{MAR}$ for the 12-hour release, by the product of ARF and RF as follows (assuming no filters):

$$M_2 = (\text{MAR}_2)(\text{ARF} \times \text{RF}) = (15.0 \text{ kg SNF})(1,000 \text{ g/kg})(2.0 \times 10^3) = 30 \text{ g SNF}.$$ 

The source term, $M_3$, for the 24-hour release (used for offsite dose calculation) is calculated by multiplying $\text{MAR}_3$, the $\text{MAR}$ for the 24-hour release, by the product of ARF and RF as follows (assuming no filters):

$$M_3 = (\text{MAR}_3)(\text{ARF} \times \text{RF}) = (42 \text{ kg SNF})(1,000 \text{ g/kg})(2.0 \times 10^3) = 84 \text{ g SNF}.$$ 

If the local exhaust system is functioning, which is likely, the HEPA filters in the local exhaust system would remove at least 99.9% of the particulate. Due to the small release rate of the check valve, no hydrogen flammability problems are expected if the local exhaust system is functioning. The bounding ARF and RF product for the filter is 0.001, which is what is used in this analysis for the mitigated cases with general and local exhaust filters included. In summary, if no filters are included, the total bounding source term for environmental doses consists of three distinct groups based on the two different types of releases (blowdown and continuous):

- $M_1 = 8.4 \text{ g SNF}$ for the first blowdown release
- $M_2 = 30 \text{ g SNF}$ for the 3 blowdown releases during 12 hours after the first
- $M_3 = 84 \text{ g SNF}$ for the 7 blowdown releases during 24 hours after the first blowdown release.
If the local exhaust and its HEPA filters (efficiency of 99.9% or ARF=0.001) are functioning, which is likely, the total bounding source term is reduced to the following:

- \( M_1 = 0.0084 \text{ g SNF for the first blowdown release} \)
- \( M_2 = 0.030 \text{ g SNF for 3 blowdown releases over 12 hours} \)
- \( M_3 = 0.084 \text{ g SNF for 7 blowdown releases over 24 hours} \)

7.5.2.3 30 lb/in\(^2\) Vent Path and Annulus Water Consequence Analysis. The dose consequences were calculated the same as the unmitigated doses, except for the different source terms. Doses were also calculated with the mitigating effects of the one surviving bank of HEPA filters in the local exhaust system. The doses are shown in Table 7-2 with and without the local exhaust HEPA filters.

7.5.3 150 lb/in\(^2\) Rupture Disk

7.5.3.1 150 lb/in\(^2\) Rupture Disk Scenario. The high-pressure thermal runaway scenario with the 150 lb/in\(^2\) rupture disk is exactly the same (same events and processes) as the unmitigated scenario except that the blowdown occurs at a pressure of 150 lb/in\(^2\) gauge (11.2 atm absolute), which is lower than the unmitigated pressure release of 345 lb/in\(^2\) gauge in Section 7.3.

The results are similar to the unmitigated case except that the blowdown occurs at 36 hours instead of 96 hours. Also, the amount of hydrogen released is much smaller. The hydrogen release and consequences are detailed below.

7.5.3.1.1 Hydrogen Deflagration Outside the Multi-Canister Overpack Caused by Overpressurization. The 150 lb/in\(^2\) blowdown release will expel about 360 g of hydrogen gas in the first 10 seconds. The 12-hour continuous release will expel an additional 27 g after the 10-s blowdown release for a total of 387 g of hydrogen gas. The volume of this release at room temperature (26.7 °C) is estimated using the ideal gas law. At a pressure of 1 atm, the 360 g of hydrogen gas will occupy about 4 m\(^3\). Diluting this volume to 20% hydrogen (a concentration that is high enough to produce destructive shock waves when it burns) requires it to mix with a volume of air that is four times greater. Thus the 360 g release needs to mix with about 16 m\(^3\) of air. For comparison, the CVDF process bays each have a volume of about 1,600 m\(^3\), with enough fresh air added (> 1 m\(^3\)/s by local and general exhaust systems) to give more than two complete air changes per hour. Hence, flammable mixtures are possible, depending on the circumstances.

For the mitigated case, the local exhaust system is functioning and the likely events following the blowdown release are summarized below.

Most of the 360 g of hydrogen is drawn into the process bay local exhaust system. For the first 10 seconds, the hydrogen average flow rate for blowdown release is about 0.4 m\(^3\)/s. Since this is about two-thirds of the nominal process bay local exhaust system flow rate (0.5 m\(^3\)/s, 1000 ft\(^3\)/min), the hydrogen concentration will be very high and the oxygen concentration very
Table 7-2. Dose Calculation Summary for Mitigated Thermal Runaway Reaction With 30 lb/in² Vent Path, Stationary Annulus Water, With and Without Local Exhaust Filters.

<table>
<thead>
<tr>
<th>Receptor location</th>
<th>Duration (hours)</th>
<th>(\chi/Q^*) (s/m³) (without stack or plume meander)</th>
<th>Unmitigated (no filters) dose rem (Sv)</th>
<th>Evaluation guideline(^b) release limits rem (Sv), unlikely(^d)</th>
<th>Safety-significant mitigated dose rem filtered exhaust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>&lt;1 (blowdown)</td>
<td>7.32 E-02</td>
<td>89 (0.89)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(100 m E)</td>
<td>12 (continuous)</td>
<td>6.28 E-03</td>
<td>27 (0.27)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>120 (1.2)</td>
<td>25 (1.0 E-01)</td>
<td>0.12 (1.2 E-03)</td>
<td></td>
</tr>
<tr>
<td>Columbia River (650 m W)</td>
<td>&lt;1 (blowdown)</td>
<td>2.44 E-03</td>
<td>3.0 (0.03)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(650 m W)</td>
<td>12 (continuous)</td>
<td>1.99 E-04</td>
<td>0.87 (0.0087)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3.9 (0.039)</td>
<td>--</td>
<td>3.9 E-03 (3.9 E-05)</td>
<td></td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>&lt;1 (blowdown)</td>
<td>1.60 E-04</td>
<td>0.20 (0.002)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3,750 m ESE)</td>
<td>12 (continuous)</td>
<td>2.73 E-05</td>
<td>0.12 (0.0012)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.32 (0.0032)</td>
<td>--</td>
<td>3.2 E-04 (3.2 E-06)</td>
<td></td>
</tr>
<tr>
<td>Hanford Site boundary (10,090 m W)</td>
<td>&lt;1 (blowdown)</td>
<td>4.48 E-05</td>
<td>0.055 (0.00055)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10,090 m W)</td>
<td>24 (continuous)</td>
<td>6.50 E-06</td>
<td>0.063 (0.00063)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.12 (0.0012)</td>
<td>5 (0.05)</td>
<td>1.2 E-04 (1.2 E-06)</td>
<td></td>
</tr>
</tbody>
</table>


\(^b\)Fifty-year committed effective dose equivalent.

\(^d\)Unlikely event frequency is >10⁴ to ≤10².

\(^e\)Evaluation guideline for onsite (100 m) receptor only.
low in the duct. However, for the first 2 seconds of release, the hydrogen flow rate is much higher at about 1.1 m$^3$/s, so that the nominal exhaust rate of about 0.5 m$^3$/s (1,000 ft$^3$/min) will not pick up all of the hydrogen. No more than 2 m$^3$ of hydrogen is expected to remain in the process bay after the blowdown starts, based on blowdown release rate and local exhaust rate for first three seconds (blowdown release rate is lower than exhaust rate after three seconds). The sudden discharge of hydrogen that is drawn into the local exhaust system will fill the process bay local exhaust system duct. When the hydrogen flow joins the air flow from the other bays, the hydrogen will be diluted to form a detonable mixture. An explosion of the hydrogen-air mixture near the HEPA filters would dislodge radioactive material and cause a fraction of it to be discharged to the environment. This accident is similar to the bounding external hydrogen explosions analyzed in Section 4.2. The release rate from a damaged HEPA filter is discussed in the ARF section that follows.

The continuous release of hydrogen is slow enough (~25 L/hr, or 0.007 L/s, on the average) that the hydrogen concentrations are quickly diluted below the lower flammability limit by the process bay local exhaust system.

There is still at most 2 m$^3$ of hydrogen, which did not get drawn in by the local exhaust system during the first 2 or 3 seconds of the blowdown release, to analyze. With very good mixing, the maximum release of 2 m$^3$ to the bay becomes a flammable volume of 10 m$^3$. If 50% of the hydrogen burns, the average pressure increase in the process bay is less than 0.35 lb/in$^2$ or 50 lb/ft$^2$. No significant structural damage is expected with this pressure. Using the method of estimating injury probabilities described in Appendix B, death by lung hemorrhage has greater than 1% chance at a distance of 1.8 m (6 ft) from the center of the free-air explosion. A worker would need to be standing within this distance from the MCO for this explosion to be fatal. Since no personnel are in the bay at the time of the deflagration, serious injury is unlikely.

7.5.3.2 150 lb/in$^2$ Rupture Disk Thermal Runaway Source Term.

7.5.3.2.1 Material at Risk. Since the derivation of the MAR is the same as the unmitigated thermal runaway, the values are summarized here. The total particulate MAR consists of two distinct groups of particulate (UO$_2$) based on the two different types of releases (blowdown and continuous):

- $\text{MAR}_1 = 30 \text{ kg SNF (34 kg UO}_2\text{)}$ for the blowdown release, which is based on all of the particulate generated between K Basin cleaning and blowdown at 150 lb/in$^2$ gauge

- $\text{MAR}_2 = 30 \text{ kg SNF (34 kg UO}_2\text{)}$ for the 12-hour continuous release, which is based on all of the particulate newly generated after blowdown plus the new particulate created before blowdown and not released during blowdown (this amount is approximately equal to $\text{MAR}_1$, as only a small percentage is released during initial blowdown).
**MAR₁ = 31 kg SNF (35 kg UO₂₂) for the 24-hour continuous release, which is based on all of the particulate newly generated after blowdown plus the new particulate created before blowdown and not released during blowdown (this amount is approximately equal to MAR₁).**

The ARFs are different for each type of release and are described in the following section.

### 7.5.3.2.2 Airborne Release Fraction and Respirable Fraction

In the following sections, the product of ARF and RF is estimated for the blowdown release (applied to MAR₁) and for the continuous release that follows the blowdown (applied to MAR₂ and MAR₃) at 150 lb/in² gauge. The effects of the local exhaust HEPA filters are also included.

**Blowdown Release.** The ARF x RF product is the same as the one used for the unmitigated blowdown, which is $2 \times 10^3$.

The source term, $M₁$, from the blowdown release is calculated by multiplying MAR₁ (see Section 7.3.1) with the product of ARF and RF as follows (assuming no filtering effects; i.e., unmitigated with respect to local exhaust HEPA filters):

$$M₁ = (MAR₁)(ARF \times RF)$$
$$= (30 \text{ kg SNF})(1,000 \text{ g/kg})(2.0 \times 10^3)$$
$$= 60 \text{ g SNF}.$$

**Continuous Releases.** The ARF x RF product for particulate release for gaseous release under debris for 12 hrs is $4.8 \times 10^5$ and for 24 hrs is $9.6 \times 10^5$ (DOE-HDBK-3010-94, Section 4.4.4.1.2, p. 4-100). The source term, $M₂$, for the continuous release is calculated by multiplying MAR₂, the MAR for the 12-hour continuous release, by the product of ARF and RF as follows (assuming no filters):

$$M₂ = (MAR₂)(ARF \times RF)$$
$$= (30 \text{ kg SNF})(1,000 \text{ g/kg})(4.8 \times 10^5)$$
$$< 1.5 \text{ g SNF}.$$

The source term, $M₃$, for the 24-hour continuous release (offsite) is calculated by multiplying MAR₃, the MAR for the 24-hour continuous release, by the product of ARF and RF as follows (assuming no filters):

$$M₃ = (MAR₃)(ARF \times RF)$$
$$= (31 \text{ kg SNF})(1,000 \text{ g/kg})(9.60 \times 10^5)$$
$$< 3 \text{ g SNF}.$$
If the local exhaust system is functioning, which is likely, the first bank of HEPA filters in the local exhaust system would remove at least 99.9% of the particulate (there are two banks of HEPA filters in series). However, since there is flammable hydrogen in the exhaust ducts, a hydrogen explosion could effect the HEPA filter's efficiency. However, even if the hydrogen explosion doesn't occur until it gets to the first bank of HEPA filters, only the first bank of HEPA filters may be rendered ineffective for any particulate release that follows. In DOE-HDBK-3010-94 (Section 5.4 HEPA Filters), ARFs and RFs are given for three categories of HEPA damage, (1) thermal stress, (2) shock effects of explosive stress, and (3) blast effects from explosive stress. The maximum ARF and RF determined for all three categories of stress is an ARF of 0.01 and an RF of 1.0, for an ARF x RF product of 0.01. Since the pressure pulse from the hydrogen explosion before the first bank of HEPA filters could reach 15 lb/in², or about 100 kPa, it may be possible that the first bank of HEPA filters could be more damaged than the data indicates in DOE-HDBK-3010-94. Hence, the first bank of HEPA filters is conservatively considered ineffective for any particulate that is still coming through the local exhaust system duct. However, the second bank of HEPA filters should not receive a pressure pulse larger than the data (equivalent to a tornado) in DOE-HDBK-3010-94 under blast effects from explosive stress. The bounding ARF and RF product is 0.01 for this category, which is used in this analysis for the 150 lb/in² rupture disk thermal runaway scenario with damaged local exhaust filters included in the scenario.

In summary, if no HEPA filters are included, the total bounding source term for environmental doses consists of three distinct groups based on the two different types of releases (blowdown and continuous):

- $M_1 = 60$ g SNF for the blowdown release ($MAR_1 = 30$ kg SNF)
- $M_2 = 1.5$ g SNF for the 12-hour continuous release ($MAR_2 = 30$ kg SNF)
- $M_3 = 3.0$ g SNF for the 24-hour continuous release ($MAR_3 = 31$ kg SNF).

If the local exhaust HEPA filters are included in the scenario, but damaged, the total bounding source term is the following (an additional 94 g SNF were added to the filter from maximum pre-existing filter conditions [see Section 4.2.3], and the ARF x RF product for a damaged HEPA filter was used):

- $M_1 = 1.54$ g SNF for the blowdown release
- $M_2 = 0.02$ g SNF for the 12-hour continuous release.
- $M_3 = 0.03$ g SNF for the 24-hour continuous release.

7.5.3.3 150 lb/in² Rupture Disk Consequence Analysis. The dose consequences were calculated the same as the unmitigated doses, except for the different source terms. Doses were also calculated with and without the mitigating effects of the damaged local exhaust filter bank. The dose consequences are shown in Table 7-3.
7.6 COMPARISON TO GUIDELINES

Comparison of Unmitigated Doses. Event tree sequences indicate that the unmitigated frequency for the MCO overpressurization accident is in the anticipated category (i.e., an unmitigated frequency greater than $10^{-2}$ per year) (see Appendix A). The unmitigated sequence considered the processing of 200 MCOs per year, common cause loss of tempered water (annulus) system flow and an isolated MCO (loss of power). The unmitigated radiological offsite dose for this event is above offsite release limits and onsite evaluation guidelines.

Comparison of Mitigated Doses. The mitigated frequency of the event tree sequence that represents this DBA as an MCO overpressurization of 150 lb/in² gauge and as an unfiltered release is $5 \times 10^{-7}$ per year, thus this mitigated DBA is beyond extremely unlikely (see Appendix A). This mitigated sequence credited SCHe injection, venting through the SCHe system vent path, relieving through the 30 lb/in² vent path, local exhaust operation and standby power, and HEPA filter functionality. With safety-significant features credited, the mitigated MCO overpressurization and unfiltered release meets both offsite release limits and onsite evaluation guidelines.

7.7 SUMMARY OF SAFETY-CLASS STRUCTURES, SYSTEMS, AND COMPONENTS AND TECHNICAL SAFETY REQUIREMENT CONTROLS

Under normal operating conditions, annulus water levels and helium flow provide adequate heat transfer to prevent MCO overpressurization. Under upset or accident conditions, safety-class equipment is required in order to ensure this capability is not lost. The heat transfer characteristics of the annulus water could be compromised by a loss of water level or high tempered water temperatures. The heat transfer characteristics of the normal helium supply could be compromised by a loss of helium flow, high MCO pressures (e.g., isolated MCO), or low process system pressures (e.g., leaks).

The checklist designators included in the accident bins, other than the accident selected as the DBA, represent additional accident sequences slightly different than the DBA. All of these binned accidents are bounded by the DBA because they have lesser or equivalent worst-case consequences and frequencies.

The accident scenarios identified in the hazard analysis for the P1 bin represent overpressurization accidents caused by elevated fuel corrosion rates (high-temperature tempered water, excessive water remaining in an MCO because of proof-of-dryness demonstration failure [instrumentation failure or operator error]), and loss of power because of flooding (HNF-SD-SNF-HIE-004). The controls in the P1 bin prevent an MCO overpressurization by monitoring the MCO pressure and by providing multiple vent paths from the MCO. Credit also is taken for controls that prevent bypass of safety systems by incorrectly proceeding with the cold vacuum drying process or by operator error. To protect the analysis assumption pertaining to the maximum rate of hydrogen generation, credit is taken for structures, systems, and components.
Table 7-3. Dose Calculation Summary for Mitigated Overpressurization with 150 lb/in² Rupture Disk with and without Local Exhaust Filters.

<table>
<thead>
<tr>
<th>Receptor location (distance, direction)</th>
<th>Duration (hours)</th>
<th>$\chi/Q^*$ (s/m³) (without stack or plume meander)</th>
<th>Unmitigated (no filters) dose(^b) rem (Sv)</th>
<th>Evaluation guideline(^a)/release limits rem (Sv), beyond extremely unlikely(^a)</th>
<th>Safety-significant mitigated dose rem (Sv) filtered exhaust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite (100 m E)</td>
<td>&lt;1 (blowdown)</td>
<td>7.32 E-02</td>
<td>640 (6.4)</td>
<td>16.4</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>12 (continuous)</td>
<td>6.28 E-03</td>
<td>1.4 (0.014)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>640 (6.4)</td>
<td>--</td>
<td>16.4 (0.16)</td>
</tr>
<tr>
<td>Columbia River (650 m W)</td>
<td>&lt;1 (blowdown)</td>
<td>2.44 E-03</td>
<td>21 (0.21)</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 (continuous)</td>
<td>1.99 E-04</td>
<td>0.04 (0.0004)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>21 (0.21)</td>
<td>--</td>
<td>0.55 (0.0055)</td>
</tr>
<tr>
<td>100 Area Fire Station (3,750 m ESE)</td>
<td>&lt;1 (blowdown)</td>
<td>1.60 E-04</td>
<td>1.4 (0.014)</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 (continuous)</td>
<td>2.73 E-05</td>
<td>0.006 (6.0 E-05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>1.4 (0.014)</td>
<td>--</td>
<td>0.036 (3.6 E-04)</td>
</tr>
<tr>
<td>Hanford Site boundary (10,090 m W)</td>
<td>&lt;1 (blowdown)</td>
<td>4.48 E-05</td>
<td>0.39 (0.0039)</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24 (continuous)</td>
<td>6.50 E-06</td>
<td>0.023 (2.3 E-05)</td>
<td>2.3 E-05</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>0.39 (0.0039)</td>
<td>--</td>
<td>0.01 (0.0001)</td>
</tr>
</tbody>
</table>


\(^b\)Fifty-year committed effective dose equivalent.

\(^a\)Beyond extremely unlikely event frequency is <10\(^-6\).
The safety-class equipment designated to prevent or mitigate the dose consequences of overpressurization accidents are described below.

**Safety-class equipment for detection of process upset:**

- **Vacuum purge system (VPS) instrumentation (high pressure trip)**

  Pressure indicators on the VPS provide MCO internal pressure information to the SCIC system, which initiates MCO isolation and SCHe actuation during process upset conditions.

- **SCIC system (monitoring process parameters)**

  The SCIC system uses programmable logic controllers, wiring to process instrumentation, signals from seismic detectors and temperature monitors, system controls, and output relays to isolate the MCO and actuate the SCHe system or cut power to the tempered water heater, if abnormal process or environmental conditions are detected.

- **Tempered water (annulus) system temperature trip**

  The tempered water (annulus) system includes antisiphon valves, low-water-level indication and alarm, and manual refill capability to ensure a minimum water level is maintained above the elevation of the fuel within the MCO. The system detects high water temperature and signals the SCIC system to actuate the tempered water trip.

- **Tempered water (annulus) system low level alarm**

  Redundant liquid level indicators are used by the tempered water (annulus) system to detect a low water level in the cask-MCO annulus and to provide a signal to the SCIC system to actuate the low-level alarm.

- **Tempered water (annulus) system level check petcocks**

  The level check petcocks provide a manual means of verifying the presence of water in the annulus. The petcocks are located in and above the double-walled portion of the tempered water (annulus) piping and are connected to the outer and inner pipes.
above the height of the fuel in the MCO. If a low-level alarm is received, the petcocks can be used to verify the presence of water in the inner or outer pipe, thus indicating the presence of water in the annulus.

- High bay temperature trip

The SCIC high bay temperature trip isolates the MCO and actuates the SCHe system so excessive temperatures in the bay cannot cause instrument inaccuracies or malfunctions that might result in MCO overpressurization.

Safety-class equipment for heat removal:

- Tempered water (annulus) system piping and antisiphon valves

A portion of the tempered water (annulus) system contains safety-class piping and antisiphon valves to ensure retention of a minimum water level above the elevation of the SNF inside the MCO.

Safety-class equipment for pressure management:

- SCHe system (vent path)

SCHe system piping and valves provide a pressure vent path to the local exhaust system precluding high pressures in the MCO.

- VPS 30 lb/in² gauge rupture disk and vent path lines and valves

The VPS 30 lb/in² gauge rupture disk and valves in the vent path to the local exhaust duct preclude high pressures.

- MCO 150 lb/in² gauge rupture disk

The MCO 150 lb/in² gauge rupture disk on the MCO provides backup capability for the 30 lb/in² gauge rupture disk on the VPS vent path line. The two rupture disks are connected or installed in different MCO process ports. Releases through the 150 lb/in² gauge rupture disk would be discharged to the process bay and swept through HEPA filters before being released to the environment.

Safety-class equipment for confinement and purge:

- Cask-MCO

The cask-MCO is a major part of the pressure boundary for confinement of radioactive materials during processing and provides connections for the process piping to the SCHe system.
The SCHe system provides two redundant and independent paths for purging and pressurizing the MCO and venting to the process vent.

- **Lines and valves to isolate and purge the MCO**

Lines and valves for isolating the MCO include the isolation valves (and air filters on air supply to valve actuators) in the VPS, general-service helium system, process water conditioning system, and SCHe system. Upon demand, all the valves close to isolate the MCO, except the SCHe system valves, which open to allow helium to the MCO.

Safety-significant equipment for confinement and dilution:

- **Process bay local exhaust HVAC and process vent system (exhaust fans and plenums, ductwork, HEPA filters, and flow switch)**

The process bay local exhaust HVAC and process vent system mitigates a release by sweeping it through HEPA filters before it is discharged outside the facility. Low flow alarms are set at 1,150 ft³/min.

- **Process bay local exhaust HVAC and process vent system process hood isolation damper and instrument air supply**

Isolation dampers in the process bay local exhaust HVAC and process vent system process hood fail closed. If power is lost, dampers will open with electrical power from the standby power system and instrument air supplied by the local dedicated tank. The hood isolation damper and instrument air supply operate in conjunction with the standby power system to facilitate HVAC operating while on standby power.

- **Reference air system (reference air header, differential pressure alarms)**

The reference air system monitors the negative pressure in the process bays and process water tank room by providing differential pressure indication and alarms to the control room for operator response.

- **Standby electrical power (diesel generator and process bay local exhaust HVAC and process vent system restart circuit)**

The standby power system provides connections to restart the local exhaust fans and supporting equipment. Operation of the local exhaust on standby power will maintain building differential pressure sufficient for confinement during facility power outages.
Process general supply/exhaust HVAC system (exhaust HEPA filter, exhaust ductwork, isolation damper)

The process general supply/exhaust HVAC system mitigates a release into the process bay or process water tank room by sweeping it through HEPA filters before discharging it outside the facility. The process general supply/exhaust HVAC system also provides confinement in conjunction with the facility structure by maintaining a negative building pressure. The system's isolation dampers fail closed to maintain negative differential pressure in the processing bays and process water tank room.

Process bay recirculation HVAC system isolation dampers (outside air inlets)

The process bay recirculation HVAC system provides fail-closed outside air inlet dampers so the local exhaust on standby power can maintain process bay differential pressure.

Assumptions made that require protection by technical safety requirements (TSRs) are listed below.

- Procedure to verify the results of the pressure rebound tests before continuing process steps

An initial pressure rebound test surveillance (pressure rise test) must be met before entry into the proof-of-dryness demonstration is allowed. Similarly, a proof-of-dryness demonstration surveillance must be met before the final pressure rebound test steps can begin. Finally, a final pressure rebound test must be met before shipment preparation steps can begin.

- Close long axial process tube port before closing filtered process exit port at the end of processing

When isolating the MCO at the end of processing, the long axial process tube port must be closed at least 5 minutes before closing the filtered process exit port. This ensures that an SCIC trip will occur if the procedure to isolate the MCO is inadvertently conducted on an MCO still to be processed.

Defense in depth features:

- General-service helium system: safety-class flow instrumentation

The general-service helium system provides SChE flow information to the SCIC system to initiate MCO isolation and SCHe actuation during process upset conditions.
10 lb/in² gauge safety relief valve for process relief

A general-service safety relief valve set at 10 lb/in² gauge and located on the process equipment skid provides pressure relief to the local exhaust duct.

The bounding MCO overpressurization accident (P:1) and the other accidents identified in the CVDF hazard analysis report (HNF-SD-SNF-HIE-004) that can potentially involve MCO overpressurization are itemized in Table 7-4, along with corresponding checklist designators, safety functions, and SSCs.

The accidents within the remaining bins require the following safety SSCs and TSRs in addition to the ones identified for the DBA (P:1):

P:2 Overpressurization due to loss of support utilities

The accident scenarios identified in the hazard analysis for the P:2 bin represent overpressurization accidents caused by loss of a support system because of accidents in adjacent bays and accidents in the spare bay. This bin also includes loss-of-power events caused by external forces (e.g., vehicle accident) and lightning strike (HNF-SD-SNF-HIE-004). The controls in the P2 bin prevent an MCO overpressurization by providing multiple vent paths from the MCO. Monitoring of process parameters is not needed for the events in this bin because the SSCs that provide venting of the MCO fail safe on loss of support utilities. Confinement and dilution are credited because of SCHe actuation.

No additional requirements result from analysis of this accident.

P:3 Overpressurization due to excessive helium supply pressure

The accident scenario identified in the hazard analysis for the P:3 bin represents an overpressurization accident caused by failure of the pressure regulators on the helium supply (general service helium or SCHe) (HNF-SD-SNF-HIE-004). The controls in the P3 bin prevent an MCO overpressurization by controlling the helium supply pressure from the general service helium system and the SCHe system.

Safety-class equipment for pressure control

- General-service helium supply system safety-class relief valves

Redundant pressure relief valves are provided on the general-service helium supply line to protect the MCO from overpressurization. General-service helium is supplied from the tube transporters at between 2,600 and 3,200 lb/in² gauge. The two pressure relief valves, which are arranged in series and set at 25 lb/in² gauge, prevent the MCO and related piping from experiencing the full supply pressure in the event of regulator failure.
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- SCHe supply pressure control valves and rupture disks

The SCHe system provides two redundant and independent paths for purging and pressurizing the MCO. Pressure control valves and rupture disks in each train protect the MCO from overpressurization by the helium bottles.

P.4 Overpressurization due to a line break caused by a seismic event

The accident scenarios identified in the hazard analysis for the P.4 bin represent overpressurization accidents caused by process upsets following a seismic event (HNF-SD-SNF-HIE-004). The controls in the P4 bin prevent an MCO overpressurization by removing reliance on nonqualified SSCs and by placing the MCO into a safe and stable configuration.

Safety-class equipment for detection of seismic events:
- SCIC seismic trip

On detecting a seismic event, the SCIC system seismic trip isolates the MCO and actuates the SCHe system and de-energize the tempered water (annulus) system to ensure the seismic event will not initiate thermal runaway.

Assumptions made that require protection by TSRs are listed below.

- Trailer placement controlled such that movement from seismic events will not impact key shutdown systems.

Before connecting CVDF systems to the MCO, the cask, which is located upon the trailer, must be positioned such that the central axis of the cask is no greater than an established safe distance from the ideal horizontal placement, as identified in HNF-3553, *Spent Nuclear Fuel Project Final Safety Analysis Report*, Annex B, "Cold Vacuum Drying Facility Final Safety Analysis Report," Chapter B4.0. This control protects the MCO during seismic events.

P.5 Overpressurization due to facility fire

The accident scenarios identified in the hazard analysis for the P.5 bin represent overpressurization accidents caused by facility fire (HNF-SD-SNF-HIE-004). The controls in the P5 bin prevent an MCO overpressurization by protecting safety-related SSCs from damage in a process bay fire. Credit also is taken for controls on the bay temperature to protect an assumption made in the fire hazards analysis.
Safety-class equipment for detection:

- SCIC process bay high temperature trip

The SCIC process bay high temperature trip acts to protect an initial condition assumption in the fire hazards analysis.

Assumptions made that require protection by TSRs are listed below:

- Combustible loadings limited

While an MCO is present in the facility, combustible loadings are limited as determined by the fire hazard analysis (SNF-4268). These limits ensure that any fire in the CVDF does not result in uncontrolled releases (e.g., fire-caused loss of process control).

- Restore bay temperature following a process bay high temperature trip

On high bay temperature trip alarm, operations must return the process bay temperature to within acceptable limits.
<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator</th>
<th>Safety function</th>
<th>Safety features</th>
<th>NRC ITS¹</th>
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</thead>
<tbody>
<tr>
<td>P.1. Overpressurization due to internal process upset of key parameters (bounding accident, PB-B-13c)</td>
<td>PB-B-03a, PB-B-13c, PB-B-13d, OU-R-02, OU-R-04</td>
<td>Prevent MCO overpressurization: Maintain parameters within limits</td>
<td>Safety-class equipment for detection of process upset: • VPS instrumentation (high pressure trip) • Tempered water (annulus) system temperature trip • Tempered water (annulus) system level alarm • Tempered water (annulus) level check petcocks • High bay temperature trip • SCIC system Safety-class equipment for heat removal • Tempered water (annulus) system piping and antisiphon valves Safety-class equipment for pressure management: • SCHe system (vent path) • 30 lb/in² rupture disk and vent path lines and valves • 150 lb/in² rupture disk Safety-class equipment for confinement, purge, and pressurization: • Cask-MCO • SCHe system • Lines and valves to isolate and purge the MCO Safety-significant equipment for confinement and dilution: • HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters, and flow switch) • HVAC/PV process hood isolation damper • Standby electrical power (diesel generator and HVAC/PV system restart circuit) • HVACD system (exhaust HEPA filter, exhaust duct work, isolation damper) • HVACB isolation dampers (outside air inlets) Safety-significant equipment for monitoring: • Reference air system (reference air header, differential pressure alarm for process bays) TSR: • Procedure to verify the results of the pressure rebound tests before continuing process steps • Close long axial process tube port before closing filtered process exit port at the end of processing</td>
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¹ NRC ITS: Nuclear Regulatory Commission Interim Technical Specifications.
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<th>Candidate accident</th>
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<th>Safety function</th>
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<tr>
<td>P.1: Overpressurization due to internal process upset of key parameters (cont.)</td>
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<td>Defense-in-depth equipment for detection:</td>
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<td></td>
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<td></td>
<td>• General service helium system: safety-class flow instrumentation</td>
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<td></td>
<td>• 10 lb/in² gauge safety relief valve for process relief</td>
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<td>P.2: Overpressurization due to loss of support utilities</td>
<td>FB-F-02a SB-F-01b SB-P-02b OU-P-04 OU-R-03</td>
<td>Prevent MCO overpressurization: Place the MCO in a safe configuration during a loss of support utilities</td>
<td>Safety-class equipment for pressure management:</td>
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<td></td>
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<td>• SCHe system (vent path)</td>
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<td></td>
<td>• 30 lb/in² gauge rupture disk and vent path lines and valves</td>
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<td>• 150 lb/in² gauge rupture disk</td>
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<td>Safety-class equipment for confinement and purge:</td>
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<td>• Cool-MCO</td>
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<td>• SCHe system</td>
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<td>• Lines and valves to isolate and purge the MCO^b</td>
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<td>Safety-significant equipment for confinement and dilution:</td>
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<td>• HVAC/PV system (exhaust fans and plenums, duct work, HEPA filters, and flow switch)</td>
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<td>• HVAC/PV process hood isolation damper</td>
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<td>• Standby electrical power (diesel generator and HVAC/PV system restart circuit)</td>
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<td>• HVACD system (exhaust HEPA filter, exhaust duct work, isolation damper)</td>
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<td>• HVACB isolation dampers (outside air inlets)</td>
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<td>Safety-significant equipment for monitoring:</td>
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<td></td>
<td>• Reference air system (reference air header, differential pressure alarm for process bays)</td>
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<td>Defense-in-depth equipment:</td>
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<td>• 10 lb/in² gauge safety relief valve for process relief</td>
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<td>Candidate accident</td>
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| P.3: Overpressurization due to excessive helium supply pressure | PB-H-11a | Prevent excessive helium pressure inside the MCO | Safety-class equipment for pressure boundary:  
  • Cask-MCO  
  Safety-class equipment for pressure control:  
  • General-service helium supply system safety-class relief valves  
  • SCHe supply pressure control valves and rupture disks  
  Defense in depth:  
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  • Place the MCO is a safe configuration following a seismic event | Safety-class equipment for pressure management:  
  • SCHe system (vent path)  
  • 30 lb/in² gauge rupture disk and vent path lines and valves  
  • 150 lb/in² gauge rupture disk  
  Safety-class for detection of seismic event:  
  • SCIC seismic trip  
  Safety-class equipment for confinement, purge, and pressurization:  
  • Cask-MCO  
  • SCHe system  
  • Lines and valves to isolate and purge the MCO | B |
|                |                      | Safety-class equipment for heat removal:  
  • Tempered water (annulus) system piping and antimonophon valves | TSR:  
  • Trailer placement controlled such that expected movement from seismic events will not impact key shutdown systems | A |
|                |                      | Defense in depth:  
  • 10 lb/in² gauge safety relief valve for process relief | |
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<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
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<td>P.5: Overpressurization caused by facility fire</td>
<td>PB-L-01</td>
<td>Protect a processing process bay against external fire</td>
<td>Safety-class equipment for detection:</td>
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<td>PB-L-02</td>
<td>PB-L-03</td>
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<td>PB-L-04</td>
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<td>Defense-in-depth equipment for process upset conditions and process bay temperature detection:</td>
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<td>PB-L-09</td>
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<td>PB-L-16</td>
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<td>Defense-in-depth equipment for heat removal:</td>
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<td>PB-P-02</td>
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<td>* Tempered water (annulus) system piping and antisiphon valves</td>
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<td>OU-P-02a</td>
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<td>* Manual refill piping and vent port</td>
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<td>* Cask-MCO</td>
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<td>Defense-in-depth equipment for shutdown:</td>
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<td>* SCHe system</td>
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<td>* Lines and valves to isolate and purge the MCOa</td>
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<td>Defense in depth:</td>
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<td>* Procedure to limit combustible loading</td>
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<td>* Fire protection system present in each bay</td>
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<td>* SCHe system</td>
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<td>* Lines and valves to isolate and purge the MCOa</td>
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NRC ITSa
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<table>
<thead>
<tr>
<th>Candidate accident</th>
<th>Checklist designator*</th>
<th>Safety function</th>
<th>Safety features</th>
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</table>

*Checklist designators are from HNF-SD-SNF-HIE-004, 1999, Cold Vacuum Drying Facility Hazard Analysis, Rev. 4, Fluor Daniel Hanford, Incorporated, Richland, Washington.

*U.S. Nuclear Regulatory Commission important-to-safety classifications: Category A = critical to safe operation, Category B = major impact on safety, Category C = minor impact to safety.

*Lines and valves to isolate the MCO include the isolation valves (and filters on air supply to valve actuators), and the air filters on the isolations valves, in the VPS, general-service helium system, PWC system, and SCHe system.

HEPA = high-efficiency particulate air (filter),
HVAC = heating, ventilation, and air conditioning,
HVAC/PV = process bay local exhaust HVAC and process vent system,
HVACB = process bay recirculation HVAC system,
HVACD = process general supply/exhaust HVAC system,
ITS = important to safety,
MCO = multi-canister overpack,
NRC = U.S. Nuclear Regulatory Commission,
SCHe = safety-class helium,
SCIC = safety-class instrumentation and control,
TSR = technical safety requirement,
VPS = vacuum purge system.
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<tr>
<td>CVDF</td>
<td>Cold Vacuum Drying Facility</td>
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<td>DBA</td>
<td>design basis accident</td>
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<td>HEPA</td>
<td>high-efficiency particulate air (filter)</td>
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<td>IXM</td>
<td>ion exchange module</td>
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A1.0 EVENT TREES FOR UNMITIGATED AND MITIGATED GASEOUS RELEASE IN A COLD VACUUM DRYING FACILITY PROCESS BAY

A1.1 ACCIDENT SCENARIO SUMMARY

The accident scenario represented in the following event trees and event tree descriptions is a gaseous release from a multi-canister overpack (MCO) into a process bay at the Cold Vacuum Drying Facility (CVDF). The gaseous release results from leaks in the vacuum processing system piping on the discharge side of the MCO during helium purge. The leak must occur undetected for more than 10 hours to cause an unacceptable onsite dose. Event trees are presented for both unmitigated (A1.2) and mitigated (A1.3) situations. In the unmitigated case, the effect of control systems is ignored; in the mitigated case, the frequency of gaseous releases in conjunction with control system failures is considered.

A1.2 FIGURE A1-1A

Figure A1-1a shows the event tree used to develop the frequency of unmitigated gaseous releases in a process bay at the CVDF. Five sequences are presented.

Initiating event (Event IE): Helium purge of MCOs during vacuum drying at a rate of 200 MCOs per year.

Sequence 1  a) Event F: The probability that the two flexible hose connections on the exit of the process vent port of the MCO maintain leak integrity is 0.999808 (1-[4.0 x 10^-6/h x 24 h x 2 connections]). The value of 4.0 x 10^-6/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 (Dexter and Perkins 1982, page 18).

b) Event PI: The probability that the 10 ft of exit piping from the process vent port of the MCO maintains its leak integrity is 0.9999976 (1-[1.0 x 10^-7/h-ft x 10 ft x 24 h]). The value of 1.0 x 10^-7/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875, INFORMAL REPORT, Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs (Eide et al. 1990, page 12).

c) Event V: The probability that one isolation valve (GOV 1*09) and two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system maintain their integrity is 0.9999928 (1-[1.0 x 10^-7/h x 24 h x 3 valves]). The value of 1.0 x 10^-7/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990, page 11).
d) Event OP: The probability that the exit line involved with helium purge is successfully installed and maintains leak integrity is 0.97 (1-\(3.0 \times 10^{-2}\)). The value of \(3.0 \times 10^{-2}\) is a value assigned to basic operator errors based on NUREG/CR-4772, Accident Sequence Evaluation Program Human Reliability Analysis Procedure (Swain 1987, Table 4-2, Note #2, page 4-5).

If the exit flexible connections do not leak AND the helium purge exit piping does not leak AND none of the three exit line valves leaks AND the exit lines have been installed correctly and do not leak, this results in normal processing.

Sequence 2

a) Event F: The probability that the two flexible hose connections on the exit of the process vent port of the MCO maintain leak integrity is 0.999808 (1-\(4.0 \times 10^{-6}/h \times 24 \ h \times 2 \ connections\)). The value of \(4.0 \times 10^{-6}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

b) Event PI: The probability that the 10 ft of exit piping from the process vent port of the MCO maintains its leak integrity is 0.9999976 (1-\(1.0 \times 10^{-8}/h\-ft \times 10 \ ft \times 24 \ h\)). The value of \(1.0 \times 10^{-8}/h\-ft\) is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

c) Event V: The probability that one isolation valve (GOV 1*09) and two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system maintain their integrity is 0.9999928 (1-\(1.0 \times 10^{-7}/h \times 3 \ valves\)). The value of \(1.0 \times 10^{-7}/h\) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

d) Event OP: The probability that operator error during installation of the exit line involved with helium purge results in a leak is 0.03 (\(3.0 \times 10^{-2}\)). The value of \(3.0 \times 10^{-2}\) is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

If the exit flexible connections do not leak AND the helium purge exit piping does not leak AND none of the three exit line valves leaks AND the exit lines have been incorrectly installed and thus leak, this results in a release that is greater than onsite guidelines.

Sequence 3

a) Event F: The probability that the two flexible hose connections on the exit of the process vent port of the MCO maintain leak integrity is 0.999808 (1-\(4.0 \times 10^{-6}/h \times 24 \ h \times 2 \ connections\)). The value of \(4.0 \times 10^{-6}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

b) Event PI: The probability that the 10 ft of exit piping from the process vent port of the MCO maintains its leak integrity is 0.9999976 (1-\(1.0 \times 10^{-8}/h\-ft \times 10 \ ft \times 24 \ h\)). The value of \(1.0 \times 10^{-8}/h\-ft\) is a value for leakage from piping
1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

c) Event V: The probability that either one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is 0.0000072 \((1.0 \times 10^{-7}/h \times 24 \text{ h} \times 3 \text{ valves})\). The value of \(1.0 \times 10^{-7}/h\) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

If the exit flexible connections do not leak AND the helium purge exit piping does not leak AND any of the three exit line valves leaks, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 4

a) Event F: The probability that the two flexible hose connections on the exit of the process vent port of the MCO maintain leak integrity is 0.999808 \((1-[4.0 \times 10^{-6}/h \times 24 \text{ h} \times 2 \text{ connections}])\). The value of \(4.0 \times 10^{-6}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

b) Event PI: The probability that the 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 \((1.0 \times 10^{-6}/h \times 10 \text{ ft} \times 24 \text{ h})\). The value of \(1.0 \times 10^{-6}/h\) is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

If the exit flexible connections do not leak AND the helium purge exit piping leaks, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 5

a) Event F: The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 \((4.0 \times 10^{-6}/h \times 24 \text{ h} \times 2 \text{ connections})\). The value of \(4.0 \times 10^{-6}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

If the exit flexible connections leak, this results in a release that is greater than onsite guidelines.

A1.3 FIGURE A1-1B

Figure A1-1b shows the event tree used to develop the frequency of a mitigated gaseous release in a process bay at the CVDF. Eleven sequences are presented.

Initiating event (Event IE): Helium purge of MCOs during vacuum drying at a rate of 200 MCOs per year.
Sequence 1 a) Event EXIT PATH INTACT: The product of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO maintain leak integrity is 0.999808 (1-[4.0 x 10^-6/h x 24 h x 2 connections]). The value of 4.0 x 10^-6/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982, page 18).

AND

The probability that the 10 ft of exit piping from the process vent port of the MCO maintains its leak integrity is 0.9999976 (1-[1.0 x 10^-7/h-ft x 10 ft x 24 h]). The value of 1.0 x 10^-7/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990, page 12).

AND

The probability that one isolation valves (GOV 1*09) and two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system maintain their integrity is 0.9999928 (1-[1.0 x 10^-7/h x 24 h x 3 valves]). The value of 1.0 x 10^-7/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990, page 11).

AND

The probability that installing the exit line involved with helium purge maintains leak integrity is 0.9997 (1-[3.0 x 10^-4]). The value of 3.0 x 10^-4 is a value assigned to basic operator error plus a post-installation test based on NUREG/CR-4772 (Swain 1987, Table 5-3, Case VI, page 5-13).

Therefore the probability that the exit path from the MCO maintains its integrity is calculated as follows:

\[(1-0.92 x 10^{-6}) \times (1-2.4 \times 10^{-6}) \times (1-7.2 \times 10^{-6}) \times (1-3.0 \times 10^{-4}) = 0.9995\]

If the exit flexible connections do not leak AND the helium purge exit piping does not leak AND none of the three exit line valves leaks AND the exit lines have been correctly installed and do not leak, this results in normal processing.

Sequence 2 a) Event EXIT PATH INTACT: The summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 (4.0 x 10^-6/h x 24 h x 2 connections). The value of 4.0 x 10^-6/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that the 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 (1.0 x 10^-8/h-ft x 10 ft x 24 h). The value of 1.0 x 10^-8/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).
OR
The probability that one isolation valve (GOV 1*09 or two needle valves (VPS-V-059 and VPS-V-061) in the exit helium purge system leak is 0.0000072 (1.0 x 10^(-9) x 24 h x 3 valves). The value of 1.0 x 10^(-9) h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR
The probability that installing the exit line involved with helium purge maintains leak integrity is 0.0003 (3.0 x 10^(-4)). The value of 3.0 x 10^(-4) is a value assigned to basic operator error plus a post-installation test based on NUREG/CR-4772 (Swain 1987).

Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

\[(1.92 \times 10^{-4}) + (2.4 \times 10^{-6}) + (7.2 \times 10^{-6}) + (3.0 \times 10^{-4}) = 5.00 \times 10^{-4}.\]

b) Event DP: The probability that a differential pressure is maintained in the bays is 0.9923 (1-\[7.7 \times 10^{-3}\]). The value of 7.7 \times 10^{-3} is the sum of the probability of a loss of electrical power (LOEP) per 24 h per MCO (3.3 \times 10^{-3}) and a false smoke detection that closes the dampers in the process bay (1 x 10^{-4}h \times 8,760 h/2 = 4.4 \times 10^{-3}). The value of 3.3 \times 10^{-3} is calculated as \(1 - e^{-(1.22/yr \times 24 h/yr \times 8760 h)} = 3.3 \times 10^{-3}\), where 1.22 LOEP events per year is the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811, *Analysis of Power Loss Data for the 200 Area Tank Farms in Support of K Basin SAR Work* (Shultz 1994, page 4) and 24 hours is the time period an MCO is judged to be vulnerable to an LOEP for this sequence. The value of 1.0 \times 10^{-4}h is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990, page 23).

c) Event HEPA FILTER OK: The probability that the high-efficiency particulate air (HEPA)-filtered vent path has HEPA filtration functioning during the release based on 4,380 hours (the average unavailability assuming tested once per year; 8,760 h/2) is 0.999943 (1-\[1.3 \times 10^{-4}/h \times 4,380 h\]). The value of 1.3 \times 10^{-4}/h is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982, page 18).

If the exit path from the process vent port of the MCO does leak AND the DP is maintained in the bays AND the HEPA filter on the exhaust path is functioning, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).
Sequence 3  a) Event EXIT PATH INTACT: The summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 (4.0 x 10^{-6} / h x 24 h x 2 connections). The value of 4.0 x 10^{-6} / h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that the 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 (1.0 x 10^{-8} / h-ft x 10 ft x 24 h). The value of 1.0 x 10^{-8} / h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is 0.0000072 (1.0 x 10^{-7} / h x 24 h x 3 valves). The value of 1.0 x 10^{-7} / h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that operator error during installation of the exit line involved with helium purge results in a leak is 0.0003 (3.0 x 10^{-4}). The value of 3.0 x 10^{-4} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

(1.92 x 10^{-4}) + (2.4 x 10^{-6}) + (7.2 x 10^{-6}) + (3.0 x 10^{-4}) = 5.00 x 10^{-4}.

b) Event DP: The probability that a differential pressure is maintained in the bays is 0.9923 (1 - [7.7 x 10^{-3}]). The value of 7.7 x 10^{-3} is the sum of the probability of an LOEP per 24 hours per MCO (3.3 x 10^{-3}) and a false smoke detection that closes the dampers in the process bay (1 x 10^{-6} / h * 8,760 h / year = 4.4 x 10^{-3}). The value of 3.3 x 10^{-3} is calculated as (1 - e^{-1.22 yr / 24 h / yr / 8760 h}) = 3.3 x 10^{-3}), where 1.22 LOEP events per year is the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 24 hours is the time period an MCO is judged to be vulnerable to an LOEP for this sequence. The value of 1.0 x 10^{-6} / h is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990, page 23).

c) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has no HEPA filtration functioning during the release based on 4,380 hours (the average unavailability assuming tested once per year; 8,760 h / 2) is 0.000057 (1.3 x 10^{-4} / h x 4,380 h). The value of 1.3 x 10^{-4} / h is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982).
If the exit path from the process vent port of the MCO does leak AND the DP is maintained in the bays AND the HEPA filter on the exhaust path is not functioning, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 4

a) Event EXIT PATH INTACT: The summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 (4.0 x 10^{-5}/h x 24 h x 2 connections). The value of 4.0 x 10^{-5}/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that the 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 (1.0 x 10^{-8}/h-ft x 10 ft x 24 h). The value of 1.0 x 10^{-8}/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is 0.0000072 (1.0 x 10^{-7}/h x 24 h x 3 valves). The value of 1.0 x 10^{-7}/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that operator error during installation of the exit line involved with helium purge results in a leak is 0.0003 (3.0 x 10^{-4}). The value of 3.0 x 10^{-4} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

\[(1.92 \times 10^{-4}) + (2.4 \times 10^{-6}) + (7.2 \times 10^{-6}) + (3.0 \times 10^{-4}) = 5.00 \times 10^{-4}.

b) Event DP: The probability that no differential pressure is maintained in the bays resulting from a loss of power per 24 hours per MCO is 3.3 x 10^{-3}. The probability of an LOEP for a 24-hours period is calculated as \(1-e^{-1.22 \text{yr}^{-1}}\), where 1.22 LOEP events per year is the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994).

c) Event DP IS DETECTED: The probability that, when the differential pressure is lost in the process bay, the loss is detected is 0.999976 \([1-(1.0 \times 10^{-6}/h \times 24 h)]\). The value of 1.0 x 10^{-6}/h is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990, page 23).
d) Event RESTORE DP: The probability that, when electrical power is lost, the backup diesel generator will start and at least one of the local exhaust fans will start is 0.9972 \( (1-\left[2.8 \times 10^{-4}\right]) \). The probability that the backup diesel generator will start (given it has enough air in its start accumulator for 10 start tries) is assumed to be 0.9977 \( (1-\left[2.3 \times 10^{-3}\right]) \). The value of \(2.3 \times 10^{-3}\) represents the failure rate of a diesel generator based on a value of \(2.3 \times 10^{-2}/\text{demand}\) and a factor of ten reduction based on the ability to try to start it ten times. The value of \(2.3 \times 10^{-2}/\text{demand}\) is the failure rate of a diesel-driven pump to start on demand. The more conservative value of \(2.3 \times 10^{-2}/\text{demand}\) is used in this calculation. The probability that either of the two local exhaust fans will start following the start of the backup diesel generator is 0.9995 \( (1-\left[5 \times 10^{-4}\right]) \). The value of \(5 \times 10^{-4}\) is based on fan failure to start probability of \(5 \times 10^{-3}/\text{demand}\) multiplied by a common-cause beta factor of 0.1. The value of \(5 \times 10^{-3}/\text{demand}\) is the failure rate of a ventilator fan failure to start on demand based on EGG-SSRE-8875 (Eide et al. 1990, page 19). Thus, the probability that the diesel generator and one of the local exhaust fans starting following LOEP is 0.9972 \( (1-\left[2.8 \times 10^{-4}\right]) \) or \((1-\left[2.3 \times 10^{-3}\right]) \times (1-\left[5 \times 10^{-4}\right]) = 0.9972\).

e) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has HEPA filtration functioning during the release based on 4,380 hours (the average unavailability assuming tested once per year, 8,760 h/2) is 0.999943 \( (1-\left[1.3 \times 10^{-4}/\text{h} \times 4,380 \text{ h}\right]) \). The value of \(1.3 \times 10^{-4}/\text{h}\) is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982, page 18).

If the exit path from the process vent port of the MCO does leak AND the DP is not maintained in the bays due to loss of power AND the DP loss is detected AND DP is restored AND the HEPA filter on the exhaust path is functioning, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 5 a) Event EXIT PATH INTACT: The summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 \( (4.0 \times 10^{-6}/\text{h} \times 24 \text{ h} \times 2 \text{ connections}) \). The value of \(4.0 \times 10^{-6}/\text{h}\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that the 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 \( (1.0 \times 10^{-8}/\text{h-ft} \times 10 \text{ ft} \times 24 \text{ h}) \). The value of
$1.0 \times 10^{-7}$/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

**OR**
The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is $0.0000072 \ (1.0 \times 10^{-7}$/h x 24 h x 3 valves). The value of $1.0 \times 10^{-7}$/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

**OR**
The probability that operator error during installation of the exit line involved with helium purge results in a leak is $0.0003 \ (3.0 \times 10^{-4})$. The value of $3.0 \times 10^{-4}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

$$(1.92 \times 10^{-4}) + (2.4 \times 10^{-6}) + (7.2 \times 10^{-6}) + (3.0 \times 10^{-4}) = 5.00 \times 10^{-4}.$$
The value of $5 \times 10^4$ is based on fan failure to start probability of $5 \times 10^{-3}$/demand times a common cause beta factor of 0.1. The value of $5 \times 10^4$/demand is the failure probability of a ventilator fan failure to start based on EGG-SSRE-8875 (Eide et al. 1990, page 19). Thus the probability that the diesel generator and one of the local exhaust fans starting following LOEP is $0.9972 \times (1-[2.8 \times 10^{-3}]) = 0.9972$.

e) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has no HEPA filtration functioning during the release based on 4,380 hours (the average unavailability assuming tested once per year; 8,760 h/2) is $0.000057 \times (10^{-8}/h \times 4,380)$ h. The value of $1.3 \times 10^{-8}$/h is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982).

If the exit path from the process vent port of the MCO does leak AND the DP is not maintained in the bays due to loss of power AND the DP loss is detected AND DP is restored AND the HEPA filter on the exhaust path is not functioning, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

Sequence 6

a) Event EXIT PATH INTACT: The summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is $0.000192 \times (4.0 \times 10^{-6}/h \times 24 h \times 2$ connections). The value of $4.0 \times 10^{-6}$/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that 10 ft of exit piping from the process vent port of the MCO leaks is $0.000024 \times (1.0 \times 10^{-7}/h \times 10$ ft $\times 24$ h). The value of $1.0 \times 10^{-7}$/h is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is $0.0000072 \times (1.0 \times 10^{-7}/h \times 24$ h $\times 3$ valves). The value of $1.0 \times 10^{-7}$/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that operator error during installation of the exit line involved with helium purge results in a leak is $0.0003 \times (3.0 \times 10^{-4})$. The value of $3.0 \times 10^{-4}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).
Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

\[(1.92 \times 10^{-5}) + (2.4 \times 10^{-6}) + (7.2 \times 10^{-8}) + (3.0 \times 10^{-10}) = 5.00 \times 10^{-4}.\]

b) Event DP: The probability that no differential pressure is maintained in the bays resulting from a loss of power per 24 hours per MCO is \(3.3 \times 10^{-3}\). The probability of an LOEP for a 24-hour period is calculated as \((1.0 - (1.22 \times 10^{-2})^{24\text{hrs}} / 8760\text{hrs}) = 3.3 \times 10^{-3}\), where 1.22 LOEP events per year is the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994).

c) Event DP IS DETECTED: The probability that, when the differential pressure is lost in the process bay, the loss is detected is \(0.999976\) \([1-(1.0 \times 10^{-6}/\text{h} \times 24\text{ h})]\). The value of \(1.0 \times 10^{-6}/\text{h}\) is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990).

d) Event RESTORE DP: The probability that when electrical power is lost, the backup diesel generator will not start or at least one of the local exhaust fans will not start is \(0.0028\) \((2.8 \times 10^{-3})\). The probability that the backup diesel generator will not start (given it has enough air in its start accumulator for 10 start tries) is assumed to be \(0.0023\) \((2.3 \times 10^{-3})\). The value of \(2.3 \times 10^{-3}\) represents the failure to start of a diesel generator based on a value of \(2.3 \times 10^{-2}/\text{demand}\) and a factor of ten reduction based on the ability to try to start it ten times. The value of \(2.3 \times 10^{-2}/\text{demand}\) is the failure probability of a gas turbine generator to fail to start based on DP-1633 (Dexter and Perkins 1982). The document EGG-SSRE-8875 (Eide et al. 1990) shows the failure of diesel-driven pumps to start on demand is \(1 \times 10^{-2}/\text{demand}\). The more conservative value of \(2.3 \times 10^{-3}/\text{demand}\) is used in this calculation. The probability that either of the two local exhaust fans will not start following the start of the backup diesel generator is \(0.0005\) \((5 \times 10^{-4})\). The value of \(5 \times 10^{-4}\) is based on fan failure to start probability of \(5 \times 10^{-3}/\text{demand}\) times a common cause beta factor of 0.1. The value of \(5 \times 10^{-3}/\text{demand}\) is the failure probability of a ventilator fan failure to start based on EGG-SSRE-8875 (Eide et al. 1990). Thus the probability that the diesel generator or one of the local exhaust fans fails to start following LOEP is \(0.0028\) \((2.8 \times 10^{-3})\) or \[((2.3 \times 10^{-3}) + (5 \times 10^{-4})) = 0.0028\].

If the exit path from the process vent port of the MCO does leak AND the DP is not maintained in the bays due to loss of power AND the DP loss is detected AND DP is not restored, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).
Sequence 7  a) Event EXIT PATH INTACT: The summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 \((4.0 \times 10^{-9}/h \times 24\ h \times 2\ connections)\). The value of \(4.0 \times 10^{-9}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 \((1.0 \times 10^{-8}/h-ft \times 10\ ft \times 24\ h)\). The value of \(1.0 \times 10^{-8}/h-ft\) is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is 0.0000072 \((1.0 \times 10^{-7}/h \times 24\ h \times 3\ valves)\). The value of \(1.0 \times 10^{-7}/h\) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that operator error during installation of the exit line involved with helium purge results in a leak is 0.0003 \((3.0 \times 10^{-4})\). The value of \(3.0 \times 10^{-4}\) is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).

Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

\[
(1.92 \times 10^{-4}) + (2.4 \times 10^{-6}) + (7.2 \times 10^{-6}) + (3.0 \times 10^{-4}) = 5.00 \times 10^{-4}
\]

b) Event DP: The probability that no differential pressure is maintained in the bays resulting from a loss of power per 24 hours per MCO is 3.3 \( \times 10^{-3}\). The probability of an LOEP for a 24-hour period is calculated as \((1 - e^{(-1.22 \times \text{yr}^{0.75})^{24\text{hrs}^{0.60\text{hrs}}}}) = 3.3 \times 10^{-3}\), where 1.22 LOEP events per year is the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994).

c) Event DP IS DETECTED: The probability that when the differential pressure is lost in the process bay that the loss is not detected is 0.000024 \((1.0 \times 10^{-6}/h \times 24\ h)\). The value of \(1.0 \times 10^{-6}/h\) is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Elde et al. 1990).

If the exit path from the process vent port of the MCO does leak AND DP is not maintained in the bays due to loss of power AND the DP loss is not detected, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).
Sequence 8

a) Event EXIT PATH INTACT: The summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is $0.000192 \times (4.0 \times 10^{-6}/\text{h} \times 24 \text{ h} \times 2 \text{ connections})$. The value of $4.0 \times 10^{-6}/\text{h}$ is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that the 10 ft of exit piping from the process vent port of the MCO leaks is $0.0000024 \times (1.0 \times 10^{-8}/\text{h-ft} \times 10 \text{ ft} \times 24 \text{ h})$. The value of $1.0 \times 10^{-8}/\text{h-ft}$ is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is $0.0000072 \times (1.0 \times 10^{-7}/\text{h} \times 24 \text{ h} \times 3 \text{ valves})$. The value of $1.0 \times 10^{-7}/\text{h}$ is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that operator error during installation of the exit line involved with helium purge results in a leak is $0.0003 \times (3.0 \times 10^{-6})$. The value of $3.0 \times 10^{-6}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

$$1.92 \times 10^{-4} + 2.4 \times 10^{-6} + 7.2 \times 10^{-6} + 3.0 \times 10^{-4} = 5.00 \times 10^{-4}.$$  

b) Event DP: The probability that no differential pressure is maintained in the bays as a result of a false smoke detector actuation of damper closure is $0.0044 \times (4.4 \times 10^{-5})$. The value of $4.4 \times 10^{-5}$ is based on a false smoke detection closing the dampers from the process bays ($1 \times 10^{-6}/\text{h} \times 8,760\text{ h/2} = 4.4 \times 10^{-3}$). The value of $1.0 \times 10^{-6}/\text{h}$ is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990).

c) Event DP IS DETECTED: The probability that, when the differential pressure is lost in the process bay, the loss is detected is $0.999976 [1-(1.0 \times 10^{-6}/\text{h} \times 24 \text{ h})]$. The value of $1.0 \times 10^{-6}/\text{h}$ is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990, page 23).

d) Event RESTORE DP: The probability that when a false smoke detector actuation closes the dampers the operators will restore the dampers to an open position within 10 hour is $0.97 (1-[3 \times 10^{-2}])$. The value of $3.0 \times 10^{-2}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).
e) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has HEPA filtration functioning during the release based on 4,380 hours (the average unavailability assuming tested once per year; 8,760 h/2) is 0.999943 (1-1.3 x 10^{-8}/h x 4,380 h). The value of 1.3 x 10^{-8}/h is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982, page 18).

If the exit path from the process vent port of the MCO does leak AND the DP is not maintained in the bays due to dampers closing on false smoke detection actuation AND the DP loss is detected AND DP is restored AND the HEPA filter on the exhaust path is functioning, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 9

a) Event EXIT PATH INTACT: The summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 (4.0 x 10^{-6}/h x 24 h x 2 connections). The value of 4.0 x 10^{-6}/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that the 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 (1.0 x 10^{-7}/h-ft x 10 ft x 24 h). The value of 1.0 x 10^{-7}/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is 0.0000072 (1.0 x 10^{-7}/h x 24 h x 3 valves). The value of 1.0 x 10^{-7}/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that operator error during installation of the exit line involved with helium purge results in a leak is 0.0003 (3.0 x 10^{-4}). The value of 3.0 x 10^{-4} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

(1.92 x 10^{-4}) + (2.4 x 10^{-6}) + (7.2 x 10^{-6}) + (3.0 x 10^{-4}) = 5.00 x 10^{-4}.

b) Event DP: The probability that no differential pressure is maintained in the bays as a result of a false smoke detector actuation of damper closure is 0.0044 (4.4 x 10^{-3}). The value of 4.4 x 10^{-3} is based on a false smoke detection closing the dampers from the process bays (1 x 10^{-6}/h * 8,760h/2
= 4.4 \times 10^3). The value of 1.0 \times 10^{-6}/h is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990).

c) Event DP IS DETECTED: The probability that, when the differential pressure is lost in the process bay, the loss is detected is 0.999976 \left[1 - \left(1.0 \times 10^{-6}/h \times 24 \text{ h}\right)\right]. The value of 1.0 \times 10^{-6}/h is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990).

d) Event RESTORE DP: The probability that when a false smoke detector actuation closes the dampers the operators will restore the dampers to an open position within 10 hours is 0.97 \left(1 - 3 \times 10^{-2}\right). The value of 3.0 \times 10^{-2} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

e) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has no HEPA filtration functioning during the release based on 4,380 hours (the average unavailability assuming tested once per year; 8,760 h/2) is 0.000057 \left(1.3 \times 10^{-9}/h \times 4,380 \text{ h}\right). The value of 1.3 \times 10^{-9}/h is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982).

If the exit path from the process vent port of the MCO does leak AND the DP is not maintained in the bays due to dampers closing on false smoke detection actuation AND the DP loss is detected AND DP is restored AND the HEPA filter on the exhaust path is not functioning, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

Sequence 10 a) Event EXIT PATH INTACT: The summation of the following probabilities:

- The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 \left(4.0 \times 10^{-6}/h \times 24 \text{ h} \times 2 \text{ connections}\right). The value of 4.0 \times 10^{-6}/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).
- OR
- The probability that the 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 \left(1.0 \times 10^{-9}/h-ft \times 10 \text{ ft} \times 24 \text{ h}\right). The value of 1.0 \times 10^{-9}/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).
- OR
- The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-4059 and VPS-V-4061) in the exit helium purge system leak is 0.0000072 \left(1.0 \times 10^{-7}/h \times 24 \text{ h} \times 3 \text{ valves}\right). The value of 1.0 \times 10^{-7}/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).
OR
The probability that operator error during installation of the exit line involved with helium purge results in a leak is 0.0003 (3.0 x 10^{-4}). The value of 3.0 x 10^{-4} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).

Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

\[(1.92 \times 10^{-4}) + (2.4 \times 10^{-5}) + (7.2 \times 10^{-6}) + (3.0 \times 10^{-4}) = 5.00 \times 10^{-4}.
\]

b) Event DP: The probability that no differential pressure is maintained in the bays as a result of a false smoke detector actuation of damper closure is 0.0044 (4.4 x 10^{-3}). The value of 4.4 x 10^{-3} is based on a false smoke detection closing the dampers from the process bays (1 x 10^{-6}/h * 8,760h/2

\[= 4.4 \times 10^{-3}\).

The value of 1.0 x 10^{-6}/h is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990).

c) Event DP IS DETECTED: The probability that, when the differential pressure is lost in the process bay, the loss is detected is 0.999976 \[1-(1.0 \times 10^{-6}/h \times 24 h)\]. The value of 1.0 x 10^{-6}/h is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990).

d) Event RESTORE DP: The probability that when a false smoke detector actuation closes the dampers the operators will not restore the dampers to an open position within 10 hours is 0.03 (3 x 10^{-2}). The value of 3.0 x 10^{-2} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

If the exit path from the process vent port of the MCO does leak AND the DP is not maintained in the bays due to dampers closing on false smoke detection actuation AND the DP loss is detected AND DP is not restored, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 11 a) Event EXIT PATH INTACT: The summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 (4.0 x 10^{-5}/h x 24 h x 2 connections). The value of 4.0 x 10^{-5}/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR
The probability that the 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 (1.0 x 10^{-8}/h-ft x 10 ft x 24 h). The value of
1.0 x 10^4/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is 0.0000072 (1.0 x 10^-7/h x 24 h x 3 valves). The value of 1.0 x 10^-7/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that operator error during installation of the exit line involved with helium purge results in a leak is 0.0003(3.0 x 10^-4). The value of 3.0 x 10^-4 is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).

Therefore the probability that the exit path from the MCO does not maintain its integrity is calculated as follows:

(1.92 x 10^-4) + (2.4 x 10^-6) + (7.2 x 10^-6) + (3.0 x 10^-4) = 5.00 x 10^-4.

b) Event DP: The probability that no differential pressure is maintained in the bays as a result of a false smoke detector actuation of damper closure is 0.0044 (4.4 x 10^-3). The value of 4.4 x 10^-3 is based on a false smoke detection closing the dampers from the process bays (1 x 10^-6/h * 8,760h/2 = 4.4 x 10^-3). The value of 1.0 x 10^-6/h is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990).

c) Event DP IS DETECTED: The probability that, when the differential pressure is lost in the process bay, the loss is not detected is 0.000024 (1.0 x 10^-6/h x 24 h). The value of 1.0 x 10^-6/h is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990).

If the exit path from the process vent port of the MCO does leak AND the DP is not maintained in the bays due to dampers closing on false smoke detection actuation AND the DP loss is not detected, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

A1.4 REFERENCES


<p>| No. of MCUs/year that experience a helium- | Flexible hose connections (2) at the | 10 feet of exit piping to isolation | 1 isolation valve or 2 needle valves | Seq. Freq. | Seq. # | Results                      |
| experience a helium-purge during vacuum | process vent part of MCO maintain | valve GOV1409 maintain integrity | maintain leak integrity | during installation of line |          |          |
| drying | integrity | | | | |          |
| INITIATING EVENT | F | PI | V | OP |          |          |
| 200 | YES | YES | YES | YES | 1.94E+02 | 1 | Normal processing |
| 200 | YES | YES | YES | NO  | 6.00E+00 | 2 | &gt; onsite guidelines |
| 200 | YES | YES | NO  | NO  | 1.44E+03 | 3 | OK |
| 200 | YES | NO  | 1.82E-04 | NO  | 4.80E-04 | 4 | OK |
| 200 | NO  | 2.40E-06 | NO  | NO  | 3.64E-02 | 5 | &gt; onsite guidelines |</p>
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<th>Differential pressure (DP) is present</th>
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Figure A1-1b. Event Tree for a Mitigated Gaseous Release in a Process Bay at the Cold Vacuum Drying Facility.
A2.0 EVENT TREES FOR UNMITIGATED AND MITIGATED LIQUID RELEASE IN THE COLD VACUUM DRYING FACILITY PROCESS WATER CONDITIONING ROOM

A2.1 ACCIDENT SCENARIO SUMMARY

The accident scenario represented in the following event trees and event tree descriptions is a liquid release in the process water conditioning (PWC) room of the CVDF. The liquid release results from spray leaks in the pressurized piping system on the discharge side of the PWC room pump. The spray leak must occur undetected for more than 10 hours to cause an unacceptable onsite dose. Event trees are developed for both unmitigated (A2.2) and mitigated (A2.3) situations; in the unmitigated case, the effects of control systems such as pressure differentials, power shutoffs, and air filtration are ignored and in the mitigated case they are included.

A2.2 FIGURE A2-1A

Figure A2-1a shows the event tree used to develop the frequency of an unmitigated liquid release in the PWC room in the CVDF. Five sequences are presented.

Initiating event (Event IE): Internal water is drained from MCOs at a rate of 200 MCOs per year.

Sequence 1  a) Event PU: The probability that the operating PWC circulation pump (PWC-P-403*) maintains its leak integrity during each MCO drain is 0.999976 (1-[3.0 x 10^-6/h x 8 h]). The value of 3.0 x 10^-6/h is a value for external leakage from a pump based on EGG-SSRE-8875, INFORMAL REPORT, Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs (Eide et al. 1990, page 12).

b) Event PI: The probability that 100 ft of piping in the PWC water circulation line maintains its leak integrity during each MCO drain is 0.999992 (1-[1.0 x 10^-4/h-ft x 100 ft x 8 h]). The value of 1.0 x 10^-4/h-ft is a value for leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990, page 12).

c) Event V: The probability that the 15 valves in the PWC circulation line maintain their integrity during each MCO drain is 0.999988 (1-[1.0 x 10^-7/h x 8 h x 15 valves]). The value of 1.0 x 10^-7/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990, page 11).

d) Event F: The probability that the two "in use" flexible hose connections to the ion exchange modules (IXMs) in the PWC circulation system maintain leak integrity during each MCO drain is 0.999936 (1-[4.0 x 10^-6/h x 8 h]
x 2 connections]). The value of $4.0 \times 10^{-6}/h$ is a value for lightly stressed hose based on DP-1633, *Component Failure-Rate Data with Potential Applicability to a Nuclear Fuel Reprocessing Plant* (Dexter and Perkins 1982, page 18).

If the operating pump does not leak AND the process water line piping does not leak AND none of the 15 process water line valves leak AND the two "in use" flexible connections to the IXMs do not leak, this results in normal processing.

Sequence 2

a) Event PU: The probability that the operating PWC circulation pump (PWC-P-403*) maintains its leak integrity during each MCO drain is $0.999976 (1 - [3.0 \times 10^{-6}/h \times 8h])$. The value of $3.0 \times 10^{-6}/h$ is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990).

b) Event PI: The probability that the 100 ft of piping in the PWC water circulation line maintains its leak integrity during each MCO drain is $0.999992 (1 - [1.0 \times 10^{-9}/h-ft \times 100 ft \times 8h])$. The value of $1.0 \times 10^{-9}/h-ft$ is a value for leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

c) Event V: The probability that the 15 valves in the PWC circulation line maintain their integrity during each MCO drain is $0.999988 (1 - [1.0 \times 10^{-7}/h \times 8h \times 15 valves])$. The value of $1.0 \times 10^{-7}/h$ is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

d) Event F: The probability that either of the two "in use" flexible hose connections to the IXMs in the PWC circulation system leak during each MCO drain is $0.000064 (4.0 \times 10^{-9}/h \times 8h \times 2$ connections). The value of $4.0 \times 10^{-9}/h$ is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

If the operating pump does not leak AND the process water line piping does not leak AND none of the 15 process water line valves leak, but either of the two "in use" flexible connections to the IXMs leak, this results in a release that is greater than onsite guidelines.

Sequence 3

a) Event PU: The probability that the operating PWC circulation pump (PWC-P-403*) maintains its leak integrity during each MCO drain is $0.999976 (1 - [3.0 \times 10^{-6}/h \times 8h])$. The value of $3.0 \times 10^{-6}/h$ is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990).

b) Event PI: The probability that the 100 ft of piping in the PWC water circulation line maintains its leak integrity during each MCO drain is $0.999992 (1 - [1.0 \times 10^{-9}/h-ft \times 100 ft \times 8h])$. The value of $1.0 \times 10^{-9}/h-ft$ is a value for
leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

c) Event V: The probability that any of the 15 valves in the PWC circulation line leak during each MCO drain is 0.000012 \((1.0 \times 10^{-7}/h \times 8 \text{ h} \times 15 \text{ valves})\). The value of \(1.0 \times 10^{-7}/h\) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

If the operating pump does not leak AND the process water line piping does not leak, but any of the 15 process water line valves leak, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 4

a) Event PU: The probability that the operating PWC circulation pump (PWC-P-403*) maintains its leak integrity during each MCO drain is 0.999976 \((1-3.0 \times 10^{-6}/h \times 8 \text{ h})\). The value of \(3.0 \times 10^{-6}/h\) is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990).

b) Event PI: The probability that a leak would occur in 100 ft of piping in the PWC circulation line during each MCO drain is 0.000008 \((1.0 \times 10^{-4}/h \times 100 \text{ ft} \times 8 \text{ h})\). The value of \(1.0 \times 10^{-4}/h \times \text{ft}\) is a value for leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

If the operating pump does not leak, but the process water line piping leaks, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 5

a) Event PU: The probability that the operating PWC circulation pump (PWC-P-403*) leaks externally during each MCO drain is 0.000024 \((3.0 \times 10^{-6}/h \times 8 \text{ h})\). The value of \(3.0 \times 10^{-6}/h\) is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990).

If the operating pump leaks externally, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

A2.3 FIGURE A2-1B

Figure A2-1b shows the event tree used to develop the frequency of a mitigated liquid release in the PWC room in the CVDF. Six sequences are presented.

Initiating event (Event IE): Internal water is drained from MCOs at a rate of 200 MCOs per year.
Sequence 1

a) Event PRES PATH INTACT: The summation of the following probabilities:

The probability that the operating PWC circulation pump (PWC-P-403*) maintains its leak integrity during each MCO drain is 0.999976 (1-[3.0 x 10^-6/h x 8 h]). The value of 3.0 x 10^-6/h is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990, page 12).

AND

The probability that the 100 ft of piping in the PWC water circulation line maintains its leak integrity during each MCO drain is 0.999992 (1-[1.0 x 10^-8/h-ft x 100 ft x 8 h]). The value of 1.0 x 10^-8/h-ft is a value for leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990, page 12).

AND

The probability that the 15 valves in the PWC circulation line maintain their integrity during each MCO drain is 0.999988 (1-[1.0 x 10^-7/h x 8 h x 15 valves]). The value of 1.0 x 10^-7/h is the highest value for external leakage for any of the five types of valves based on EGG-SSRE-8875 (Eide et al. 1990, page 11).

AND

The probability that the two "in use" flexible hose connections to the IXMs in the PWC circulation system maintain leak integrity during each MCO drain is 0.999936 (1-[4.0 x 10^-9/h x 8 h x 2 connections]). The value of 4.0 x 10^-9/h is a value for lightly stressed hose based on 18 DP-1633 (Dexter and Perkins 1982).

Therefore the probability that the pressurized path from the operating PWC circulating water pump maintains its integrity is calculated as follows:

\[(1-2.4 \times 10^{-5}) \times (1-8.0 \times 10^{-6}) \times (1-1.2 \times 10^{-7}) \times (1-6.4 \times 10^{-5}) = 0.999892.\]

If the operating pump does not leak AND the process water line piping does not leak AND none of the 15 process water line valves leak AND the two "in use" flexible connections to the IXMs do not leak, this results in normal processing.

Sequence 2

a) Event PRES PATH INTACT: The summation of the following probabilities:

The probability that the operating PWC circulation pump (PWC-P-403*) leaks externally during each MCO drain is 0.000024 (3.0 x 10^-6/h x 8 h). The value of 3.0 x 10^-6/h is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that a leak would occur in the 100 ft of piping in the PWC circulation line during each MCO drain is 0.000008 (1.0 x 10^-8/h-ft x 100 ft x 8 h). The value of 1.0 x 10^-8/h-ft is a value for leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).
The probability that any of the 15 valves in the PWC circulation line leak during each MCO drain is 0.000012 \((1.0 \times 10^{-7}/h \times 8 \text{ h} \times 15 \text{ valves})\). The value of \(1.0 \times 10^{-7}/h\) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

The probability that either of the two "in use" flexible hose connections to the IXMs in the PWC circulation system leak during each MCO drain is \(0.000064 \text{ (4.0} \times 10^{-6}/h \times 8 \text{ h} \times 2 \text{ connections})\). The value of \(4.0 \times 10^{-6}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

Therefore the probability that the pressurized path from the PWC circulating water pump does not maintain its integrity is calculated as follows:

\[
(2.4 \times 10^{-5}) + (8.0 \times 10^{-6}) + (1.2 \times 10^{-5}) + (6.4 \times 10^{-5}) = 1.08 \times 10^{-4}.
\]

b) Event DP: The probability that a differential pressure is maintained in the PWC room is \(0.9956 \text{ (1-[4.4} \times 10^{-3})\}). The value of \(4.4 \times 10^{-3}\) is based on a false smoke detection closing the dampers from the PWC room \((1 \times 10^{-6}/h \times 8,760 \text{ h}/2 = 4.4 \times 10^{-3})\). The value of \(1.0 \times 10^{-6}/hr\) is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990, page 23). It is recognized that an LOEP would also shut down the general exhaust fans but it is also recognized that an LOEP would shut down the PWC room pump (thus stopping the spray).

c) Event HEPA FILTERS OK: The probability that the HEPA-filtered vent path has HEPA filtration functioning during the release based on 4,380 \(h\) (the average unavailability assuming tested once per year; \(8,760 \text{ h}/2 = 4.380 \text{ h}\)) is 0.999943 \(\text{ (1-[1.3} \times 10^{-8}/h \times 4,380 \text{ h})\}). The value of \(1.3 \times 10^{-8}/h\) is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982, page 18).

If a leak occurs from the PWC room operating pump, piping, valves, or IXM connections AND the differential pressure is maintained in the PWC room AND the HEPA filter on the exhaust path is functioning, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 3 a) Event PRES PATH INTACT: The summation of the following probabilities:

The probability that the operating PWC circulation pump (PWC-P-403*) leaks externally during each MCO drain is 0.000024 \((3.0 \times 10^{-6}/h \times 8 \text{ h})\). The value of \(3.0 \times 10^{-6}/h\) is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that a leak would occur in the 100 ft of piping in the PWC circulation line during each MCO drain is 0.000008 \((1.0 \times 10^{-9}/h-\text{ft})\).
x 100 ft x 8 h). The value of $1.0 \times 10^{4}$/h-ft is a value for leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that any of the 15 valves in the PWC circulation line leak during each MCO drain is $0.000012 (1.0 \times 10^{-7}$/h x 8 h x 15 valves). The value of $1.0 \times 10^{-7}$/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that either of the two "in use" flexible hose connections to the IXMs in the PWC circulation system leak during each MCO drain is $0.000064 (4.0 \times 10^{-6}$/h x 8 h x 2 connections). The value of $4.0 \times 10^{-6}$/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

Therefore the probability that the pressurized path from the PWC circulating water pump does not maintain its integrity is calculated as follows:

\[
(2.4 \times 10^{-5}) + (8.0 \times 10^{-6}) + (1.2 \times 10^{-5}) + (6.4 \times 10^{-5}) = 1.08 \times 10^{-4}.
\]

b) Event DP: The probability that a differential pressure is maintained in the PWC room is $0.9956 (1-[4.4 \times 10^{-3}])$. The value of $4.4 \times 10^{-3}$ is based on a false smoke detection closing the dampers from the PWC room ($1 \times 10^{6}$/h * 8,760h/2 = $4.4 \times 10^{-3}$). The value of $1.0 \times 10^{-6}$/h is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990). It is recognized that an LOEP would also shut down the general exhaust fans but it is also recognized that an LOEP would shut down the PWC room pump (thus stopping the spray).

c) Event HEPA FILTERS OK: The probability that the HEPA-filtered vent path has no HEPA filtration functioning during the release based on 4,380 h (the average unavailability assuming tested once per year; 8,760 h/2) is $0.000057 (1.3 \times 10^{-4}$/h x 4,380 h). The value of $1.3 \times 10^{-4}$/h is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982).

If a leak occurs from the PWC room operating pump, piping, valves, or IXM connections AND the differential pressure is maintained in the PWC room AND the HEPA filter on the exhaust path is not functioning, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 4 a) Event PRES PATH INTACT: The summation of the following probabilities:

The probability that the operating PWC circulation pump (PWC-P-403*) leaks externally during each MCO drain is $0.000024 (3.0 \times 10^{-6}$/h x 8 h). The value of $3.0 \times 10^{-6}$/h is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990).
OR
The probability that a leak would occur in the 100 ft of piping in the PWC circulation line during each MCO drain is 0.000008 \((1.0 \times 10^{-9}/\text{h-ft} \times 100 \text{ ft} \times 8 \text{ h})\). The value of \(1.0 \times 10^{-9}/\text{h-ft}\) is a value for leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR
The probability that any of the 15 valves in the PWC circulation line leak during each MCO drain is 0.000012 \((1.0 \times 10^{-7}/\text{h} \times 8 \text{ h} \times 15 \text{ valves})\). The value of \(1.0 \times 10^{-7}/\text{h}\) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR
The probability that either of the two "in use" flexible hose connections to the IXMs in the PWC circulation system leak during each MCO drain is 0.000064 \((4.0 \times 10^{-9}/\text{h} \times 8 \text{ h} \times 2 \text{ connections})\). The value of \(4.0 \times 10^{-9}/\text{h}\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

Therefore the probability that the pressurized path from the PWC circulating water pump does not maintain its integrity is calculated as follows:

\[(2.4 \times 10^{-5}) + (8.0 \times 10^{-6}) + (1.2 \times 10^{-5}) + (6.4 \times 10^{-5}) = 1.08 \times 10^{-4}\]

b) Event DP: The probability that a differential pressure is not maintained in the PWC room is 0.0044 \((4.4 \times 10^{-3})\). The value of \(4.4 \times 10^{-3}\) is based on a false smoke detection closing the dampers from the PWC room \((1 \times 10^{-6}/\text{h} \times 8,760\text{h} = 4.4 \times 10^{-3}\)\). The value of \(1.0 \times 10^{-6}/\text{h}\) is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990). It is recognized that an LOEP would also shut down the general exhaust fans but it is also recognized that an LOEP would shut down the PWC room pump (thus stopping the spray).

c) Event DP IS DETECTED: The probability, that when the differential pressure is lost in the PWC room, the differential pressure is detected is 0.999988 \([1-(1.0 \times 10^{-6}/\text{h} \times 12 \text{ h})]\). The value of \(1.0 \times 10^{-6}/\text{h}\) is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990, page 23).

d) Event SWITCH OFF PUMP: The probability that, when the differential pressure is lost in the PWC room and the differential pressure is detected, the PWC circulating water pump will be manually shut off is 0.97 \([1-(3.0 \times 10^{-2})]\). The value of \(3.0 \times 10^{-2}\) is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).

If a leak occurs from the PWC room operating pump, piping, valves, or IXM connections AND the differential pressure is not maintained in the PWC room AND the differential pressure is detected AND the PWC circulating water pump is
manually shut off before 10 h of spray release, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 5

a) Event PRES PATH INTACT: The summation of the following probabilities:

The probability that the operating PWC circulation pump (PWC-P-403*) leaks externally during each MCO drain is 0.000024 \((3.0 \times 10^{-6}/h \times 8\ h)\). The value of \(3.0 \times 10^{-6}/h\) is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990).

**OR**

The probability that a leak would occur in the 100 ft of piping in the PWC circulation line during each MCO drain is 0.000008 \((1.0 \times 10^{-8}/h-ft \times 100\ ft \times 8\ h)\). The value of \(1.0 \times 10^{-8}/h-ft\) is a value for leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

**OR**

The probability that any of the 15 valves in the PWC circulation line leak during each MCO drain is 0.000012 \((1.0 \times 10^{-7}/h \times 8\ h \times 15\ valves)\). The value of \(1.0 \times 10^{-7}/h\) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

**OR**

The probability that either of the two "in use" flexible hose connections to the IXMs in the PWC circulation system leak during each MCO drain is 0.000064 \((4.0 \times 10^{-6}/h \times 8\ h \times 2\ connections)\). The value of \(4.0 \times 10^{-6}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

Therefore the probability that the pressurized path from the PWC circulating water pump does not maintain its integrity is calculated as follows:

\[(2.4 \times 10^{-5}) + (8.0 \times 10^{-6}) + (1.2 \times 10^{-5}) + (6.4 \times 10^{-5}) = 1.08 \times 10^{-4}\.

b) Event DP: The probability that a differential pressure is not maintained in the PWC room is 0.0044 \((4.4 \times 10^{-3})\). The value of \(4.4 \times 10^{-3}\) is based on a false smoke detection closing the dampers from the PWC room \((1 \times 10^{-6}/h \times 8,760\ h / 2 = 4.4 \times 10^{-3}\).

The value of \(1 \times 10^{-6}/h\) is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990). It is recognized that an LOEP would also shut down the general exhaust fans but it is also recognized that an LOEP would shut down the PWC room pump (thus stopping the spray).

**c)** Event DP IS DETECTED: The probability that, when the differential pressure is lost in the PWC room, the differential pressure is detected is 0.999988 \([1-(1.0 \times 10^{-6}/h \times 12\ h)]\). The value of \(1.0 \times 10^{-6}/h\) is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990).
d) Event SWITCH OFF PUMP: The probability that, when the differential pressure is lost in the PWC room and the differential pressure is detected, the PWC circulating water pump will not be manually shut off is 0.03 (3.0 x 10^{-2}). The value of 3.0 x 10^{-2} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

If a leak occurs from the PWC room operating pump, piping, valves, or IXM connections AND the differential pressure is not maintained in the PWC room AND the differential pressure is detected AND the PWC circulating water pump is not shut off, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 6

a) Event PRES PATH INTACT: The summation of the following probabilities:

The probability that the operating PWC circulation pump (PWC-P-403*) leaks externally during each MCO drain is 0.000024 (3.0 x 10^{-6}/h x 8 h). The value of 3.0 x 10^{-6}/h is a value for external leakage from a pump based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that a leak would occur in the 100 ft of piping in the PWC circulation line during each MCO drain is 0.000008 (1.0 x 10^{-6}/h-ft x 100 ft x 8 h). The value of 1.0 x 10^{-6}/h-ft is a value for leakage from a 1-in. to 3-in. diameter pipe (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that any of the 15 valves in the PWC circulation line leak during each MCO drain is 0.000012 (1.0 x 10^{-7}/h x 8 h x 15 valves). The value of 1.0 x 10^{-7}/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that either of the two "in use" flexible hose connections to the IXMs in the PWC circulation system leak during each MCO drain is 0.000064 (4.0 x 10^{-6}/h x 8 h x 2 connections). The value of 4.0 x 10^{-6}/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

Therefore the probability that the pressurized path from the PWC circulating water pump does not maintain its integrity is calculated as follows:

\[(2.4 \times 10^{-5}) + (8.0 \times 10^{-6}) + (1.2 \times 10^{-5}) + (6.4 \times 10^{-5}) = 1.08 \times 10^{-4}\.

b) Event DP: The probability that a differential pressure is not maintained in the PWC room is 0.0044 (4.4 x 10^{-3}). The value of 4.4 x 10^{-3} is based on a false smoke detection closing the dampers from the PWC room (1 x 10^{-6}/h * 8,760h/2 = 4.4 x 10^{-3}). The value of 1.0 x 10^{-6}/h is a value for instrument indicator failure based on EGG-SSRE-8875 (Eide et al. 1990). It is recognized that an LOEP would also shut down the general exhaust fans but
it is also recognized that an LOEP would shut down the PWC room pump (thus stopping the spray).

c) Event DP IS DETECTED: The probability that, when the differential pressure is lost in the PWC room, the differential pressure is not detected is 0.000012 (1.0 x 10^-6/h x 12 h). The value of 1.0 x 10^-6/h is the failure rate of a pressure sensor to function when it was supposed to function based on EGG-SSRE-8875 (Eide et al. 1990).

If a leak occurs from the PWC room operating pump, piping, valves, or IXM connections AND the differential pressure is not maintained in the PWC room AND the differential pressure is not detected, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

A2.4 REFERENCES


### Event Tree for Unmitigated Liquid Release in the Process Water Conditioning Room in the Cold Vacuum Drying Facility

<table>
<thead>
<tr>
<th>Initiating Event</th>
<th>PWC-403# Maintains Leak Integrity</th>
<th>All 500 Feet of Process Water Piping Maintain Leak Integrity</th>
<th>All IS Process Water Line Valves Maintain Leak Integrity</th>
<th>Flexible Hose Connections to IXMs Maintain Leak Integrity</th>
<th>Seq. #</th>
<th>Results</th>
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<tbody>
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<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>2.40E-05</td>
<td>DK</td>
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<tr>
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<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>8.00E-06</td>
<td>OK</td>
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<tr>
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<tr>
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<td>NO</td>
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<td>1.20E-05</td>
<td>OK</td>
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<tr>
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<td>NO</td>
<td>2.00E+02</td>
<td>Normal processing</td>
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<tr>
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<td>NO</td>
<td>YES</td>
<td>1.20E+02</td>
<td>&gt; onsite guidelines</td>
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<td>DK</td>
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A3.0 EVENT TREES FOR UNMITIGATED AND MITIGATED HYDROGEN EXPLOSION WHILE THE CASK-MULTI-CANISTER OVERPACKS ARE VENTED IN A COLD VACUUM DRYING FACILITY PROCESS BAY

A3.1 ACCIDENT SCENARIO SUMMARY

The accident scenario represented in the following event trees and event tree descriptions is a hydrogen explosion that occurs outside the MCO in a process bay or in the local exhaust ductwork of the CVDF. Hydrogen gas is generated in the cask-MCO during transport from K Basins and is vented to the local exhaust before the cask lid is removed. An ignition source is assumed to be present in the bay or in the ductwork, which ignites the hydrogen. Event trees are presented for both unmitigated (A3.2) and mitigated (A3.3) situations. In the unmitigated case, hydrogen leak and subsequent ignition and explosion are examined without including the effect of equipment and human controls; in the mitigated case, controls are included.

A3.2 FIGURE A3-1A

Figure A3-1a shows the event tree used to develop the frequency of an unmitigated hydrogen explosion while a cask-MCO is being vented in a process bay at the CVDF. Four sequences are presented.

Initiating event (Event IE): Cask-MCOs are vented before vacuum drying is begun, at a rate of 200 cask-MCOs per year.

Sequence 1

a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask-MCO is NOT sufficient to form a flammable mixture in the local exhaust line is judged to be 0.9. The value of 0.9 is based on engineering judgment that 9 out of 10 cask-MCOs received at the CVDF will not contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

If the hydrogen accumulation in the cask-MCO is NOT sufficient to form a flammable mixture in the local exhaust line, this results in normal processing.

Sequence 2

a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line is judged to be 0.1. The value of 0.1 is based on engineering judgment that 1 out of 10 cask-MCOs received at the CVDF will contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

b) Event HOSE LEAK: The probability that the flexible hose connections on the cask venting hose maintain leak integrity is 0.97 (1-[3.0 x 10^{-2}]). The value of
3.0 x 10^2 is a value assigned to basic operator errors based on NUREG/CR-4772, *Accident Sequence Evaluation Program Human Reliability Analysis Procedure* (Swain 1987, Table 4-2, Note 2, page 4-5).

c) Event LOCAL EXHAUST: The probability that the local exhaust is running because the power has not been lost is 0.9978 (1-[2.2 x 10^{-3}]). The value of 2.2 x 10^{-3} is the probability of an LOEP per 16 h per MCO. The value of 2.2 x 10^{-3} is calculated as (1-e^{-1.22yr^{-16}h\cdot yr^{-8760h}}) = 2.2 x 10^{-3}, where 1.22 LOEP events per year is the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811, *Analysis of Power Loss Data for the 200 Area Tank Farms in Support of K Basin SAR Work* (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

If the hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose maintains its integrity AND local exhaust is running, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 3

a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line is judged to be 0.1. The value of 0.1 is based on engineering judgment that 1 out of 10 cask-MCOs received at the CVDF will contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

b) Event HOSE Leak: The probability that the flexible hose connections on the cask venting hose maintain leak integrity is 0.97 (1-[3.0 x 10^{-2}]). The value of 3.0 x 10^{-2} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note 2, page 4-5).

c) Event LOCAL EXHAUST: The probability that the local exhaust is not running because the power has been lost is 0.0022 (2.2 x 10^{-3}). The value of 2.2 x 10^{-3} is the probability of an LOEP per 16 h per MCO. The value of 2.2 x 10^{-3} is calculated as (1-e^{-1.22yr^{-16}h\cdot yr^{-8760h}}) = 2.2 x 10^{-3}, where 1.22 LOEP events per year is the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811, (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

If the hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose maintains its leak integrity AND the local exhaust is not running, this results in an explosion in the ductwork with a release that is greater than onsite guidelines.
Sequence 4  a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line is judged to be 0.1. The value of 0.1 is based on engineering judgment that 1 out of 10 cask-MCOs received at the CVDF will contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

b) Event HOSE Leak: The probability that the flexible hose connections on the cask venting hose leaks is 0.03 (3.0 x 10^{-2}). The value of 3.0 x 10^{-2} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note 2, page 4-5).

If the hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose leaks, this results in an explosion in the bay with possible worker injury.

A3.3 FIGURE A3-1B

Figure A3-1b shows the event tree used to develop the frequency of a mitigated hydrogen explosion while the cask-MCO is being vented in a process bay at the CVDF. Eight sequences are presented.

Initiating event (Event IE): Cask-MCOs are vented before vacuum drying is begun, at a rate of 200 cask-MCOs per year.

Sequence 1  a) Event H2 ACCUM: The probability that hydrogen accumulation in the Cask-MCO is NOT sufficient to form a flammable mixture in the local exhaust line is judged to be 0.9. The value of 0.9 is based on engineering judgment that 9 out of 10 cask-MCOs received at the CVDF will not contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

If the hydrogen accumulation in the cask-MCO is NOT sufficient to form a flammable mixture in the local exhaust line, this results in normal processing.

b) Event HOSE LEAK: The probability that the flexible hose connections on the cask venting hose maintain leak integrity is 0.97 (1-[3.0 x 10^{-2}]). The value of 3.0 x 10^{-2} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note 2, page 4-5).
Event FLOW RESTRICTION: The probability that the flow restriction is correctly installed in the cask vent line is assessed as 0.9997 (1-[3.0 x 10^{-4}]). The value of 3.0 x 10^{-4} is a value assigned to basic operator errors and independent verification based on NUREG/CR-4772, Accident Sequence Evaluation Program Human Reliability Analysis Procedure (Swain 1987, Table 5-3, Case VIII, page 5-13). The value of 3.0 x 10^{-4} can also be attributed to a flow restriction design that minimizes the possibility that the device would not be installed (such that the process could not continue without it) or that it would not be installed improperly (such that it failed to perform its function).

Event LOCAL EXHAUST: The probability that the local exhaust is running prior to venting (considering the probability that site power could be lost for a 15-min period prior to venting) is 0.9999652 (1-[1.22 LOEP events/year * 1year/8,760h * 15min/60min]). The value of 1.22 LOEP/year related to the Hanford Site is found in WHC-EP-0811, Analysis of Power Loss Data for the 200 Area Tank Farms in Support of K Basin SAR Work (Shultz 1994, page 4).

If the hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose maintains its integrity AND the flow restriction device is in place in the cask vent line AND the local exhaust is running, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 3

a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line is judged to be 0.1. The value of 0.1 is based on engineering judgment that 1 out of 10 cask-MCOs received at the CVDF will contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

b) Event HOSE LEAK: The probability that the flexible hose connections on the cask venting hose maintain leak integrity is 0.97 (1-[3.0 x 10^{-2}]). The value of 3.0 x 10^{-2} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note 2, page 4-5).

c) Event FLOW RESTRICTION: The probability that the flow restriction is correctly installed in the cask vent line is assessed as 0.9997 (1-[3.0 x 10^{-4}]). The value of 3.0 x 10^{-4} is a value assigned to basic operator errors and independent verification based on NUREG/CR-4772 (Swain 1987). The value of 3.0 x 10^{-4} can also be attributed to a flow restriction design that minimizes the possibility that the device would not be installed (such that the process could not continue without it) or that it would not be installed improperly (such that it failed to perform its function).
d) Event LOCAL EXHAUST: The probability that the local exhaust is not running prior to venting (considering the probability that site power could be lost for a 15-min period prior to venting) is 0.0000348 (1.22 LOEP events/year * 1year/8,760h * 15min/60min). The value of 1.22 LOEP/year related to the Hanford Site is found in WHC-EP-0811 (Shultz 1994).

e) Event INTERLOCK: The probability that a cask venting interlocked isolation valve does close on low local exhaust flow is 0.9997 (1-[3.0 x 10^{-4}]). The value of 3.0 x 10^{-4} is a value for a relay to open (or close) on demand based on EGG-SSRE-8875, INFORMAL REPORT, Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs (Eide et al. 1990, page 21).

If the hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose maintains its integrity AND the flow restriction device is in place in the cask vent line AND the local exhaust is not running AND the low local exhaust flow interlocked cask venting isolation valve functions as designed (venting is stopped on low local exhaust flow) this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 4

a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line is judged to be 0.1. The value of 0.1 is based on engineering judgment that 1 out of 10 cask-MCOs received at the CVDF will contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

b) Event HOSE LEAK: The probability that the flexible hose connections on the cask venting hose maintain leak integrity is 0.97 (1-[3.0 x 10^{-2}]). The value of 3.0 x 10^{-2} is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note 2, page 4-5).

c) Event FLOW RESTRICTION: The probability that the flow restriction is correctly installed in the cask vent line is assessed as 0.9997 (1-[3.0 x 10^{-4}]). The value of 3.0 x 10^{-4} is a value assigned to basic operator errors and independent verification based on NUREG/CR-4772 (Swain 1987). The value of 3.0 x 10^{-4} can also be attributed to a flow restriction design that minimizes the possibility that the device would not be installed (such that the process could not continue without it) or that it would not be installed improperly (such that it failed to perform its function).

d) Event LOCAL EXHAUST: The probability that the local exhaust is not running prior to venting (considering the probability that site power could be lost for a 15-min period prior to venting) is 0.0000348 (1.22 LOEP
events/year * 1year/8,760h * 15min/60min). The value of 1.22 LOEP/year related to the Hanford Site is found in WHC-EP-0811 (Shultz 1994).

e) Event INTERLOCK: The probability that a cask venting interlocked isolation valve does not close on low local exhaust flow is 0.0003 (3.0 x 10^-4). The value of 3.0 x 10^-4 is a value for a relay to open (or close) on demand based on EGG-SSRE-8875 (Eide et al. 1990, page 21).

f) Event HEPA LOADING: The probability that the HEPA loading is maintained below 9.4 g of spent nuclear fuel is 0.9997 (1-3.0 x 10^-4). The value of 3.0 x 10^-4 is a value assigned to basic operator errors and independent verification based on NUREG/CR-4772 (Swain 1987) and relates to the fact that multiple radiation measurements on the HEPA filter housings will have to be ignored to allow the HEPA filter loading to approach 9.4 g of spent nuclear fuel.

If the hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose maintains its integrity AND the flow restriction device is in place in the cask vent line AND the local exhaust is not running AND the low local exhaust flow interlocked cask venting isolation valve fails to function as designed (venting is not stopped on low local exhaust flow) AND the HEPA filter loading is less than 9.4 g of spent nuclear fuel, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

Sequence 5

a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line is judged to be 0.1. The value of 0.1 is based on engineering judgment that 1 out of 10 cask-MCOs received at the CVDF will contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

b) Event HOSE LEAK: The probability that the flexible hose connections on the cask venting hose maintain leak integrity is 0.97 (1-3.0 x 10^-2). The value of 3.0 x 10^-2 is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note 2, page 4-5).

c) Event FLOW RESTRICTION: The probability that the flow restriction is correctly installed in the cask vent line is assessed as 0.9997 (1-3.0 x 10^-4). The value of 3.0 x 10^-4 is a value assigned to basic operator errors and independent verification based on NUREG/CR-4772 (Swain 1987). The value of 3.0 x 10^-4 can also be attributed to a flow restriction design that minimizes the possibility that the device would not be installed (such that the process could not continue without it) or that it would not be installed improperly (such that it failed to perform its function).
d) Event LOCAL EXHAUST: The probability that the local exhaust is not running prior to venting (considering the probability that site power could be lost for a 15-min period prior to venting) is 0.0000348 (1.22 LOEP events/year * 1year/8,760h * 15min/60min). The value of 1.22 LOEP/year related to the Hanford Site is found in WHC-EP-0811 (Shultz 1994).

e) Event INTERLOCK: The probability that a cask venting interlocked isolation valve does not close on low local exhaust flow is 0.0003 (3.0 x 10^-4). The value of 3.0 x 10^-4 is a value for a relay to open (or close) on demand based on EGG-SSRE-8875 (Eide et al. 1990, page 21).

f) Event HEPA LOADING: The probability that the HEPA loading is above 9.4 g of spent nuclear fuel is 0.0003 (3.0 x 10^-4). The value of 3.0 x 10^-4 is a value assigned to basic operator errors and independent verification based on NUREG/CR-4772 (Swain 1987) and relates to the fact that multiple radiation measurements on the HEPA filter housings will have to be ignored to allow the HEPA filter loading to approach 9.4 g of spent nuclear fuel.

If the hydrogen accumulation in the cask–MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose maintains its integrity AND the flow restriction device is in place in the cask vent AND the local exhaust is not running AND the low local exhaust flow interlocked cask venting isolation valve fails to function as designed (venting is not stopped on low local exhaust flow) AND the HEPA filter loading is greater than 9.4 g of spent nuclear fuel, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

Sequence 6

a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask–MCO is sufficient to form a flammable mixture in the local exhaust line is judged to be 0.1. The value of 0.1 is based on engineering judgment that 1 out of 10 cask–MCOs received at the CVDF will contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

b) Event HOSE LEAK: The probability that the flexible hose connections on the cask venting hose maintain leak integrity is 0.97 (1-[3.0 x 10^-2]). The value of 3.0 x 10^-2 is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note 2, page 4-5).

c) Event FLOW RESTRICTION: The probability that the flow restriction is not correctly installed in the cask vent line is assessed as 0.0003 (3.0 x 10^-4). The value of 3.0 x 10^-4 is a value assigned to basic operator errors and independent verification based on NUREG/CR-4772 (Swain 1987). The value of 3.0 x 10^-4 can also be attributed to a flow restriction design that minimizes the possibility that the device would not be installed (such that the process could not continue without it) or that it would not be installed improperly (such that it failed to perform its function).
d) Event HEPA LOADING: The probability that the HEPA loading is maintained below 9.4 g of spent nuclear fuel is 0.9997 (1-\[3.0 \times 10^{-4}\]). The value of 3.0 \times 10^{-4} is a value assigned to basic operator errors and independent verification based on NUREG/CN-4772 (Swain 1987) and relates to the fact that multiple radiation measurements on the HEPA filter housings will have to be ignored to allow the HEPA filter loading to approach 9.4 g of spent nuclear fuel.

If the hydrogen accumulation in the cask–MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose maintains its integrity AND the flow restriction device is not in place in the cask vent line AND the HEPA filter loading is less than 9.4 g of spent nuclear fuel, this results in an explosion in the ductwork with a release that is less than onsite guidelines.

Sequence 7

a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask–MCO is sufficient to form a flammable mixture in the local exhaust line is judged to be 0.1. The value of 0.1 is based on engineering judgment that 1 out of 10 cask–MCOs received at the CVDF will contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

b) Event HOSE LEAK: The probability that the flexible hose connections on the cask venting hose maintain leak integrity is 0.97 (1-\[3.0 \times 10^{-2}\]). The value of 3.0 \times 10^{-2} is a value assigned to basic operator errors based on NUREG/CN-4772 (Swain 1987, Table 4-2, Note 2, page 4-5).

c) Event FLOW RESTRICTION: The probability that the flow restriction is not correctly installed in the cask vent line is assessed as 0.0003 (3.0 \times 10^{-4}). The value of 3.0 \times 10^{-4} is a value assigned to basic operator errors and independent verification based on NUREG/CN-4772 (Swain 1987). The value of 3.0 \times 10^{-4} can also be attributed to a flow restriction design that minimizes the possibility that the device would not be installed (such that the process could not continue without it) or that it would not be installed improperly (such that it failed to perform its function).

d) Event HEPA LOADING: The probability that the HEPA loading is above 9.4 g of spent nuclear fuel is 0.0003 (3.0 \times 10^{-4}). The value of 3.0 \times 10^{-4} is a value assigned to basic operator errors and independent verification based on NUREG/CN-4772 (Swain 1987) and relates to the fact that multiple radiation measurements on the HEPA filter housings will have to be ignored to allow the HEPA filter loading to approach 9.4 g of spent nuclear fuel.

If the hydrogen accumulation in the cask–MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose maintains its integrity AND the flow restriction device is not in place in the cask vent line AND the HEPA filter loading is greater than 9.4 g of spent nuclear fuel, this results in an
explosion in the ductwork with a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 8

a) Event H2 ACCUM: The probability that hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line is judged to be 0.1. The value of 0.1 is based on engineering judgment that 1 out of 10 cask-MCOs received at the CVDF will contain enough hydrogen to form a flammable mixture in the local exhaust line under any conditions.

b) Event HOSE LEAK: The probability that the flexible hose connections on the cask venting hose leak is 0.03 (3.0 x 10^-2). The value of 3.0 x 10^-2 is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note 2, page 4-5).

If the hydrogen accumulation in the cask-MCO is sufficient to form a flammable mixture in the local exhaust line AND the cask venting hose leaks, this results in an explosion in the bay with possible worker injury.

A3.4 REFERENCES


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Figure A7-18. Event Tree for an Unmitigated Hydrogen Explosion While Venting the Multi-Canister Overpack Cask in a Process Bay at the Cold Vacuum Drying Facility

<table>
<thead>
<tr>
<th>Number of MCDS processed through CVDF in one year</th>
<th>H₂ accumulation in cask is not sufficient to form flammable mixtures, externally</th>
<th>Cask venting hose remains intact (no leaks to the process bay)</th>
<th>Local exhaust is running</th>
<th>Seq. #</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>INITIATING EVENT</td>
<td>H₂ ACCUM</td>
<td>HOSE LEAK</td>
<td>LOCAL EXHAUST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>YES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.80E+02</td>
<td>1 Normal processing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO</td>
<td>YES</td>
<td>2 OK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.94E+01</td>
<td>3 Explosion in duct, &gt; onsite guidelines</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NO</td>
<td>4 Explosion and possible worker injury</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.00E-01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

H₂ EXP Ext MCDS During Tank Venting CVDEXH5U, THE 6-14-99
Figure A3-1b. Event Tree for a Mitigated Hydrogen Explosion While Venting the Multi-Canister Overpack Cask in a Process Bay at the Cold Vacuum Drying Facility.
A4.0 EVENT TREES FOR UNMITIGATED AND MITIGATED INTERNAL HYDROGEN EXPLOSION RESULTING FROM AIR INGRESS AT THE COLD VACUUM DRYING FACILITY

A4.1 ACCIDENT SCENARIO SUMMARY

The accident scenario represented in the following event trees and event tree descriptions is a hydrogen explosion that occurs inside the MCO at the CVDF. This internal hydrogen explosion results from hydrogen generation and accumulation in the MCO and a line leak that allows air to flow into the MCO during vacuum processing as the pressure is equalized in the MCO. It is assumed that an ignition source is present in the MCO which ignites the flammable mixture. Event trees are presented for both unmitigated (A4.2) and mitigated (A4.3) situations. In the unmitigated case, the effect of engineered controls such as the introduction of safety-class helium (SCHe) is ignored; in the mitigated case, engineered controls and implementation of a maintenance program on the pneumatic valves are considered.

A4.2 FIGURE A4-1A

Figure A4-1a shows the event tree used to develop the frequency of an unmitigated internal hydrogen explosion as a result of air ingress to the MCO during vacuum drying at the CVDF. Three sequences are presented.

Initiating event (Event IE): MCOs experience vacuum drying at the CVDF, at a rate of 200 MCOs per year.

Sequence 1 a) Event HE FLOW MAINTAIN: The probability that adequate helium flow is maintained during the MCO drying process (thus no flammable mixture exists) is 0.944 (1-[5.6 x 10^{-2}]). If the helium flow is inadvertently interrupted by the operator or by an actuation of the isolation valve, adequate normal helium flow will not be maintained. The probability that adequate helium is not maintained is 5.6 x 10^{-2} (3.0 x 10^{-2} + 2.6 x 10^{-2} = 5.6 x 10^{-2}). The value of 3.0 x 10^{-2} is a value assigned to basic operator errors based on NUREG/CR-4772, Accident Sequence Evaluation Program Human Reliability Analysis Procedure (Swain 1987, Table 4-2, Note #2, page 4-5). The value of 2.6 x 10^{-2} is the probability that the isolation valve is inadvertently activated. The value is derived as follows: EGG-SSRE-8875, INFORMAL REPORT, Generic Component Failure Data Base for Light Water Reactor and Liquid Sodium Reactor PRAs (Eide et al. 1990, page 11) shows that the rate of spurious operation for a pneumatic valve is 3.0 x 10^{-6} per hour or 2.6 x 10^{-2} per year (3.0 x 10^{-6} x 8,760 = 2.6 x 10^{-2}).

If adequate helium flow is maintained during the MCO drying process, this results in normal processing.
Sequence 2  

a) Event HE FLOW MAINTAIN: The probability that adequate helium flow is not maintained during the MCO drying process (thus flammable mixture exists) is $5.6 \times 10^{-2}$ ($3.0 \times 10^{-2} + 2.6 \times 10^{-2} = 5.6 \times 10^{-2}$). The value of $3.0 \times 10^{-2}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987). The value of $2.6 \times 10^{-2}$ is the probability that the isolation valve is inadvertently activated. The value is derived as follows: EGG-SSRE-8875 (Eide et al. 1990) shows that the rate of spurious operation for a pneumatic valve is $3.0 \times 10^6$ per hour or $2.6 \times 10^2$ per year ($3.0 \times 10^6 \times 8760 = 2.6 \times 10^2$).

b) Event LEAK TIGHT: The probability that the inlet and exit piping from the process vent port of the MCO maintain leak integrity is 0.97 ($1 - 3.0 \times 10^{-2}$). Possible causes of integrity failure are human failure (incorrectly installing hose and pipe connections, not performing leak verification) or equipment failure (pipe rupture). The value of $3.0 \times 10^{-2}$ is a value assigned to basic operator errors (failure of connecting the hose correctly), based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5). A value of $4.0 \times 10^{-6}$/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 (Dexter and Perkins 1982, page 18). The probability of the hose rupture during a 30-h process time is $4.0 \times 10^{-6}$/h x 30 = $1.2 \times 10^{-4}$. The operator error dominates. Therefore, the probability that inlet and exit piping from the process vent port of the MCO do not maintain leak integrity is $3.0 \times 10^{-2}$.

If adequate helium flow is not maintained AND the inlet or exit flexible lines maintain their integrity during vacuum drying, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 3  

a) Event HE FLOW MAINTAIN: The probability that adequate helium flow is not maintained during the MCO drying process (thus flammable mixture exists) is $5.6 \times 10^{-2}$ ($3.0 \times 10^{-2} + 2.6 \times 10^{-2} = 5.6 \times 10^{-2}$). The value of $3.0 \times 10^{-2}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987). The value of $2.6 \times 10^{-2}$ is the probability that the isolation valve is inadvertently activated. The value is derived as follows: EGG-SSRE-8875 (Eide et al. 1990) shows that the rate of spurious operation for a pneumatic valve is $3.0 \times 10^6$ per hour or $2.6 \times 10^2$ per year ($3.0 \times 10^6 \times 8760 = 2.6 \times 10^2$).

b) Event LEAK TIGHT: The probability that inlet and the exit piping from the process vent port of the MCO do not maintain leak integrity is $3.0 \times 10^{-2}$ mainly due to human error without leak verification. The value of $3.0 \times 10^{-2}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).
If adequate helium flow is not maintained AND the inlet or exit flexible lines do not maintain their integrity during vacuum drying, a flammable mixture might be formed due to air ingress and an internal explosion might occur with a release that is greater than onsite guidelines.

**A4.3 FIGURE A4-1B**

Figure A4-1b shows the event tree used to develop the frequency of a mitigated internal hydrogen explosion due to air ingress during vacuum drying. Four sequences are presented.

**Initiating event (Event IE): MCOs experience vacuum drying, at a rate of 200 MCOs per year.**

**Sequence 1**

a) **Event HE FLOW MAINTAIN**: The probability that adequate helium flow is maintained during the MCO drying process (thus no flammable mixture exists) is 0.957 (1 - [4.3 x 10⁻⁴]). If the helium flow is inadvertently interrupted by the operator or by an actuation of the isolation valve, adequate normal helium flow will not be maintained. The probability that adequate helium is not maintained is 4.3 x 10⁻⁴ (3.0 x 10⁻² + 1.3 x 10⁻² = 4.3 x 10⁻²). The value of 3.0 x 10⁻² is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5). The value of 1.3 x 10⁻² is the probability that the isolation valve is inadvertently activated. The value is derived as follows: EGG-SSRE-8875 (Eide et al. 1990) shows that the rate of spurious operation for a pneumatic valve is 3.0 x 10⁻⁶ per hour or 2.6 x 10⁻⁴ per year (3.0 x 10⁻⁶ x 8,760 = 2.6 x 10⁻⁴). However, the value could be reduced to 1.3 x 10⁻² because of a maintenance program but the maintenance program was not credited in this calculation.

If adequate helium flow is maintained during MCO drying process, this results in normal processing.

**Sequence 2**

a) **Event HE FLOW MAINTAIN**: The probability that adequate helium flow is not maintained during the MCO drying process (thus flammable mixture exists) is 4.3 x 10⁻⁴ (3.0 x 10⁻² + 1.3 x 10⁻² = 4.3 x 10⁻²). The value of 3.0 x 10⁻² is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987). The value of 1.3 x 10⁻² is the probability that the isolation valve is inadvertently activated. The value is derived as follows: EGG-SSRE-8875 (Eide et al. 1990) shows that the rate of spurious operation for a pneumatic valve is 3.0 x 10⁻⁶ per hour or 2.6 x 10⁻⁴ per year (3.0 x 10⁻⁶ x 8,760 = 2.6 x 10⁻⁴). However, the value could be reduced to 1.3 x 10⁻² through implementation of a maintenance program but the maintenance program was not credited in this calculation.

b) **Event SCHe INJECTION**: The probability that the SCHe injection is initiated with a 2-min delay on loss of normal helium flow is 0.9999 (1 - [1.0 x 10⁻⁴]).
There are two helium injection lines. Each line is isolated by a pneumatic isolation valve. The probability that an pneumatic isolation valve fails to open on demand is $1.0 \times 10^{-3}$, which is based on EGG-SSRE-8875 (Eide et al. 1990, page 11). The probability of a failure of either of the two applicable isolation valves per demand should be $1.0 \times 10^{-6}$, given independent failures. Considering common cause failure and a common cause beta factor of 0.1, the probability of a failure of either of the two applicable isolation valves is estimated to be $1.0 \times 10^{-4}$ ($1.0 \times 10^{-3} \times 0.1 = 1.0 \times 10^{-4}$).

If adequate helium flow is not maintained during MCO drying process AND the SCHe actuates as designed, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 3  

a) Event HE FLOW MAINTAIN: The probability that adequate helium flow is not maintained during the MCO drying process (thus flammable mixture exists) is $4.3 \times 10^{-3}$ ($3.0 \times 10^{-2} + 1.3 \times 10^{-2} = 4.3 \times 10^{-2}$). The value of $3.0 \times 10^{-2}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987). The value of $2.6 \times 10^{-2}$ is the probability that the isolation valve is inadvertently activated. The value is derived as follows: EGG-SSRE-8875 (Eide et al. 1990) shows that the rate of spurious operation for a pneumatic valve is $3.0 \times 10^{-6}$ per hour or $2.6 \times 10^{-2}$ per year ($3.0 \times 10^{-6} \times 8,760 = 2.6 \times 10^{-2}$). However, the value could be reduced to $1.3 \times 10^{-2}$ through implementation of a maintenance program but the maintenance program was not credited in this calculation.

b) Event SCHE INJECTION: The probability that the SCHe injection is not initiated with a 2-min delay on loss of normal helium flow is $1.0 \times 10^{-4}$. There are two helium injection lines. Each line is isolated by a pneumatic isolation valve. The probability that a pneumatic isolation valve fails to open on demand is $1.0 \times 10^{-3}$, which is based on EGG-SSRE-8875 (Eide et al. 1990). The probability of a failure of either of the two applicable isolation valves per demand should be $1.0 \times 10^{-6}$, given independent failures. Considering common cause failure and a common cause beta factor of 0.1, the probability of a failure of either of the two applicable isolation valves is estimated to be $1.0 \times 10^{-4}$ ($1.0 \times 10^{-3} \times 0.1 = 1.0 \times 10^{-4}$).

c) Event LEAK TIGHT: The probability that the inlet and exit piping from the process vent port of the MCO maintains its leak integrity is 0.9997 (1-3.0 x 10^{-4}) mainly due to human performance with leak verification. The value of $3.0 \times 10^{-4}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987, Case VI, page 5-13).

If adequate helium flow is not maintained during the MCO drying process AND the SCHe is not injected AND the inlet or exit flexible lines maintain their integrity
during vacuum drying, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 4

a) Event HE FLOW MAINTAIN: The probability that adequate helium flow is not maintained during the MCO drying process (thus flammable mixture exists) is $4.3 \times 10^{-2} (3.0 \times 10^{-2} + 1.3 \times 10^{-2} = 4.3 \times 10^{-2})$. The value of $3.0 \times 10^{-2}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987). The value of $2.6 \times 10^{-2}$ is the probability that the isolation valve is inadvertently activated. The value is derived as follows: EGG-SSRE-8875 (Eide et al. 1990) shows that the rate of spurious operation for a pneumatic valve is $3.0 \times 10^{-6}$ per hour or $2.6 \times 10^{-2}$ per year ($3.0 \times 10^{-6} \times 8,760 = 2.6 \times 10^{-2}$). However, the value could be reduced to $1.3 \times 10^{-2}$ through implementation of a maintenance program but the maintenance program was not credited in this calculation.

b) Event SCHe INJECTION: The probability that the SCHe injection is not initiated with two minutes delay on loss of normal helium flow is $1.0 \times 10^{-4}$. There are two helium injection lines. Each line is isolated by a pneumatic isolation valve. The probability that a pneumatic isolation valve fails to open on demand is $1.0 \times 10^{-3}$, which is based on EGG-SSRE-8875 (Eide et al. 1990). The probability of a failure of either of the two applicable isolation valves per demand should be $1.0 \times 10^{-6}$, given independent failures. Considering common cause failure and a common cause beta factor of 0.1, the probability of a failure of either of the two applicable isolation valves is estimated to be $1.0 \times 10^{-4} (1.0 \times 10^{-3} \times 0.1 = 1.0 \times 10^{-4})$.

c) Event LEAK TIGHT: The probability that the inlet and exit piping from the process vent port of the MCO does not maintain its leak integrity is 0.0003 ($3.0 \times 10^{-4}$) mainly due to human performance with leak verification. The value of $3.0 \times 10^{-4}$ is a value assigned to basic operator errors based on NUREG/CR-4772 (Swain 1987).

If adequate helium flow is not maintained during the MCO drying process AND the SCHe is not injected AND inlet or exit flexible lines do not maintain their integrity during vacuum drying, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

A4.4 REFERENCES


<table>
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<tr>
<th>INITIATING EVENT</th>
<th>Adequate helium flow is maintained during MCO drying process, no flam. mixture</th>
<th>Inlet or exit lines maintain their integrity during vacuum drying</th>
<th>Seq. Freq.</th>
<th>Seq. #</th>
<th>Results</th>
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<td></td>
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<td>1.89E+02</td>
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<td></td>
<td>3.36E-01</td>
<td>3</td>
<td>Explosion, &gt; onsite guidelines</td>
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### Figure A4-1b: Event Tree for a Mitigated Internal Hydrogen Explosion Due to Air Ingress at the Cold Vacuum Drying Facility

<table>
<thead>
<tr>
<th>INITIATING EVENT</th>
<th>STEPS</th>
<th>SEQ. FREQ.</th>
<th>SEQ. #</th>
<th>RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 MCDs/year are processed at CVDF</td>
<td>Adequate helium flow is maintained during MCD drying process, no flash mixture</td>
<td>2.00E-05</td>
<td>1</td>
<td>Normal processing</td>
</tr>
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<td></td>
<td>SCA injection (with 2 minute delay) on loss of normal helium flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inlet or exit lines maintain their integrity during vacuum drying</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>SSF FLOW MAINTAIN</td>
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<td>SCHE INJECTION</td>
<td></td>
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<td></td>
<td>LEAK TIGHT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td>1.09E+02</td>
<td>1</td>
<td>Normal processing</td>
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<tr>
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<td>1.12E+00</td>
<td>2</td>
<td>OK</td>
<td></td>
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<td></td>
<td>1.12E-03</td>
<td>3</td>
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</tr>
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<td></td>
<td>3.6E-04</td>
<td>4</td>
<td>&lt;1E-6/yr</td>
<td></td>
</tr>
</tbody>
</table>

Internal Hydrogen Explosion Due to Air Ingress CVDHY4M.TRE 8-31-99
A5.0 EVENT TREES FOR A THERMAL EXCURSION IN A MULTI-CANISTER OVERPACK IN A COLD VACUUM DRYING FACILITY PROCESS BAY

Event trees and event tree descriptions are presented for thermal excursions in an MCO in a CVDF process bay. Four scenarios are examined. The first scenario is a design basis accident (DBA) thermal excursion caused by a loss of coolant that results in either an exhaust line breach or HEPA filter failure. The next three scenarios are not DBAs but represent other thermal excursion scenarios that did not address a release from an MCO but did include controls to help prevent the thermal excursions from occurring. Therefore the first non-DBA scenario is similar to the DBA thermal excursion scenario excluding a release path from the MCO; the second non-DBA scenario is a thermal excursion that results from degraded vacuum operation; and the third non-DBA scenario is a thermal excursion that occurs when the tempered water system (TWS) is operating higher than 50 °C, resulting in high fuel temperatures. Of these four scenarios, only the first is a DBA and includes unmitigated and mitigated thermal excursions. The latter three scenarios include mitigation (preventive controls but no consequence mitigation controls).

A5.1 DESIGN BASIS ACCIDENT SCENARIO SUMMARY

The DBA scenario represented in the following event trees and event tree descriptions is a thermal excursion. This thermal excursion is caused by the loss of tempered water in the cask-MCO annulus and high fuel temperatures. A release from the MCO involves either an exhaust line breach or HEPA filter failure.

A5.1.1 Figure A5-1a

Figure A5-1a shows the event tree used to develop the frequency of unmitigated thermal excursions resulting from a loss of coolant accident in a process bay at the CVDF.

Initiating event (Event IE): Processing of MCOs at CVDF at a rate of 200 MCOs/yr.

Sequence a) Event TWS ANNULUS OK: The probability that the TWS annulus water is maintained during processing is 0.9999975 (1 - [2.5 x 10^-6]). The value of 2.5 x 10^-6 is a summation of the probability of a section of single-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing) (1 x 10^-7/h x 16 h) and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability (5 x 10^4 x 16 h/8,760 h). The value of 1 x 10^-7/h is the failure rate of a 1 to 3 in. piping leakage per foot of pipe (1 x 10^-4/h-ft) times an assumed 10 ft of piping of concern. The value of 1 x 10^4/h-ft is based on EGG-8875, INFORMAL REPORT, Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs.
The value of $5 \times 10^{-4}$ is an assumed value for a common-cause event that should bound any undefined common-cause event.

If the TWS annulus water is maintained, this results in normal processing.

Sequence 2  

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is $0.0000025 \times 2.5 \times 10^{4}$ ($2.5 \times 10^{4}$). The value of $2.5 \times 10^{-4}$ is a summation of the probability of a section of single-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) $(1 \times 10^{-7}/h \times 16 \ h)$ and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability $(5 \times 10^{-4} \times 16 \ h/8,760 \ h)$. The value of $1 \times 10^{-7}/h$ is the failure rate of a 1 to 3 in. piping leakage per foot of pipe $(1 \times 10^{-6}/h$-$ft$) times an assumed 10 ft of piping of concern. The value of $1 \times 10^{-6}/h$-$ft$ is based on EGG-8875 (Eide et al. 1990). The value of $5 \times 10^{-4}$ is an assumed value for a common-cause event that should bound any undefined common-cause event.

If the TWS annulus water is not maintained, this results in a release that is greater than offsite guidelines.

A5.1.2 Figure A5-1b

Figure A5-1b shows the event tree used to develop the frequency of a mitigated thermal excursion (loss of coolant accident) in a process bay at the CVDF.

Initiating event (Event IE): Processing of MCOs at CVDF at a rate of 200 MCOs/yr.

Sequence 1  

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is maintained during processing is $0.9999989 (1 - [1.1 \times 10^{-4}])$. The value of $1.1 \times 10^{-4}$ is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) $(1 \times 10^{-7}/h \times 16 \ h)$ involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability $(5 \times 10^{-4} \times 16 \ h/8,760 \ h)$. The value of $1 \times 10^{-7}/h$ is the failure rate of a 1 to 3 in. piping leakage per foot of pipe $(1 \times 10^{-6}/h$-$ft$) times an assumed 10 ft of piping of concern. The value of $1 \times 10^{-6}/h$-$ft$ is based on EGG-8875 (Eide et al. 1990, page 12). The value of $5 \times 10^{-4}$ is an assumed value for a common-cause event that should bound any undefined common-cause event.

If the TWS annulus water is maintained, this results in normal processing.
Sequence 2  

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.0000011 (1.1 x 10^-6). The value of 1.1 x 10^-6 is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) (1 x 10^-7/h x 16 h) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability (5 x 10^-4 x 16 h/8,760 h). The value of 1 x 10^-7/h is the failure rate of a 1 to 3 in. piping leakage per foot of pipe (1 x 10^-8/h-ft) times an assumed 10 ft of piping of concern. The value of 1 x 10^-4/h is based on EGG-8875 (Eide et al. 1990, page 12). The value of 5 x 10^-4 is an assumed value for a common-cause event that should bound any undefined common-cause event. 

b) Event TWS RECOVERY: The probability that TWS annulus water loss can be recovered from is 0.997 (1-[3 x 10^-3]). The value of 3 x 10^-3/demand is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772, Accident Sequence Evaluation Program Human Reliability Analysis Procedure (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water. 

c) Event VPS LINE INTEG.: The probability that the vacuum purge system (VPS) line integrity is maintained is a product of the following probabilities: 

The probability that the two flexible hose connections on the exit of the process vent port of the MCO maintain leak integrity is 0.999808 (1-[4.0 x 10^-6/h x 24 h x 2 connections]). The value of 4.0 x 10^-6/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 (Dexter and Perkins 1982). 

AND 
The probability that 10 ft of exit piping from the process vent port of the MCO maintains its leak integrity is 0.9999976 (1-[1.0 x 10^-7/h-ft x 10 ft x 24 h]). The value of 1.0 x 10^-7/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990). 

AND 
The probability that one isolation valves (GOV 1*09) and two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system maintain their integrity is 0.9999928 (1-[1.0 x 10^-7/h x 24 h x 3 valves]). The value of 1.0 x 10^-7/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990). 

AND 
The probability that installing the exit line involved with helium purge maintains leak integrity is 0.9997 (1-[3.0 x 10^-4]). The value of 3.0 x 10^-4 is a
value assigned to basic operator error plus a post-installation test based on NUREG/CR-4772 (Swain 1987, Table 5-3, Case VI, page 5-13).

Therefore the probability that the vacuum line integrity is maintained is calculated as follows:

\[(1-1.92 \times 10^{-6}) \times (1-2.4 \times 10^{-6}) \times (1-7.2 \times 10^{-6}) \times (1-3.0 \times 10^{-4}) = 0.99950.\]

If the TWS annulus water is not maintained AND the TWS annulus water is restored AND the VPS line integrity is maintained, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 3

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.0000011 (1.1 x 10^{-6}). The value of 1.1 x 10^{-6} is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing) \(1 \times 10^{3}/h \times 16 h\)) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability \(5 \times 10^{-4} x 16 h/8,760 h\). The value of \(1 \times 10^{3}/h\) is the failure rate of a 1 to 3 in. piping leakage per foot of pipe \(1 \times 10^{8}/h\)-ft times an assumed 10 ft of piping of concern. The value of \(1 \times 10^{8}/h\)-ft is based on EGG-8875 (Eide et al. 1990, page 12). The value of \(5 \times 10^{-4}\) is an assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss can be recovered from is 0.997 (1-13 x 10^{-3}). The value of \(3 \times 10^{-3}/demand\) is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the error to make sure the first operator completed refilling the annulus with water.

c) Event VPS LINE INTEG.: The probability that the VPS line integrity is not maintained is a summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 \(4.0 \times 10^{6}/h \times 24 h \times 2\) connections). The value of \(4.0 \times 10^{6}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 \(1.0 \times 10^{8}/h\)-ft \(10 ft \times 24 h\). The value of \(1.0 \times 10^{8}/h\)-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).
OR

The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is 0.0000072 (1.0 x 10^-7/h x 24 h x 3 valves). The value of 1.0 x 10^-7/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that installing the exit line involved with helium purge maintains leak integrity is 0.0003 (3.0 x 10^-4). The value of 3.0 x 10^-4 is a value assigned to basic operator error plus a post-installation test based on NUREG/CR-4772 (Swain 1987, Table 5-3, Case VI, page 5-13).

Therefore the probability that the vacuum line integrity is maintained is calculated as follows:

\[ 1.92 \times 10^{-4} + 2.4 \times 10^{-6} + 7.2 \times 10^{-6} + 3.0 \times 10^{-4} = 5.00 \times 10^{-4}. \]

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(Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.

c) Event VPS LINE INTEG.: The probability that the VPS line integrity is not maintained is a summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 \((4.0 \times 10^{-6}/h \times 24 \text{ h} \times 2 \text{ connections})\). The value of \(4.0 \times 10^{-6}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR

The probability that 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 \((1.0 \times 10^{-8}/\text{h-ft} \times 10 \text{ ft} \times 24 \text{ h})\). The value of \(1.0 \times 10^{-8}/\text{h-ft}\) is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is 0.0000072 \((1.0 \times 10^{-7}/h \times 24 \text{ h} \times 3 \text{ valves})\). The value of \(1.0 \times 10^{-7}/h\) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR

The probability that installing the exit line involved with helium purge maintains leak integrity is 0.0003 \((3.0 \times 10^{-4})\). The value of \(3.0 \times 10^{-4}\) is a value assigned to basic operator error plus a post-installation test based on NUREG/CR-4772 (Swain 1987, Table 5-3, Case VI, page 5-13).

Therefore the probability that the vacuum line integrity is maintained is calculated as follows:

\[
1.92 \times 10^{-4} + 2.4 \times 10^{-6} + 7.2 \times 10^{-6} + 3.0 \times 10^{-4} = 5.00 \times 10^{-4}.
\]

d) Event BLDG FLOW MAINT.: The probability that the building exhaust flow is not maintained and the HEPA filters are not functioning as designed is 0.00019 \((1.9 \times 10^{-4})\). The value of \(1.9 \times 10^{-4}\) is obtained by solving the branches of the event tree for helium leak (CVDGAS3M.TRE) starting with the top event DP to the top event HEPA FILTERS OK that result in consequences of unfiltered release. This involves parts of sequences 3, 5, 6, 7, 9, 10, and 11.

If the TWS annulus water is not maintained AND the TWS annulus water is restored AND the VPS line integrity is not maintained AND the building exhaust flow is not maintained and the HEPA filters are not functioning, this results in a sequence that has a frequency beyond extremely unlikely (<1 × 10⁻⁶/year).
Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.000001 \( (1.1 \times 10^{-6}) \). The value of \( 1.1 \times 10^{-6} \) is a summation of the probability of a section of double-walled pipe failing {based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing \( ) (1 \times 10^{-7}/h \times 16 \text{ h}) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability \( (5 \times 10^{-4} \times 16 \text{ h} / 8,760 \text{ h}) \). The value of \( 1 \times 10^{-7}/h \) is the failure rate of a 1 to 3 in. piping leakage per foot of pipe \( (1 \times 10^{-9}/\text{h-ft}) \) times an assumed 10 ft of piping of concern. The value of \( 1 \times 10^{-4}/\text{h-ft} \) is based on EGG-8875 (Eide et al. 1990, page 12). The value of \( 5 \times 10^{-4} \) is an assumed value for a common-cause event that should bound any undefined common-cause event.

Event TWS RECOVERY: The probability that TWS annulus water loss cannot be recovered from is 0.003 \( (3 \times 10^{-3}) \). The value of \( 3 \times 10^{-3}/\text{demand} \) is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the error to make sure the first operator completed refilling the annulus with water.

Event HE FLOW MAINTAIN: The probability that helium flow is maintained from the normal helium supply is 0.987 \( (1-0.3 \times 10^{-2}) \). The value of \( 0.3 \times 10^{-2} \) represents a spurious failure of the isolation valves failing closed {based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2) \( (3 \times 10^{-4}/\text{h} \times 8,760 \text{ h}/2) \). The value of \( 1 \times 10^{-4}/\text{h} \) is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

event 8/4/4: The probability that the safety-class instrumentation and control (SCIC) timer functions properly by initiating the first 4-h logic which turns off the vacuum and allows the MCO to pressurize is 0.9999 \( (1-[1 \times 10^{-4}]) \). The value of \( 1 \times 10^{-4} \) represents a failure of the SCIC failure \( (1 \times 10^{-4}/\text{h} \times 100 \text{ h}) \) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of \( 1 \times 10^{-4}/\text{h} \) represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

Event VPS LINE INTEG.: The probability that the VPS line integrity is maintained is a product of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO maintain leak integrity is 0.999808 \( (1-[4.0 \times 10^{-6}/\text{h} \times 24 \text{ h} \times 2 \text{ connections}]) \). The value of \( 4.0 \times 10^{-6}/\text{h} \) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).
The probability that 10 ft of exit piping from the process vent port of the MCO maintains its leak integrity is 0.9999976 \( (1 - [1.0 \times 10^{-8}/h \times 10 \text{ ft} \times 24 \text{ h}]) \). The value of \( 1.0 \times 10^{-8}/h \)-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

The probability that one isolation valves (GOV 1*09) and two needle valves (VPS-V-059 and VPS-V-061) in the exit helium purge system maintain their integrity is 0.9999928 \( (1 - [1.0 \times 10^{-7}/h \times 24 \text{ h} \times 3 \text{ valves}]) \). The value of \( 1.0 \times 10^{-7}/h \) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

The probability that installing the exit line involved with helium purge maintains leak integrity is 0.9997 \( (1 - [3.0 \times 10^{-4}]) \). The value of \( 3.0 \times 10^{-4} \) is a value assigned to basic operator error plus a post-installation test based on NUREG/CRA-4772 (Swain 1987, Table 5-3, Case VI, page 5-13).

Therefore the probability that the vacuum line integrity is maintained is calculated as follows:
\[
(1 - 1.92 \times 10^{-4}) \times (1 - 2.4 \times 10^{-6}) \times (1 - 7.2 \times 10^{-6}) \times (1 - 3.0 \times 10^{-4}) = 0.99950
\]

Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has HEPA filtration functioning during the release based on 4,380 h (the average unavailability assuming tested once per year; 8,760 h/2) is 0.999943 \( (1 - [1.3 \times 10^{-8}/h \times 4,380 \text{ h}]) \). The value of \( 1.3 \times 10^{-8}/h \) is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982, page 18).

If the TWS annulus water is not maintained AND the TWS annulus water is not restored AND the normal helium flow is maintained AND the 8/4/4 logic cycle is initiated AND the VPS line integrity is maintained AND the HEPA filters function, this results in a sequence that has a frequency beyond extremely unlikely (\(< 1 \times 10^{-9}/\text{year}\)).
assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss cannot be recovered from is 0.003 (3 x 10^{-3}). The value of 3 x 10^{3}/demand is a value assigned to basic operator errors (0.03) based on NUREG/CN-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.

c) Event HE FLOW MAINTAIN: The probability that helium flow is maintained from the normal helium supply is 0.987 (1-[1.3 x 10^{-2}]). The value of 1.3 x 10^{-2} represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)) (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic which turns off the vacuum and allows the MCO to pressurize is 0.9999 (1-[1 x 10^{-4}]). The value of 1 x 10^{-4} represents a failure of the SCIC failure (1 x 10^{-9}/h x 100 h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of 1 x 10^{-9}/h represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

e) Event VPS LINE INTEG.: The probability that the VPS line integrity is maintained is a product of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO maintain leak integrity is 0.999808 (1-[4.0 x 10^{-6}/h x 24 h x 2 connections]). The value of 4.0 x 10^{-6}/h is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982). AND

The probability that 10 ft of exit piping from the process vent port of the MCO maintains its leak integrity is 0.9999976 (1-[1.0 x 10^{-9}/h-ft x 10 ft x 24 h]). The value of 1.0 x 10^{-9}/h-ft is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990). AND

The probability that one isolation valves (GOV 1*09) and two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system maintain their integrity is 0.9999928 (1-[1.0 x 10^{-7}/h x 24 h x 3 valves]). The value of 1.0 x 10^{-7}/h is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).
AND
The probability that installing the exit line involved with helium purge maintains leak integrity is 0.9997 \( (1 - [3.0 \times 10^{-4}]) \). The value of \( 3.0 \times 10^{-4} \) is a value assigned to basic operator error plus a post-installation test based on NUREG/CR-4772 (Swain 1987, Table 5-3, Case VI, page 5-13).

Therefore the probability that the vacuum line integrity is maintained is calculated as follows:
\[
(1 - 1.92 \times 10^{-4}) \times (1 - 2.4 \times 10^{-6}) \times (1 - 7.2 \times 10^{-6}) \times (1 - 3.0 \times 10^{-4}) = 0.99950
\]

f) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has no HEPA filtration functioning during the release based on 4,380 h (the average unavailability assuming tested once per year; 8,760 h/2) is \( 0.000057 \) \( (1.3 \times 10^{-8}/h \times 4,380 \text{ h}) \). The value of \( 1.3 \times 10^{-8}/h \) is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982, page 18).

If the TWS annulus water is not maintained AND the TWS annulus water is not restored AND the normal helium flow is maintained AND the 8/4/4 logic cycle is initiated AND the VPS line integrity is maintained AND the HEPA filters are not functioning, this results in a sequence that has a frequency beyond extremely unlikely (<\( 1 \times 10^{-6} \)/year).

Sequence 7 a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is \( 0.000001 \) \( (1.1 \times 10^{-6}) \). The value of \( 1.1 \times 10^{-6} \) is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) \( (1 \times 10^7/h \times 16 \text{ h}) \) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability \( (5 \times 10^{-4} \times 16 \text{ h}/8,760 \text{ h}) \). The value of \( 1 \times 10^7/h \) is the failure rate of a 1 to 3 in. piping leakage per foot of pipe \( (1 \times 10^7/h \text{ ft}) \) times an assumed 10 ft of piping of concern. The value of \( 1 \times 10^{-4} \text{ ft} \) is based on EGG-8875 (Eide et al. 1990, page 12). The value of \( 5 \times 10^{-4} \) is an assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss cannot be recovered from is \( 0.003 \) \( (3 \times 10^{-5}) \). The value of \( 3 \times 10^{-5}/\text{demand} \) is a value assigned to basic operator errors \( (0.03) \) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.
c) Event HE FLOW MAINTAIN: The probability that helium flow is maintained from the normal helium supply is 0.987 \((1 - \{1.3 \times 10^{-2}\})\). The value of \(1.3 \times 10^{-2}\) represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)) \((3 \times 10^{-6}/h \times 8,760/h/2))\). The value of \(3 \times 10^{-6}/h\) is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic which turns off the vacuum and allows the MCO to pressurize is 0.9999 \((1 - [1 \times 10^{-4}])\). The value of \(1 \times 10^{-4}\) represents a failure of the SCIC failure \((1 \times 10^{-6}/h \times 100\) h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of \(1 \times 10^{-6}/h\) represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

e) Event VPS LINE INTEG.: The probability that the VPS line integrity is not maintained is a summation of the following probabilities:

The probability that the two flexible hose connections on the exit of the process vent port of the MCO leak is 0.000192 \((4.0 \times 10^{-6}/h \times 24 \times 2\) connections). The value of \(4.0 \times 10^{-6}/h\) is a value for lightly stressed hose based on DP-1633 (Dexter and Perkins 1982).

OR
The probability that 10 ft of exit piping from the process vent port of the MCO leaks is 0.0000024 \((1.0 \times 10^{-9}/h\cdot\text{ft} \times 10 \text{ ft} \times 24 \text{ h})\). The value of \(1.0 \times 10^{-9}/h\cdot\text{ft}\) is a value for leakage from piping 1 in. to 3 in. in diameter (per foot) based on EGG-SSRE-8875 (Eide et al. 1990).

OR
The probability that one isolation valve (GOV 1*09) or two needle valves (VPS-V-*059 and VPS-V-*061) in the exit helium purge system leak is 0.0000072 \((1.0 \times 10^{-6}/h \times 24 \text{ h} \times 3\) valves). The value of \(1.0 \times 10^{-6}/h\) is the highest value for external leakage for any of five types of valves based on EGG-SSRE-8875 (Eide et al. 1990).

OR
The probability that installing the exit line involved with helium purge maintains leak integrity is 0.0003 \((3.0 \times 10^{-4})\). The value of \(3.0 \times 10^{-4}\) is a value assigned to basic operator error plus a post-installation test based on NUREG/CR-4772 (Swain 1987, Table 5-3, Case VI, page 5-13).

Therefore the probability that the vacuum line integrity is maintained is calculated as follows:
\[
1.92 \times 10^{-4} + 2.4 \times 10^{-6} + 7.2 \times 10^{-6} + 3.0 \times 10^{-4} = 5.00 \times 10^{-4}.
\]
If the TWS annulus water is not maintained AND the TWS annulus water is not restored AND the normal helium flow is maintained AND the 8/4/4 logic cycle is initiated AND the VPS line integrity is not maintained, this results in a sequence that has a frequency beyond extremely unlikely (<1 x 10^(-6) /year).

Sequence 8

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.0000011 (1.1 x 10^(-6)). The value of 1.1 x 10^(-6) is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) (1 x 10^(-7)/h x 16 h) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability (5 x 10^(-4) x 16 h/8,760 h). The value of 1 x 10^(-7)/h is the failure rate of a 1 to 3 in. piping leakage per foot of pipe (1 x 10^(-6)/h-ft) times an assumed 10 ft of piping of concern. The value of 1 x 10^(-6)/h-ft is based on EGG-8875 (Eide et al. 1990, page 12). The value of 5 x 10^(-4) is an assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss cannot be recovered from is 0.003 (3 x 10^(-3)). The value of 3 x 10^(-3) is based on basic operator errors (0.03) times the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.

c) Event HE FLOW MAINTAIN: The probability that helium flow is maintained from the normal helium supply is 0.987 (1-[1.3 x 10^(-1)]). The value of 1.3 x 10^(-1) represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)) (3 x 10^(-6)/h x 8,760 h/2). The value of 3 x 10^(-6)/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer fails to function properly by initiating the first 4-h logic which turns off the vacuum and allows the MCO to pressurize is 0.0001 (1 x 10^(-4)). The value of 1 x 10^(-4) represents a failure of the SCIC failure (1 x 10^(-5)/h x 100 h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of 1 x 10^(-5)/h represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

If the TWS annulus water is not maintained AND the TWS annulus water is not restored AND the normal helium flow is maintained AND the 8/4/4 logic cycle is
Sequence 9

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.0000011 (1.1 x 10^{-6}). The value of 1.1 x 10^{-6} is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) (1 x 10^{-7}/h x 16 h) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability (5 x 10^{-4} x 16 h/8,760 h). The value of 1 x 10^{-7}/h is the failure rate of a 1 to 3 in. piping Leakage per foot of pipe (1 x 10^{-9}/h-ft) times an assumed 10 ft of piping of concern. The value of 1 x 10^{-4}/h-ft is based on EGG-8875 (Eide et al. 1990, page 12). The value of 5 x 10^{-4} is an assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss cannot be recovered from is 0.003 (3 x 10^{-5}). The value of 3 x 10^{-5}/demand is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.

c) Event HE FLOW MAINTAIN: The probability that helium flow is not maintained from the normal helium supply is 0.013 (1.3 x 10^{-2}). The value of 1.3 x 10^{-2} represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2) (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

If the TWS annulus water is not maintained AND the TWS annulus water is not restored AND the normal helium flow is not maintained, this results in a sequence that has a frequency beyond extremely unlikely (<1 x 10^{-6}/year).

A5.2 EVENT TREES FOR THREE MITIGATED THERMAL EXCursion SCENARIOS WITHOUT RELEASE IN A COLD VACUUM DRYING FACILITY PROCESS BAY

The three accident scenarios that are represented in the following mitigated event trees and event tree descriptions are three different thermal excursion scenarios. The three scenarios are not DBAs but represent other thermal excursion scenarios that did not address a release from an MCO but did include controls to help prevent the thermal excursion from occurring. The first
mitigated thermal excursion scenario, presented in Section A5.2.1, is similar to the DBA thermal excursion discussed in Section A5.1. The differences between this scenario and the previous DBA scenario is the exclusion of a release path from the MCO following the creation of high temperatures in the MCO. The second mitigated thermal excursion scenario, presented in Section A5.2.2, occurs when degraded vacuum operation results in high fuel temperatures. The third mitigated thermal excursion scenario, presented in Section A5.2.3, occurs when the tempered water heater is operating higher than 50 °C resulting in high fuel temperatures.

A5.2.1 Figure A5-2

Figure A5-2 (CVDTHR1Z.TRE) shows the event tree used to develop the frequency of a mitigated thermal excursion resulting from a loss of coolant accident without a release path to the process bay at the CVDF.

Initiating event (Event IE): Processing of MCOs at CVDF at a rate of 200 MCOs/yr.

Sequence 1  a) Event TWS ANNULUS OK: The probability that the TWS annulus water is maintained during processing is 0.99999989 (1 - [1.1 x 10^-6]). The value of 1.1 x 10^-6 is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) (1 x 10^-7/h x 16 h) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability (5 x 10^-4 x 16 h/8,760 h). The value of 1 x 10^-7/h is the failure rate of a 1 to 3 in. piping leakage per foot of pipe (1 x 10^-9/h-ft) times an assumed 10 ft of piping of concern. The value of 1 x 10^-9/h-ft is based on EGG-8875 (Eide et al. 1990, page 12). The value of 5 x 10^-4 is an assumed value for a common-cause event that should bound any undefined common-cause event.

If the TWS annulus water is maintained, normal fuel temperatures are the result.

Sequence 2  a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.0000011 (1 x 10^-6). The value of 1.1 x 10^-6 is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) (1 x 10^-7/h x 16 h) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability (5 x 10^-4 x 16 h/8,760 h). The value of 1 x 10^-7/h is the failure rate of a 1 to 3 in. piping leakage per foot of pipe (1 x 10^-9/h-ft) times an assumed 10 ft of piping of concern. The value of 1 x 10^-9/h-ft is based on EGG-8875 (Eide et al. 1990, page 12). The value of 5 x 10^-4 is an
assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss can be recovered from is 0.997 (1-\(3 \times 10^{-3}\)). The value of \(3 \times 10^{-3}/\text{demand}\) is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.

If the TWS annulus water is not maintained AND the TWS annulus water is restored, normal fuel temperatures are the result.

**Sequence 3**

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.000001 (1.1 \(\times 10^{-6}\)). The value of 1.1 \(\times 10^{-6}\) is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) \((1 \times 10^{-7}/h \times 16 \text{ h})\) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability \((5 \times 10^{-4} \times 16 \text{ h}/8,760 \text{ h})\). The value of \(1 \times 10^{-7}/\text{h}\) is the failure rate of a 1 to 3 in. piping leakage per foot of pipe \((1 \times 10^{-6}/\text{h-ft})\) times an assumed 10 ft of piping of concern. The value of \(1 \times 10^{-6}/\text{h-ft}\) is based on EGG-8875 (Eide et al. 1990, page 12). The value of \(5 \times 10^{-4}\) is an assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss cannot be recovered from is 0.003 \((3 \times 10^{-3})\). The value of \(3 \times 10^{-3}/\text{demand}\) is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.

c) Event HE FLOW MAINTAIN: The probability that helium flow is maintained from the normal helium supply is 0.987 (1-[1.3 \(\times 10^{-2}\)]). The value of 1.3 \(\times 10^{-2}\) represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)) \((3 \times 10^{-6}/\text{h} \times 8,760 \text{ h/2})\). The value of \(3 \times 10^{-6}/\text{h}\) is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic which turns off the vacuum and allows the MCO to pressurize is 0.9999 (1-[1 \(\times 10^{-4}\)]). The value of \(1 \times 10^{-4}\) represents a
failure of the SCIC failure \((1 \times 10^{-6}/h \times 100 \text{ h})\) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of \(1 \times 10^{-6}/h\) represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

If the TWS annulus water is not maintained AND the TWS annulus water is not restored AND the normal helium flow is maintained AND the 8/4/4 logic cycle is initiated, there will be no high fuel temperatures.

Sequence 4

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.0000011 \((1.1 \times 10^{-6})\). The value of \(1.1 \times 10^{-6}\) is a summation of the probability of a section of double-walled pipe failing \((\text{based on } 16 \text{ h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing )}) \((1 \times 10^{-7}/h \times 16 \text{ h})\) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability \((5 \times 10^{-4}/h \times 16 \text{ h}/8,760 \text{ h})\). The value of \(1 \times 10^{-7}/h\) is the failure rate of a 1 to 3 in. piping leakage per foot of pipe \((1 \times 10^{-9}/h\text{-ft})\) times an assumed 10 ft of piping of concern. The value of \(5 \times 10^{-4}/h\text{-ft}\) is based on EGG-8875 (Eide et al. 1990, page 12). The value of \(5 \times 10^{-4}\) is an assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss cannot be recovered from is 0.003 \((3 \times 10^{-3})\). The value of \(3 \times 10^{-3}/\text{demand}\) is a value assigned to basic operator errors \((0.03)\) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.

c) Event HE FLOW MAINTAIN: The probability that helium flow is maintained from the normal helium supply is 0.987 \((1-[1.3 \times 10^{-2}])\). The value of \(1.3 \times 10^{-2}\) represents a spurious failure of the isolation valves failing closed \((\text{based on } 4,380 \text{ h (the average unavailability assuming valves checked once per year for conservatism; } 8,760 \text{ h/2})}) \((3 \times 10^{-6}/h \times 8,760 \text{ h/2})\). The value of \(3 \times 10^{-6}/h\) is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer fails to function properly by initiating the first 4-h logic, which turns off the vacuum and allows the MCO to pressurize, is 0.0001 \((1 \times 10^{-4})\). The value of \(1 \times 10^{-4}\) represents a failure of the SCIC failure \((1 \times 10^{-6}/h \times 100 \text{ h})\) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of \(1 \times 10^{-6}/h\) represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).
If the TWS annulus water is not maintained AND the TWS annulus water is not restored AND the normal helium flow is maintained AND the 8/4/4 logic cycle is not initiated, there will be local fuel temperatures of 650 °C.

Sequence 5

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.000001 (1.1 x 10^{-6}). The value of 1.1 x 10^{-6} is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) (1 x 10^{-7}h x 16 h) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability (5 x 10^{-4} x 16 h/8,760 h). The value of 1 x 10^{-7}/h is the failure rate of a 1 to 3 in. piping leakage per foot of pipe (1 x 10^{-6}/h-ft) times an assumed 10 ft of piping of concern. The value of 1 x 10^{-4}/h-ft is based on EGG-8875 (Eide et al. 1990, page 12). The value of 5 x 10^{-4} is an assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss cannot be recovered from is 0.003 (3 x 10^{-3}). The value of 3 x 10^{-3}/demand is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.

c) Event HE FLOW MAINTAIN: The probability that helium flow is not maintained from the normal helium supply is 0.013 (1.3 x 10^{-2}). The value of 1.3 x 10^{-2} represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)) (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic, which turns off the vacuum and allows the MCO to pressurize, is 0.9999 (1-[1 x 10^{-4}]). The value of 1 x 10^{-4} represents a failure of the SCIC failure (1 x 10^{-6}/h x 100 h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of 1 x 10^{-6}/h represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

If the TWS annulus water is not maintained AND the TWS annulus water is not restored AND the normal helium flow is not maintained AND the 8/4/4 logic cycle is initiated, there will be no high fuel temperatures.
Sequence 6

a) Event TWS ANNULUS OK: The probability that the TWS annulus water is not maintained during processing is 0.000001 (1.1 x 10^-6). The value of 1.1 x 10^-6 is a summation of the probability of a section of double-walled pipe failing (based on 16 h (the length of time an MCO is judged to be vulnerable to a thermal excursion during processing)) (1 x 10^-7/h x 16 h) involving a common-cause adjustment of 0.1 based on a beta factor of 0.1 and the probability that an undefined common-cause event will fail the piping during the 16 h of vulnerability (5 x 10^-4 x 16 h/8,760 h). The value of 1 x 10^-7/h is the failure rate of a 1 to 3 in. piping leakage per foot of pipe (1 x 10^-8/h-ft) times an assumed 10 ft of piping of concern. The value of 5 x 10^-4 is an assumed value for a common-cause event that should bound any undefined common-cause event.

b) Event TWS RECOVERY: The probability that TWS annulus water loss cannot be recovered from is 0.003 (3 x 10^-3). The value of 3 x 10^-3/demand is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5) times a value of 0.1 as the probability that a second operator fails to make sure the first operator completed refilling the annulus with water.

c) Event HE FLOW MAINTAIN: The probability that helium flow is not maintained from the normal helium supply is 0.013 (1.3 x 10^-2). The value of 1.3 x 10^-2 represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism: 8,760 h/2)) (3 x 10^-6/h x 8,760 h/2). The value of 3 x 10^-6/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer fails to function properly by initiating the first 4-h logic, which turns off the vacuum and allows the MCO to pressurize, is 0.0001 (1 x 10^-4). The value of 1 x 10^-4 represents a failure of the SCIC failure (1 x 10^-6/h x 100 h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of 1 x 10^-6/h represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

If the TWS annulus water is not maintained AND the TWS annulus water is not restored AND the normal helium flow is not maintained AND the 8/4/4 logic cycle is not initiated, there will be high fuel temperatures greater than 650 °C.
A5.2.2 Figure A5-3

Figure A5-3 (CVDTHR2Y.TRE) shows the event tree used to develop the frequency of a mitigated thermal excursion resulting from a degraded vacuum operation without a release path to the process bay at the CVDF.

Initiating event (Event IE): Processing of MCOs at CVDF at a rate of 200 MCOs/yr.

Sequence 1  

a) Event VACUUM MAINTAIN: The probability that the vacuum pump operates at its required effectiveness is 0.987 (1-[1.3 x 10^{-2}]). The value of 1.3 x 10^{-2} represents a leakage failure of the vacuum pump such that its effectiveness is reduced {based on 4,380 h (the average unavailability assuming pump checked once per year for conservatism; 8,760 h/2)} (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the external leakage failure rate for a motor-driven pump based on EGG-8875 (Eide et al. 1990, page 12).

If the vacuum pump maintains its effectiveness, normal fuel temperatures are the result.

b) Event HE FLOW CONTINUE: The probability that helium flow is maintained from the normal helium supply is 0.987 (1-[1.3 x 10^{-2}]). The value of 1.3 x 10^{-2} represents a spurious failure of the isolation valves failing closed {based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)} (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

If the vacuum pump does not maintain its effectiveness AND the purge helium flow is maintained, normal fuel temperatures are the result.

Sequence 2  

a) Event VACUUM MAINTAIN: The probability that the vacuum pump does not operate at its required effectiveness is 0.013 (1.3 x 10^{-2}). The value of 1.3 x 10^{-2} represents a leakage failure of the vacuum pump such that its effectiveness is reduced {based on 4,380 h (the average unavailability assuming pump checked once per year for conservatism; 8,760 h/2)} (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the external leakage failure rate for a motor-driven pump based on EGG-8875 (Eide et al. 1990, page 12).

b) Event HE FLOW CONTINUE: The probability that helium flow is maintained from the normal helium supply is 0.987 (1-[1.3 x 10^{-2}]). The value of 1.3 x 10^{-2} represents a spurious failure of the isolation valves failing closed {based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)} (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

If the vacuum pump does not maintain its effectiveness AND the purge helium flow is maintained, normal fuel temperatures are the result.
The value of $3 \times 10^{-6}$/h is the external leakage failure rate for a motor-driven pump based on EGG-8875 (Eide et al. 1990, page 12).

b) Event HE FLOW CONTINUE: The probability that helium flow is not maintained from the normal helium supply is 0.013 ($1.3 \times 10^{-2}$). The value of $1.3 \times 10^{-2}$ represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)) $(3 \times 10^{-6}$/h x 8,760 h/2). The value of $3 \times 10^{-6}$/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

c) Event AUTO SCHe INJECT: The probability that the SCHe injection will occur given there is no helium flow and the pressure is above 12 torr after 5 min is 0.9999 ($1 - [1 \times 10^{-4}]$). The value of $1 \times 10^{-4}$ represents the common-cause failure to open on demand of either of the two applicable pneumatic SCHe isolation valves that provide helium injection ($1 \times 10^{-3}$/demand times a beta factor of 0.1. The value of $1 \times 10^{-3}$/demand is a value for a pneumatic valve failing to open on demand based on EGG-8875 (Eide et al. 1990, page 11).

If the vacuum pump does not maintain its effectiveness AND the purge helium flow is not maintained AND the automatic SCHe injection occurs, normal fuel temperatures are the result.

Sequence 4

a) Event VACUUM MAINTAIN: The probability that the vacuum pump does not operate at its required effectiveness is 0.013 ($1.3 \times 10^{-2}$). The value of $1.3 \times 10^{-2}$ represents a leakage failure of the vacuum pump such that its effectiveness is reduced (based on 4,380 h (the average unavailability assuming pump checked once per year for conservatism; 8,760 h/2)) $(3 \times 10^{-6}$/h x 8,760 h/2). The value of $3 \times 10^{-6}$/h is the external leakage failure rate for a motor-driven pump based on EGG-8875 (Eide et al. 1990, page 12).

b) Event HE FLOW CONTINUE: The probability that helium flow is not maintained from the normal helium supply is 0.013 ($1.3 \times 10^{-2}$). The value of $1.3 \times 10^{-2}$ represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)) $(3 \times 10^{-6}$/h x 8,760 h/2). The value of $3 \times 10^{-6}$/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

c) Event AUTO SCHe INJECT: The probability that the SCHe injection will not occur given there is no helium flow and the pressure is above 12 torr after 5 min is 0.0001 ($1 \times 10^{-4}$). The value of $1 \times 10^{-4}$ represents the common-cause
failure to open on demand of either of the two applicable pneumatic SCHe isolation valves that provide helium injection (1 x 10^{-3}/demand times a beta factor of 0.1. The value of 1 x 10^{-3}/demand is a value for a pneumatic valve failing to open on demand based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic, which turns off the vacuum and allows the MCO to pressurize, is 0.9999 (1-[1 x 10^{-4}]). The value of 1 x 10^{-4} represents a failure of the SCIC failure (1 x 10^{-6}/h x 100 h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of 1 x 10^{-6}/h represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

e) Event RESTORE VACUUM: The probability that the vacuum pump’s effectiveness can be restored after monitoring indicates a decrease in effectiveness is 0.97 (1-[3 x 10^2]). The value of 3 x 10^2/demand is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).

If the vacuum pump does not maintain its effectiveness AND the purge helium flow is not maintained AND the SCHe injection does not occur AND the 8/4/4 logic cycle is initiated AND the operator restores the vacuum pump effectiveness, normal fuel temperatures are the result.

Sequence 5  

a) Event VACUUM MAINTAIN: The probability that the vacuum pump does not operate at its required effectiveness is 0.013 (1.3 x 10^{-2}). The value of 1.3 x 10^{-2} represents a leakage failure of the vacuum pump such that its effectiveness is reduced {based on 4,380 h (the average unavailability assuming pump checked once per year for conservatism; 8,760 h/2)} (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the external leakage failure rate for a motor-driven pump based on EGG-8875 (Eide et al. 1990, page 12).

b) Event HE FLOW CONTINUE: The probability that helium flow is not maintained from the normal helium supply is 0.013 (1.3 x 10^{-2}). The value of 1.3 x 10^{-2} represents a spurious failure of the isolation valves failing closed {based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)} (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

c) Event AUTO SCHE INJECT: The probability that the SCHe injection will not occur given there is no helium flow and the pressure is above 12 torr after 5 min is 0.0001 (1 x 10^{-4}). The value of 1 x 10^{-4} represents the common-cause failure to open on demand of either of the two applicable pneumatic SCHe
isolation valves that provide helium injection (1 x 10^{-3}/demand) times a beta factor of 0.1. The value of 1 x 10^{-3}/demand is a value for a pneumatic valve failing to open on demand based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic, which turns off the vacuum and allows the MCO to pressurize, is 0.9999 (1 - [1 x 10^{-4}]). The value of 1 x 10^{-4} represents a failure of the SCIC failure (1 x 10^{-6}/h x 100 h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of 1 x 10^{-6}/h represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

e) Event RESTORE VACUUM: The probability that the vacuum pump's effectiveness cannot be restored after monitoring indicates a decrease in effectiveness is 0.03 (3 x 10^{-2}). The value of 3 x 10^{-2}/demand is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).

If the vacuum pump does not maintain its effectiveness AND the purge helium flow is not maintained AND the SCHe injection does not occur AND the 8/4/4 logic cycle is initiated AND the operator does not restore the vacuum pump effectiveness, normal fuel temperatures are the result.

Sequence 6

a) Event VACUUM MAINTAIN: The probability that the vacuum pump does not operate at its required effectiveness is 0.013 (1.3 x 10^{-2}). The value of 1.3 x 10^{-2} represents a leakage failure of the vacuum pump such that its effectiveness is reduced (based on 4,380 h (the average unavailability assuming pump checked once per year for conservatism; 8,760 h/2)) (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the external leakage failure rate for a motor-driven pump based on EGG-8875 (Eide et al. 1990, page 12).

b) Event HE FLOW CONTINUE: The probability that helium flow is not maintained from the normal helium supply is 0.013 (1.3 x 10^{-2}). The value of 1.3 x 10^{-2} represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)) (3 x 10^{-6}/h x 8,760 h/2). The value of 3 x 10^{-6}/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

c) Event AUTO SCHE INJECT: The probability that the SCHe injection will not occur given there is no helium flow and the pressure is above 12 torr after 5 min is 0.0001 (1 x 10^{-4}). The value of 1 x 10^{-4} represents the common-cause failure to open on demand of either of the two applicable pneumatic SCHe isolation valves that provide helium injection (1 x 10^{-3}/demand times a beta
factor of 0.1. The value of $1 \times 10^3$/demand is a value for a pneumatic valve failing to open on demand based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic, which turns off the vacuum and allows the MCO to pressurize, is 0.0001 ($1 \times 10^{-4}$). The value of $1 \times 10^{-4}$ represents a failure of the SCIC failure ($1 \times 10^{-6}$/h x 100 h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of $1 \times 10^{-6}$/h represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

e) Event RESTORE VACUUM: The probability that the vacuum pump’s effectiveness can be restored after monitoring indicates a decrease in effectiveness is 0.97 (1 - [3 x $10^{-2}$]). The value of 3 x $10^{-2}$/demand is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).

If the vacuum pump does not maintain its effectiveness AND the purge helium flow is not maintained AND the SCHe injection does not occur AND the 8/4/4 logic cycle is not initiated AND the operator restores the vacuum pump effectiveness, normal fuel temperatures are the result.

Sequence 7

a) Event VACUUM MAINTAIN: The probability that the vacuum pump does not operate at its required effectiveness is 0.013 ($1.3 \times 10^{-2}$). The value of $1.3 \times 10^{-2}$ represents a leakage failure of the vacuum pump such that its effectiveness is reduced (based on 4,380 h (the average unavailability assuming pump checked once per year for conservatism; 8,760 h/2)) (3 x $10^{-6}$/h x 8,760 h/2). The value of 3 x $10^{-6}$/h is the external leakage failure rate for a motor-driven pump based on EGG-8875 (Eide et al. 1990, page 12).

b) Event HE FLOW CONTINUE: The probability that helium flow is not maintained from the normal helium supply is 0.013 ($1.3 \times 10^{-2}$). The value of $1.3 \times 10^{-2}$ represents a spurious failure of the isolation valves failing closed (based on 4,380 h (the average unavailability assuming valves checked once per year for conservatism; 8,760 h/2)) (3 x $10^{-6}$/h x 8,760 h/2). The value of 3 x $10^{-6}$/h is the spurious failure value for pneumatic valves based on EGG-8875 (Eide et al. 1990, page 11).

c) Event AUTO SCHe INJECT: The probability that the SCHe injection will not occur given there is no helium flow and the pressure is above 12 torr after 5 min is 0.0001 ($1 \times 10^{-4}$). The value of $1 \times 10^{-4}$ represents the common-cause failure to open on demand of either of the two applicable pneumatic SCHe isolation valves that provide helium injection ($1 \times 10^{0}$/demand times a beta
factor of 0.1. The value of $1 \times 10^3$/demand is a value for a pneumatic valve failing to open on demand based on EGG-8875 (Eide et al. 1990, page 11).

d) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic, which turns off the vacuum and allows the MCO to pressurize, is 0.0001 \((1 \times 10^{-4})\). The value of \(1 \times 10^{-4}\) represents a failure of the SCIC failure \((1 \times 10^{-4}/h \times 100 \text{ h})\) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of \(1 \times 10^{-4}/h\) represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

e) Event RESTORE VACUUM: The probability that the vacuum pump’s effectiveness cannot be restored after monitoring indicates a decrease in effectiveness is 0.03 \((3 \times 10^{-2})\). The value of \(3 \times 10^{-2}/\text{demand}\) is a value assigned to basic operator errors \((0.03)\) based on NUREG/CR-4772 (Swain 1987, Table 4-2, Note #2, page 4-5).

If the vacuum pump does not maintain its effectiveness AND the purge helium flow is not maintained AND the SCHe injection does not occur AND the 8/4/4 logic cycle is not initiated AND the operator does not restore the vacuum pump effectiveness, fuel temperatures greater than 650 °C will occur.

A5.2.2 Figure A5-4

Figure A5-4 (CVDTHR3Y.TRE) shows the event tree used to develop the frequency of a mitigated thermal excursion that results when a tempered water heater is left on high (HIH-HTR) without a release path to the process bay at the CVDF.

Initiating event (Event IE): Processing of MCOs at CVDF at a rate of 200 MCOs/yr.

Sequence 1

\[\text{a) Event TWS HEATER NORM.: The probability that the TWS heater is operating in its normal range is 0.99956 (1-}[4.4 \times 10^{-4}])\]. The value of \(4.4 \times 10^{-4}\) represents an immersion heater failing in the overheat mode \(\text{(based on 4,380 h (the average unavailability assuming heater checked once per year for conservatism; 8,760 h/2)})\} (1 \times 10^{-7}/h \times 8,760 \text{ h/2}). The value of \(1 \times 10^{-7}/h\) is the failure rate for an immersion heater to overheat based on EGG-8875 (Eide et al. 1990, page 22).

If the TWS heater is operating in its normal range, normal fuel temperatures are the result.

Sequence 2

\[\text{a) Event TWS HEATER NORM.: The probability that the TWS heater is not operating in its normal range is 0.00044 (4.4 \times 10^{-4})\]. The value of \(4.4 \times 10^{-4}\) represents an immersion heater failing in the overheat mode \(\text{(based on 4,380 h)}\]
(the average unavailability assuming heater checked once per year for conservatism; 8,760 h/2)} (1 x 10^{-7}/h x 8,760 h/2). The value of 1 x 10^{-7}/h is the failure rate for an immersion heater to overheat based on EGG-8875 (Eide et al. 1990, page 22).

b) Event DETECT HIGH TEMP: The probability that the SCIC system detects the high TWS temperature and the power is automatically shut off to the heater is 0.9997 (1-[3 x 10^{-4}]). The value of 3 x 10^{-4} represents a protective relay failing to open on demand based on EGG-8875 (Eide et al. 1990, page 21).

If the TWS heater is not operating in its normal range (overheating) AND SCIC detects the high TWS temperature and automatically shuts off power to the TWS heater, normal fuel temperatures are the result.

Sequence 3

a) Event TWS HEATER NORM.: The probability that the TWS heater is not operating in its normal range is 0.00044 (4.4 x 10^{-4}). The value of 4.4 x 10^{-4} represents an immersion heater failing in the overheat mode (based on 4,380 h (the average unavailability assuming heater checked once per year for conservatism; 8,760 h/2)} (1 x 10^{-7}/h x 8,760 h/2). The value of 1 x 10^{-7}/h is the failure rate for an immersion heater to overheat based on EGG-8875 (Eide et al. 1990, page 22).

b) Event DETECT HIGH TEMP: The probability that the SCIC system does not detect the high TWS temperature and the power is not automatically shut off to the heater is 0.0003 (3 x represents a protective relay failing to open on demand based on EGG-8875 (Eide et al. 1990, page 21).

c) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic, which turns off the vacuum and allows the MCO to pressurize, is 0.9999 (1-[1 x 10^{-4}]). The value of 1 x 10^{-4} represents a failure of the SCIC failure (1 x 10^{-9}/h x 100 h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of 1 x 10^{-9}/h represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

If the TWS heater is not operating in its normal range (overheating) AND SCIC does not detect the high TWS temperature and automatically shut off power to the TWS heater AND the 8/4/4 logic cycle is initiated, normal fuel temperatures are the result.

Sequence 4

a) Event TWS HEATER NORM.: The probability that the TWS heater is not operating in its normal range is 0.00044 (4.4 x 10^{-4}). The value of 4.4 x 10^{-4} represents an immersion heater failing in the overheat mode (based on 4,380 h...
(the average unavailability assuming heater checked once per year for conservatism; 8,760 h/2)) (1 x 10^{-7}/h x 8,760 h/2). The value of 1 x 10^{-7}/h is the failure rate for an immersion heater to overheat based on EGG-8875 (Eide et al. 1990, page 22).

b) Event DETECT HIGH TEMP: The probability that the SCIC system does not detect the high TWS temperature and the power is not automatically shut off to the heater is 0.0003 (3 x 10^{-4}). The value of 3 x 10^{-4} represents a protective relay failing to open on demand based on EGG-8875 (Eide et al. 1990, page 21).

c) Event 8/4/4: The probability that the SCIC timer functions properly by initiating the first 4-h logic, which turns off the vacuum and allows the MCO to pressurize, is 0.0001 (1 x 10^{-4}). The value of 1 x 10^{-4} represents a failure of the SCIC function (1 x 10^{-6}/h x 100 h) assuming 100 h between processing of MCOs (therefore verified as functional every 100 h). The value of 1 x 10^{-6}/h represents an instrumentation control indicator failure as referenced in EGG-8875 (Eide et al. 1990, page 23).

If the TWS heater is not operating in its normal range (overheating) AND SCIC does not detect the high TWS temperature and automatically shut off power to the TWS heater AND the 8/4/4 logic cycle is not initiated, high fuel temperatures are the result.

A5.3 REFERENCES


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<td>&gt; offsite guidelines</td>
</tr>
</tbody>
</table>

Figure A5-1a. Event Tree for an Unmitigated Thermal Excursion (Loss of Coolant Accident) in a Process Bay at the Cold Vacuum Drying Facility.
Figure A5-1b. Event Tree for a Mitigated Thermal Excursion (Loss of Coolant Accident) in a Process Bay at the Cold Vacuum Drying Facility.
Figure A5-2. Event Tree for a Mitigated Thermal Excursion (Loss of Coolant Accident without Release) in a Process Bay at the Cold Vacuum Drying Facility.

<table>
<thead>
<tr>
<th>MCs processed at CVDF per year</th>
<th>Double walled TWS pipe maintains integrity</th>
<th>TWS annulus water loss recovery</th>
<th>Continuous helium flow is maintained</th>
<th>SCIC timer initiates 3rd stage logic which turns off vacuum &amp; allows MC to press.</th>
<th>Seq.Freq.</th>
<th>Seq. #</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>YES</td>
<td>TWS ANNULUS OK</td>
<td>TWS RECOVERY</td>
<td>HE FLOW MAINTAIN</td>
<td>6/4/4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.00E-02</td>
<td>1</td>
<td>Normal temperatures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.19E-04</td>
<td>2</td>
<td>Normal temperatures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.51E-07</td>
<td>3</td>
<td>No high temperatures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.51E-11</td>
<td>4</td>
<td>Localized fuel temperatures of 650C 15hr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.50E-09</td>
<td>5</td>
<td>No high temperatures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.50E-13</td>
<td>8</td>
<td>High fuel temperatures in about 11 hrs</td>
</tr>
</tbody>
</table>

Thermal Excursion at CVDF (LOCAL), Semi-Mitigated 0VD1HR1Z.THE 5-24-99
Figure A5-3. Event Tree for a Mitigated Thermal Excursion (Degraded Vacuum without Release) in a Process Bay at the Cold Vacuum Drying Facility.
<table>
<thead>
<tr>
<th>MCDs processed at CV0 per year</th>
<th>TWS heater is operating in its normal range</th>
<th>SCIC detects TWS high temp. (1E-5) &amp; auto. shut off power to heater (3E-4)</th>
<th>SCIC maintains the B/4/4 logic</th>
<th>Seq. Freq.</th>
<th>Seq. #</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>IE</td>
<td>TWS HEATER NORM.</td>
<td>DETECT HIGH TEMP</td>
<td>B/4/4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>YES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.40E-04</td>
<td>NO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Thermal Excursion at CV0F (HIH-HTR). Semimitigated CV0THR3Y.TRE 4-23-99**
A6.0 EVENT TREES FOR UNMITIGATED AND MITIGATED MULTI-CANISTER OVERPACK OVERPRESSURIZATION IN A COLD VACUUM DRYING FACILITY PROCESS BAY

A6.1 ACCIDENT SCENARIO SUMMARY

The accident scenario represented in the following event trees and event tree descriptions is overpressurization of an MCO. This overpressurization occurs when the tempered water flow through the cask-MCO annulus is lost and the MCO is isolated from all process lines into or out of the MCO. A release from the MCO involves a pressurized blowdown from the MCO. It is assumed that pressure builds up over many hours before blowdown occurs. Event trees are presented for unmitigated (A6.2) and mitigated (A6.3) situations. In the unmitigated case, the effect of engineered controls such as pressure relief and ventilating systems is ignored and in the mitigated case these features are included.

A6.2 FIGURE A6-1a

Figure A6-1a shows the event tree used to develop the frequency of an unmitigated MCO overpressurization resulting from a loss of TWS flow when the MCO is isolated in a process bay at the CVDF. Two sequences are presented.

Initiating event (Event IE): MCOs are processed at CVDF at a rate of 200 MCOs per year.

Sequence 1 a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask-MCO annulus is maintained AND the MCO is unisolated is 0.9978 (1-[2.2 x 10^{-3}]). The value of 2.2 x 10^{-3} is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate an SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated, the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of 2.2 x 10^{-3} is calculated as \(1-e^{-1.22 \text{yr}^{-1} \times 16 \text{h} \times 8 \text{ valves}} = 2.2 \times 10^{-3}\) where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811, *Analysis of Power Loss for the 200 Area Tank Farms in Support of K Basin SAR Work* (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

If the TWS flow through the cask-MCO annulus is maintained and the MCO is not isolated, this results in normal processing.

Sequence 2 a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask-MCO annulus is not maintained AND the MCO is isolated is 0.0022
(2.2 x 10^{-3}). The value of 2.2 x 10^{-3} is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of 2.2 x 10^{-3} is calculated as \(1 - e^{-(1.22 \times 10^{-1} \times 16 \times 8760)} = 2.2 \times 10^{-3}\) where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

If the TWS flow through the cask–MCO annulus is lost AND the MCO becomes isolated, there is a high pressure blowdown.

A6.3 FIGURE A6-1b

Figure A6-1b shows the event tree used to develop the frequency of a mitigated MCO overpressurization in a process bay at the CVDF. Eleven sequences are presented.

Initiating event (Event IE): MCOs are processed at CVDF at a rate of 200 MCOs per year.

Sequence 1  a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask–MCO annulus is maintained AND the MCO is unisolated is 0.9978 (1-[2.2 x 10^{-3}]). The value of 2.2 x 10^{-3} is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate an SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of 2.2 x 10^{-3} is calculated as \(1 - e^{-(1.22 \times 10^{-1} \times 16 \times 8760)} = 2.2 \times 10^{-3}\) where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811, Analysis of Power Loss for the 200 Area Tank Farms in Support of K Basin SAR Work (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

If the TWS flow through the cask–MCO annulus is lost AND the MCO becomes not isolated, this results in normal processing.

Sequence 2  a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask–MCO annulus is not maintained AND the MCO is isolated is 0.0022 (2.2 x 10^{-6}). The value of 2.2 x 10^{-3} is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively
assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of $2.2 \times 10^{-3}$ is calculated as $(1-e^{-(1.22 \times 10^{-4} \times 16 \times 3600 s)} = 2.2 \times 10^{-3})$ where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

b) Event SCHE ACTUATION: The probability that the SCHe valves will be actuated given an LOEP is $0.9999 (1-[1 \times 10^{-4}])$. The value of $1 \times 10^{-4}$ represents the common cause failure of either of the two applicable SCHe isolation valves failing to open on demand ($1 \times 10^{-4}$/demand multiplied by a beta factor of 0.1). The value of $1 \times 10^{-4}$/demand is a value for a pneumatic valve failing to open on demand based on EGG-8875, INFORMAL REPORT, Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs (Eide et al. 1990, page 11).

c) Event 10 PSIG: The probability that the pressure in the MCO is relieved through the SCHe system 10 psig pressure relief path is $0.9997 (1-[3 \times 10^{-4}])$. The value of $3 \times 10^{-4}$ represents the failure of a safety valve to open on demand. The value of $3 \times 10^{-4}$/demand is based on EGG-8875 (Eide et al. 1990, page 11).

If the TWS flow through the cask-MCO annulus is lost and the MCO becomes isolated AND SCHe system actuates applicable isolation valves to open AND 10 psig vent path of the SCHe system relieves the pressure from the MCO, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

### Sequence 3

a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask-MCO annulus is not maintained AND the MCO is isolated is $0.0022 (2.2 \times 10^{-3})$. The value of $2.2 \times 10^{-3}$ is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of $2.2 \times 10^{-3}$ is calculated as $(1-e^{-(1.22 \times 10^{-4} \times 16 \times 3600 s)} = 2.2 \times 10^{-3})$ where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

b) Event SCHE ACTUATION: The probability that the SCHe valves will be actuated given an LOEP is $0.9999 (1-[1 \times 10^{-4}])$. The value of $1 \times 10^{-4}$ represents the common cause failure of either of the two applicable SCHe
isolation valves failing to open on demand \(1 \times 10^{-3}/\text{demand}\) multiplied by a beta factor of 0.1). The value of \(1 \times 10^{-3}/\text{demand}\) is a value for a pneumatic valve failing to open on demand based on (Eide et al. 1990, page 11).

c) Event 10 PSIG: The probability that the pressure in the MCO is not relieved through the SCHe system 10 psig pressure relief path is 0.0003 \((3 \times 10^{-4})\). The value of \(3 \times 10^{-4}\) represents the failure of a safety valve to open on demand. The value of \(3 \times 10^{-4}/\text{demand}\) is based on EGG-8875 (Eide et al. 1990).

d) Event 30 PSIG: The probability that the pressure in the MCO is relieved through the 30 psig rupture disk vent path is 0.997 \((1-[3 \times 10^{-3}])\). The value of \(3 \times 10^{-3}\) represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and quality assurance (QA) program. The value of \(3 \times 10^{-3}/\text{demand}\) is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772, *Accident Sequence Evaluation Program Human Reliability Analysis Procedure*, (Swain 1987) with 0.1 for a good QA program.

e) Event DG & LOC. FAN OP: The probability that the backup diesel generator will start (given it has enough air in its start accumulator for 10 start tries) is assumed to be 0.9977 \((1-[2.3 \times 10^{-3}])\). The value of \(2.3 \times 10^{-3}\) represents the failure to start of a diesel generator based on a value of \(2.3 \times 10^{-3}/\text{demand}\) and a factor of ten reduction based on the ability to try to start it ten times. The value of \(2.3 \times 10^{-3}/\text{demand}\) is the failure probability of a gas turbine generator to fail to start based on DP-1633, *Component Failure-Rate Data with Potential Applicability to a Nuclear Fuel Reprocessing Plant* (Dexter and Perkins 1982, page 17). The document EGG-SSRE-8875 (Eide et al. 1990, page 12) shows the failure of diesel-driven pumps to start on demand is \(1 \times 10^{-3}/\text{demand}\). The more conservative value of \(2.3 \times 10^{-3}/\text{demand}\) will be used in this calculation. The probability that either of the two local exhaust fans will start following the start of the backup diesel generator is 0.9995 \((1-[5 \times 10^{-4}])\). The value of \(5 \times 10^{-4}\) is based on fan failure to start probability of \(5 \times 10^{-3}/\text{demand}\) times a common cause beta factor of 0.1. The value of \(5 \times 10^{-4}/\text{demand}\) is the failure probability of a ventilator fan failure to start based on EGG-SSRE-8875, (Eide et al. 1990, page 19). Thus the probability that the diesel generator and one of the local exhaust fans starting following LOEP is 0.9972 \((1-[2.8 \times 10^{-3}])\) or \((1-[2.3 \times 10^{-3}]) \times (1-[5 \times 10^{-4}]) = 0.9972\).

f) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has HEPA filtration functioning during the release based on 4,380 h (the average unavailability assuming tested once per year; 8,760 h/2) is 0.999943 \((1-[1.3 \times 10^{-4}/h \times 4,380 \text{ h}])\). The value of \(1.3 \times 10^{-4}/h\) is the value for HEPA.
filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982).

If the TWS flow through the cask-MCO annulus is lost AND the MCO becomes isolated AND SCHe system actuates applicable isolation valves to open AND 10 psig vent path of the SCHe system does not relieve the pressure from the MCO AND the 30 psig rupture disk is successful in relieving MCO pressure AND the backup diesel generator starts and one of two local exhaust fans restart AND the HEPA filters function, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 4

a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask-MCO annulus is not maintained AND the MCO is isolated is 0.0022 (2.2 x 10^{-3}). The value of 2.2 x 10^{-3} is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of 2.2 x 10^{-3} is calculated as \(1-e^{-\frac{1.22 \text{LOEP}}{16 \text{h}}\times\frac{8760 \text{h}}{16 \text{h}}} = 2.2 \times 10^{-3}\) where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

b) Event SCHE ACTUATION: The probability that the SCHe valves will be actuated given an LOEP is 0.9999 (1 - [1 x 10^{-4}]). The value of 1 x 10^{-4} represents the common cause failure of either of the two applicable SCHe isolation valves failing to open on demand \(1 \times 10^{-3}/\text{demand} \times \beta = 1 \times 10^{-4}/\text{demand} \times 0.1\). The value of 1 x 10^{-4}/demand is a value for a pneumatic valve failing to open on demand based on (Eide et al. 1990, page 11).

c) Event 10 PSIG: The probability that the pressure in the MCO is not relieved through the SCHe system 10 psig pressure relief path is 0.0003 (3 x 10^{-4}). The value of 3 x 10^{-4} represents the failure of a safety valve to open on demand. The value of 3 x 10^{-4}/demand is based on EGG-8875 (Eide et al. 1990).

d) Event 30 PSIG: The probability that the pressure in the MCO is relieved through the 30 psig rupture disk vent path is 0.997 (1 - [3 x 10^{-3}]). The value of 3 x 10^{-3} represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of 3 x 10^{-3} is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.
e) Event DG & LOC. FAN OP: The probability that the backup diesel generator will start (given it has enough air in its start accumulator for 10 start tries) is assumed to be 0.9977 \((1-\{2.3 \times 10^{-3}\})\). The value of \(2.3 \times 10^{-3}\) represents the failure to start of a diesel generator based on a value of \(2.3 \times 10^{-2}/\text{demand}\) and a factor of ten reduction based on the ability to try to start it ten times. The value of \(2.3 \times 10^{-2}/\text{demand}\) is the failure probability of a gas turbine generator to fail to start based on DP-1633 (Dexter and Perkins 1982, page 17). The document EGG-SSRE-8875 (Eide et al. 1990, page 12) shows the failure of diesel-driven pumps to start on demand is \(1 \times 10^{-2}/\text{demand}\). The more conservative value of \(2.3 \times 10^{-3}/\text{demand}\) will be used in this calculation. The probability that either of the two local exhaust fans will start following the start of the backup diesel generator is 0.9995 \((1-\{5 \times 10^{-4}\})\). The value of \(5 \times 10^{-4}\) is based on fan failure to start probability of \(5 \times 10^{-3}/\text{demand}\) times a common cause beta factor of 0.1. The value of \(5 \times 10^{-3}/\text{demand}\) is the failure probability of a ventilator fan failure to start based on EGG-SSRE-8875, (Eide et al. 1990, page 19). Thus the probability that the diesel generator and one of the local exhaust fans starting following LOEP is 0.9972 \((1-\{2.8 \times 10^{-3}\})\) or \((\{1-\{2.3 \times 10^{-3}\}\} \times \{1-\{5 \times 10^{-4}\}\} = 0.9972\). 

f) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has no HEPA filtration functioning during the release based on 4,380 h (the average unavailability assuming tested once per year; 8,760 h/2) is 0.000057 \((1.3 \times 10^{-8}/h \times 4,380 \text{ h})\). The value of \(1.3 \times 10^{-8}/\text{h}\) is the value for HEPA filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter and Perkins 1982).

If the TWS flow through the cask–MCO annulus is lost AND the MCO becomes isolated AND SCHe system actuates applicable isolation valves to open AND 10 psig vent path of the SCHe system does not relieve the pressure from the MCO AND the 30 psig rupture disk is successful in relieving MCO pressure AND the backup diesel generator starts and one of two local exhaust fans restart AND the HEPA filters fail to function, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask–MCO annulus is not maintained AND the MCO is isolated is 0.0022 \((2.2 \times 10^{-3})\). The value of \(2.2 \times 10^{-3}\) is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of \(2.2 \times 10^{-3}\) is calculated as \(1-e^{-\{1.22\text{ yr}^{-1} \times 16\text{ h}\times 8\text{ valves}\}} = 2.2 \times 10^{-3}\) where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in...
WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

b) Event SCHE ACTUATION: The probability that the SCHe valves will be actuated given an LOEP is 0.9999 (1-1 x 10^-4). The value of 1 x 10^-4 represents the common cause failure of either of the two applicable SCHe isolation valves failing to open on demand (1 x 10^-3/demand multiplied by a beta factor of 0.1). The value of 1 x 10^-3/demand is a value for a pneumatic valve failing to open on demand based on (Eide et al. 1990, page 11).

c) Event 10 PSIG: The probability that the pressure in the MCO is not relieved through the SCHe system 10 psig pressure relief path is 0.0003 (3 x 10^-4). The value of 3 x 10^-4 represents the failure of a safety valve to open on demand. The value of 3 x 10^-4/demand is based on EGG-8875 (Eide et al. 1990).

d) Event 30 PSIG: The probability that the pressure in the MCO is relieved through the 30 psig rupture disk vent path is 0.997 (1-3 x 10^-3). The value of 3 x 10^-3 represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of 3 x 10^-3 is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.

e) Event DG & LOC. FAN OP: The probability that the backup diesel generator will not start (given it has enough air in its start accumulator for 10 start tries) is assumed to be 0.0023 (2.3 x 10^-3). The value of 2.3 x 10^-3 represents the failure to start of a diesel generator based on a value of 2.3 x 10^-3/demand and a factor of ten reduction based on the ability to try to start it ten times. The value of 2.3 x 10^-3/demand is the failure probability of a gas turbine generator to fail to start based on DP-1633 (Dexter and Perkins 1982, page 17). The document EGG-SSRE-8875 (Eide et al. 1990, page 12) shows the failure of diesel-driven pumps to start on demand is 1 x 10^-2/demand. The more conservative value of 2.3 x 10^-2/demand will be used in this calculation. The probability that either of the two local exhaust fans will not start following the start of the backup diesel generator is 0.0005 (5 x 10^-4). The value of 5 x 10^-4 is based on fan failure to start probability of 5 x 10^-3/demand times a common cause beta factor of 0.1. The value of 5 x 10^-3/demand is the failure probability of a ventilator fan failure to start based on EGG-SSRE-8875, (Eide et al. 1990, page 19). Thus the probability that the diesel generator and one of the local exhaust fans not starting following LOEP is 0.0028 (2.8 x 10^-3) or \((2.3 \times 10^{-3}) + (5 \times 10^{-4}) = 0.0028\).

If the TWS flow through the cask–MCO annulus is lost AND the MCO becomes isolated AND SCHe system actuates applicable isolation valves to open AND
10 psig vent path of the SCHe system does not relieve the pressure from the MCO AND the 30 psig rupture disk is successful in relieving MCO pressure AND the backup diesel generator fails to start or one of two local exhaust fans fail to restart, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

Sequence 6

a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask–MCO annulus is not maintained AND the MCO is isolated is 0.0022 (2.2 x 10^-3). The value of 2.2 x 10^-3 is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of 2.2 x 10^-3 is calculated as (1-e^(-(1.22 yr^-1 yr^-16 h*yr^-1760 h)) = 2.2 x 10^-3) where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

b) Event SCHe ACTUATION: The probability that the SCHe valves will be actuated given an LOEP is 0.9999 (1-[1 x 10^-4]). The value of 1 x 10^-4 represents the common cause failure of either of the two applicable SCHe isolation valves failing to open on demand (1 x 10^-3/demand multiplied by a beta factor of 0.1). The value of 1 x 10^-3/demand is a value for a pneumatic valve failing to open on demand based on (Eide et al. 1990, page 11).

c) Event 10 PSIG: The probability that the pressure in the MCO is not relieved through the SCHe system 10 psig pressure relief path is 0.0003 (3 x 10^-4). The value of 3 x 10^-4 represents the failure of a safety valve to open on demand. The value of 3 x 10^-4/demand is based on EGG-8875 (Eide et al. 1990).

d) Event 30 PSIG: The probability that the pressure in the MCO is not relieved through the 30 psig rupture disk vent path is 0.003 (3 x 10^-3). The value of 3 x 10^-3 represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of 3 x 10^-3 is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.

e) Event 150 PSIG: The probability that the pressure in the MCO is relieved through the 150 psig rupture disk vent path is 0.997 (1-[3 x 10^-3]). The value of 3 x 10^-3 represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of 3 x 10^-3 is a value assigned to
If the TWS flow through the cask–MCO annulus is lost AND the MCO becomes isolated AND SCHe system actuates applicable isolation valves to open AND 10 psig vent path of the SCHe system does not relieve the pressure from the MCO AND the 30 psig rupture disk is not successful in relieving MCO pressure AND the 150 psig rupture disk is successful in relieving MCO pressure, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

**Sequence 7**  

**a)** Event TWS FLOW & UNISO: The probability that the TWS flow through the cask–MCO annulus is not maintained AND the MCO is isolated is 0.0022 (2.2 x 10^-3). The value of 2.2 x 10^-3 is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of 2.2 x 10^-3 is calculated as (1-e^(-1.22 yr^-1 16 hr yr^-1 760 hr)) = 2.2 x 10^-3 where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

**b)** Event SCHE ACTUATION: The probability that the SCHe valves will be actuated given an LOEP is 0.9999 (1-[1 x 10^-4]). The value of 1 x 10^-4 represents the common cause failure of either of the two applicable SCHe isolation valves failing to open on demand (1 x 10^-4/demand multiplied by a beta factor of 0.1). The value of 1 x 10^-3/demand is a value for a pneumatic valve failing to open on demand based on (Eide et al. 1990, page 11).

**c)** Event 10 PSIG: The probability that the pressure in the MCO is not relieved through the SCHe system 10 psig pressure relief path is 0.0003 (3 x 10^-4). The value of 3 x 10^-4 represents the failure of a safety valve to open on demand. The value of 3 x 10^-4/demand is based on EGG-8875 (Eide et al. 1990).

**d)** Event 30 PSIG: The probability that the pressure in the MCO is not relieved through the 30 psig rupture disk vent path is 0.003 (3 x 10^-3). The value of 3 x 10^-3 represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of 3 x 10^-3 is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.
e) Event 150 PSIG: The probability that the pressure in the MCO is not relieved through the 150 psig rupture disk vent path is 0.003 \((3 \times 10^{-3})\). The value of \(3 \times 10^{-3}\) represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of \(3 \times 10^{-3}\) is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.

If the TWS flow through the cask–MCO annulus is lost AND the MCO becomes isolated AND SCHe system actuates applicable isolation valves to open AND 10 psig vent path of the SCHe system does not relieve the pressure from the MCO AND the 30 psig rupture disk is not successful in relieving MCO pressure AND the 150 psig rupture disk is not successful in relieving MCO pressure, this results in a sequence that has a frequency beyond extremely unlikely (<1E-6/year).

Sequence 8

a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask–MCO annulus is not maintained AND the MCO is isolated is 0.0022 \((2.2 \times 10^{-3})\). The value of \(2.2 \times 10^{-3}\) is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of \(2.2 \times 10^{-3}\) is calculated as \(1 - e^{-\left(1.22 \times 10^{-9} \times 16 \times 3600\right)} = 2.2 \times 10^{-3}\) where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

b) Event SCHE ACTUATION: The probability that the SCHe valves will not be actuated given an LOEP is 0.0001 \((1 \times 10^{-4})\). The value of \(1 \times 10^{-4}\) represents the common cause failure of either of the two applicable SCHe isolation valves failing to open on demand \((1 \times 10^{-3}/\text{demand multiplied by a beta factor of 0.1)}\). The value of \(1 \times 10^{-3}/\text{demand}\) is a value for a pneumatic valve failing to open on demand based on (Eide et al. 1990, page 11).

c) Event 30 PSIG: The probability that the pressure in the MCO is relieved through the 30 psig rupture disk vent path is 0.997 \((1-[3 \times 10^{-3}])\). The value of \(3 \times 10^{-3}\) represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of \(3 \times 10^{-3}\) is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.

d) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path has HEPA filtration functioning during the release based on 4,380 h (the
average unavailability assuming tested once per year; 8,760 h/2) is 0.999943
\(1 - [1.3 \times 10^{-8}/h \times 4,380\ h]\). The value of \(1.3 \times 10^{-8}/h\) is the value for HEPA
filter failure related to a fuel reprocessing facility based on DP-1633 (Dexter
and Perkins 1982).

If the TWS flow through the cask–MCO annulus is lost AND the MCO becomes
isolated AND SCHe system does not actuate applicable isolation valves to open
AND the 30 psig rupture disk is successful in relieving MCO pressure AND the
HEPA filters function, this results in a release that is less than onsite guidelines.

Sequence 9

a) Event TWS FLOW & UNISO: The probability that the TWS flow through
the cask–MCO annulus is not maintained AND the MCO is isolated is 0.0022
\(2.2 \times 10^{-3}\). The value of \(2.2 \times 10^{-3}\) is the probability of LOEP per 16 h per
MCO that would be a common cause initiator that would shut down the TWS
pump and initiate a SCHe isolation and purge signal. It is conservatively
assumed that if the SCHe isolation is initiated the eight pneumatic isolation
valves will close, isolating the MCO with a probability of 1.0. The value of
\(2.2 \times 10^{-3}\) is calculated as \(1 - e^{-\left(1.22 \times 10^{16} \times 8760\right)} = 2.2 \times 10^{-3}\) where 1.22 LOEP
events per year is based on the average frequency of offsite power losses in
the 200 Areas over a 20-year period (1972 to 1992) as documented in
WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is
judged to be vulnerable to an LOEP for this sequence.

b) Event SCHE ACTUATION: The probability that the SCHe valves will not be
actuated given an LOEP is 0.0001 (1 \times 10^{-4}). The value of \(1 \times 10^{-4}\) represents
the common cause failure of either of the two applicable SCHe isolation
valves failing to open on demand \(1 \times 10^{-3}/\text{demand}\) multiplied by a beta factor
of 0.1). The value of \(1 \times 10^{-3}/\text{demand}\) is a value for a pneumatic valve failing
to open on demand based on (Eide et al. 1990, page 11).

c) Event 30 PSIG: The probability that the pressure in the MCO is relieved
through the 30 psig rupture disk vent path is 0.997 \(1 - [3 \times 10^{-3}]\). The value of
\(3 \times 10^{-3}\) represents the failure of the rupture disk to relieve at its design
pressure as a result of human error in the manufacture, procurement,
installation, and QA program. The value of \(3 \times 10^{-3}\) is a value assigned to
basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with
0.1 for a good QA program.

d) Event HEPA FILTER OK: The probability that the HEPA-filtered vent path
has no HEPA filtration functioning during the release based on 4,380 h (the
average unavailability assuming tested once per year; 8,760 h/2) is 0.000057
\(1.3 \times 10^{-8}/h \times 4,380\ h\). The value of \(1.3 \times 10^{-8}/h\) is the value for HEPA filter
failure related to a fuel reprocessing facility based on DP-1633 (Dexter and
Perkins 1982).
If the TWS flow through the cask-MCO annulus is lost AND the MCO becomes isolated AND SCHe system does not actuate applicable isolation valves to open AND the 30 psig rupture disk is successful in relieving MCO pressure AND the HEPA filters fail to function, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

**Sequence 10**

a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask-MCO annulus is not maintained AND the MCO is isolated is 0.0022 (2.2 x 10^-3). The value of 2.2 x 10^-3 is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of 2.2 x 10^-3 is calculated as (1-e^(-1.22 LOEP x yr^1.22 yr^8760h)) = 2.2 x 10^-3) where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

b) Event SCHE ACTUATION: The probability that the SCHe valves will not be actuated given an LOEP is 0.0001 (1 x 10^-4). The value of 1 x 10^-4 represents the common cause failure of either of the two applicable SCHe isolation valves failing to open on demand (1 x 10^-3/demand multiplied by a beta factor of 0.1). The value of 1 x 10^-3/demand is a value for a pneumatic valve failing to open on demand based on (Eide et al. 1990, page 11).

c) Event 30 PSIG: The probability that the pressure in the MCO is not relieved through the 30 psig rupture disk vent path is 0.003 (3 x 10^-3). The value of 3 x 10^-3 represents the failure of the rupture disk to relieve its pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of 3 x 10^-3 is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.

d) Event 150 PSIG: The probability that the pressure in the MCO is relieved through the 150 psig rupture disk vent path is 0.997 (1-[3 x 10^-3]). The value of 3 x 10^-3 represents the failure of the rupture disk to relieve its pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of 3 x 10^-3 is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.

If the TWS flow through the cask-MCO annulus is lost AND the MCO becomes isolated AND SCHe system does not actuate applicable isolation valves to open AND the 30 psig rupture disk is not successful in relieving MCO pressure AND
the 150 psig rupture disk is successful in relieving MCO pressure, this results in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

Sequence 11

a) Event TWS FLOW & UNISO: The probability that the TWS flow through the cask-MCO annulus is not maintained AND the MCO is isolated is 0.0022 ($2.2 \times 10^{-3}$). The value of $2.2 \times 10^{-3}$ is the probability of LOEP per 16 h per MCO that would be a common cause initiator that would shut down the TWS pump and initiate a SCHe isolation and purge signal. It is conservatively assumed that if the SCHe isolation is initiated the eight pneumatic isolation valves will close, isolating the MCO with a probability of 1.0. The value of $2.2 \times 10^{-3}$ is calculated as $(1-e^{-(1.22(16\text{h})/8760\text{h})}) = 2.2 \times 10^{-3}$ where 1.22 LOEP events per year is based on the average frequency of offsite power losses in the 200 Areas over a 20-year period (1972 to 1992) as documented in WHC-EP-0811 (Shultz 1994, page 4) and 16 h is the time period an MCO is judged to be vulnerable to an LOEP for this sequence.

b) Event SCHe ACTUATION: The probability that the SCHe valves will not be actuated given an LOEP is 0.0001 ($1 \times 10^{-4}$). The value of $1 \times 10^{-4}$ represents the common cause failure of either of the two applicable SCHe isolation valves failing to open on demand ($1 \times 10^{-4}$/demand multiplied by a beta factor of 0.1). The value of $1 \times 10^{-4}$/demand is a value for a pneumatic valve failing to open on demand based on (Eide et al. 1990, page 11).

c) Event 30 PSIG: The probability that the pressure in the MCO is not relieved through the 30 psig rupture disk vent path is 0.003 ($3 \times 10^{-3}$). The value of $3 \times 10^{-3}$ represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of $3 \times 10^{-3}$ is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.

d) Event 150 PSIG: The probability that the pressure in the MCO is not relieved through the 150 psig rupture disk vent path is 0.003 ($3 \times 10^{-3}$). The value of $3 \times 10^{-3}$ represents the failure of the rupture disk to relieve at its design pressure as a result of human error in the manufacture, procurement, installation, and QA program. The value of $3 \times 10^{-3}$ is a value assigned to basic operator errors (0.03) based on NUREG/CR-4772 (Swain 1987) with 0.1 for a good QA program.

If the TWS flow through the cask-MCO annulus is lost AND the MCO becomes isolated AND SCHe system does not actuate applicable isolation valves to open AND the 30 psig rupture disk is not successful in relieving MCO pressure AND the 150 psig rupture disk is not successful in relieving MCO pressure, this results
in a release that meets evaluation guidelines associated with the frequency of this sequence (OK).

A6.4 REFERENCES


<table>
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<th>Seq. #</th>
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A7.0 CLOSURE PACKAGE FOR FREQUENCY OF SHIPPING MULTI-CANISTER OVERPACKS TO THE CANISTER STORAGE BUILDING FROM THE COLD VACUUM DRYING FACILITY WITH GREATER THAN 200 GRAMS OF WATER

A7.1 SUMMARY

This closure package addresses the issue of the frequency of receiving an MCO at the Canister Storage Building (CSB) with greater than 200 g of water as a result of a process failure at the CVDF. The conclusion of this closure package is that the frequency of an MCO arriving at CSB with greater than 200 g of water as a result of a process failure at the CVDF is incredible (or less than $1 \times 10^{-6}$/year). The bases for this conclusion are the CVDF operational procedures, the processing rate of 200 MCOs per year, and the specific controls on calibration of tempered water temperature transmitters and responses to extensive drying times.

A7.2 STATEMENT OF THE ISSUE

The concern is that an MCO could arrive at CSB with more than 200 g of water as a result of a CVDF process failure. If the frequency of more water than has been assumed to be in an MCO upon arrival at CSB is NOT incredible (or NOT less than $1 \times 10^{-6}$/year), then additional measures may need to be taken to reduce the risk of this scenario. If an MCO can arrive at CSB containing more than the expected amount of water with a credible frequency, then the situation would be an unanalyzed safety scenario.

A7.3 BASIS OF CLOSURE

The basis for closure of this issue involves three parts:

- Identifying the possible ways that more than 200 g of water could be present in an MCO at CSB as a result of a process failure at CVDF

- Estimating the probability of greater than 200 g of water existing in an MCO at CSB based on the procedural steps to prevent that occurrence

- Recommending various procedural or administrative controls that would justify the frequency of an MCO with more than 200 g of water arriving at CSB as a result of a process failure at CVDF.

The identification of possible ways that more than 200 g of water could be present in an MCO at CSB involved multiple independent engineers identifying the failures that would have to occur to result in more water in an MCO than expected at CSB. A logic diagram was then constructed that included information identified by the independent engineers. The logic diagram
portrays in a graphical form the failures that would have to occur to result in more water in an MCO than expected at CSB.

Estimated probabilities are associated with the various failures represented on the logic diagram used to identify the possible ways that more than 200 g of water could be present in an MCO at CSB. These probabilities were combined with the rate of MCOs being shipped per year to represent an estimated frequency that more than 200 g of water could be present in an MCO at CSB from the identified pathways.

A7.4 DISCUSSION

Figure A7-1 shows the logic diagram in fault tree format for the possible ways that more than 200 g of water could be present in an MCO at CSB as a result of process failures at CVDF. This logic diagram represents the logic including procedural controls that must be protected to credit the probabilistic numbers used in the fault tree. Each box with a circle underneath, except the one representing the number of MCOs shipped per year, represents a failure that could contribute to that more than 200 g of water being present in an MCO at CSB. The failures are combined through logic gates, either AND gates (flat bottom, semicircle top) or OR gates (arched bottom and arrow head top). An AND gate means that all inputs to the gate from below are required to occur for the result represented in the box above the gate. An OR gate means that any one input to the gate from below is sufficient for the result represented in the box above the gate. The numbers associated with each box with a circle and with each gate are estimated individual probabilities or combined probabilities, respectively. The number under the top box represents the estimated frequency of an MCO arriving at CSB with more water than anticipated.

The estimated probabilities of failures resulting from water addition or instrument miscalibration are discussed in the following sections.

A7.4.1 Probability of Failures Related to Water Addition

Failure event T441, quick disconnect DI-QD-*110 was not disconnected as required, was given a probability of 3x10^-2. The value of 3.0 x 10^-2 is a value assigned to basic operator errors based on NUREG/CR-4772, Accident Sequence Evaluation Program Human Reliability Analysis Procedure (Swain 1987, Table 4-2, Note #2, page 4-5).

Failure event T442, the common-cause leakage failure of both gas operated valves GOV 1*11 and GOV 1*17 as a result of failure of backflush, was given a probability of 1 x 10^-6 in the 1-hour time period before the MCO is isolated by unhooking lines prior to shipment to CSB times a beta factor of 0.1. This value is based on internal leakage failure rate for a pneumatically operated valve at 1x10^-6/hr as given in EGG-SSRE-8875, Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs (Eide et al., page 11), multiplied by a 1-hour time at risk times a beta factor of 0.1. [Events T441 and T442 combine to result in the situation represented by gate T341 that water is added through the demineralized water system to
an MCO prior to shipment to CSB. This would result in an MCO arriving at CSB with more water (from very little extra water to an MCO full of water) than anticipated.]

Failure event T445, vacuum pumping system condenser VPS-COND-2*13 tubes leak into the condenser shell, was given a probability of $1 \times 10^{-2}$ assuming a highly conservative time at risk of 8,760 hours (1 year). This value is based on heat exchanger tube leakage failure rate at $1 \times 10^{-6}$/hr as given in EGG-SSRE-8875, p. 12, multiplied by an 8,760-hour time at risk.

Failure event T446, vacuum pumping system condenser isolation valve GOV-1*05 internally leaks, was given a probability of $8.8 \times 10^{-3}$ assuming a highly conservative time at risk of 8,760 hours (1 year). This value is based on pneumatic valve internal leakage failure rate at $1 \times 10^{-6}$/hr as given in EGG-SSRE-8875, p. 11, multiplied by an 8,760-hour time at risk.

Failure event T447, vacuum pumping system condenser isolation valve GOV-2*22 internally leaks, was given a probability of $8.8 \times 10^{-3}$ assuming a highly conservative time at risk of 8,760 hours (1 year). This value is based on pneumatic valve internal leakage failure rate at $1 \times 10^{-6}$/hr as given in EGG-SSRE-8875, p. 11, multiplied by an 8,760-hour time at risk.

Failure event T448, vacuum pumping system condenser isolation valve GOV-1*09 internally leaks, was given a probability of $2.5 \times 10^{-5}$ assuming a time at risk of 0.25 h (15 min, time prior to second rebound test). This value is based on pneumatic valve internal leakage failure rate at $1 \times 10^{-6}$/hr as given in EGG-SSRE-8875, p. 11, multiplied by an 0.25-h time at risk. [Events T445, T446, T447, and T448 combine to result in the situation represented by gate T342 that water is added through the vacuum pumping system to an MCO prior to shipment to CSB. This would result in an MCO arriving at CSB with more water (from very little extra water to an MCO full of water) than anticipated.]

The probabilities represented by gates T341 and T342 are summed to yield the probability of the situation represented by gate T211. Gate T211 represents water added to an MCO immediately prior to shipment to CSB. The probability representing gate T211 is multiplied by the number of MCOs per year that are processed to yield the frequency of MCOs with more than 200 g of water as a result of water additions represented by gate T10.

A7.4.2 Probability of Failure Related to Miscalibration

Failure event T213A, miscalibration of three temperature transmitters such that the transmitters read 46 °C when the tempered water is really less than 40 °C but greater than 31 °C, was given a probability of $5 \times 10^{-9}$. The value of $5 \times 10^{-9}$ is a value assigned to basic operator error and involving a post calibration test that would identify any significant miscalibration involving three components (temperature transmitters) based on NUREG/CR-4772 (Swain 1987, Table 5-5, Case VI for 3 components with high dependence and parallel systems, page 5-17).

Failure event T213B, operator fails to notice and respond to extensive drying time as indicated in step 36 of the CVDF Operations Manual, was given a probability of $3 \times 10^{-3}$. 

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The value of $3 \times 10^{-3}$ is a value assigned to basic operator error and an second person involved in the diagnosis of the extensive time for drying based on NUREG/CR-4772 (Swain 1987, Table 5-3, Case III, page 5-12).

[Events T213A and T213B combine to result in the situation represented by gate T213 that an MCO is processed but miscalibrations allows the MCO to pass rebound tests with more than 200 g water still inside the MCO. [This would result in an MCO arriving at the CSB with more water (but probably very little extra water) than anticipated.] The probability representing gate T213 is multiplied by the number of calibrations of the three tempered water temperature transmitters per year to yield the frequency of MCOs with more than 200 g of water as a result of miscalibrations represented by gate T11.

Based on the summation of the frequency of MCOs per year with more than 200 g water from either water additions or miscalibrations is represented by the frequency associated with the gate TOOMUCH. This frequency is about $8 \times 10^{-7}$/year.

A7.5 RECOMMENDATIONS

To protect the assumptions associated with the probabilities discussed above, two controls need to receive special attention. First, there must be a post-calibration test related to the tempered water temperature transmitters that will be capable of detecting miscalibration of the transmitters. Second, step 36 in the CVDF Operations Manual indicates that if extensive time is required to qualify for the initial pressure rebound test then a decision must be made and possible analysis performed as to the reason for the extended time to dry. Credit was given assuming at least one additional individual (other than the individual originally identifying the extended time frame) will be involved in the decision making process as to what subsequent actions should be taken.

A7.6 REFERENCES


Figure A7-1. Logic Diagram Showing the Circumstances that Would Allow More than 200 Grams of Water to be Present in a Multi-Canister Overpack at the Canister Storage Building as a Result of Failures at the Cold Vacuum Drying Facility.
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APPENDIX B

CALCULATIONS SUPPORTING THE ANALYSIS OF HYDROGEN EXPLOSIONS AT THE COLD VACUUM DRYING FACILITY
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**LIST OF TERMS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVDF</td>
<td>Cold Vacuum Drying Facility</td>
</tr>
<tr>
<td>HEPA</td>
<td>high-efficiency particulate air (filter)</td>
</tr>
<tr>
<td>HVAC</td>
<td>heating, ventilation, and air conditioning</td>
</tr>
<tr>
<td>MCO</td>
<td>multi-canister overpack</td>
</tr>
<tr>
<td>PWC</td>
<td>process water conditioning</td>
</tr>
<tr>
<td>SNF</td>
<td>spent nuclear fuel</td>
</tr>
<tr>
<td>TNT</td>
<td>trinitrotoluene</td>
</tr>
</tbody>
</table>
APPENDIX B

CALCULATIONS SUPPORTING THE ANALYSIS OF HYDROGEN EXPLOSIONS AT THE COLD VACUUM DRYING FACILITY

Parameters, assumptions, and calculations used in analyzing postulated hydrogen combustion accidents at the Cold Vacuum Drying Facility (CVDF) are presented in this appendix. The calculations presented include the following:

- Hydrogen generation rates
- Flammability limits for mixtures of hydrogen and helium in air
- Temperature and pressure that result from hydrogen combustion under adiabatic conditions
- Probability that a hydrogen explosion will harm an individual standing nearby
- Multi-canister overpack (MCO) particulate inventory and release factors
- MCO void space (when full of water) particulate inventory and release factors
- High-efficiency particulate air (HEPA) filter particulate inventory and release factors
- Particulate inventory for the process water conditioning (PWC) receiver tanks
- Mathematical model for connected tank spaces to represent gas concentrations in the MCO and PWC receiver tanks during MCO draining.

B1.0 HYDROGEN GENERATION RATES

Hydrogen is generated in the MCO primarily by corrosion of uranium in the spent nuclear fuel (SNF). Some additional hydrogen is generated by uranium hydride reactions. The radiolytic decomposition of water and water-containing chemicals generates very little hydrogen during the brief period the MCO is inside the CVDF. The chemical reactions of uranium metal and uranium hydride in water and in the presence of oxygen are listed below.
• Oxygen-free reactions:

\[ U + 2\cdot H_2O \rightarrow UO_2 + 2\cdot H_2 \]
\[ 2\cdot UH_3 + 4\cdot H_2O \rightarrow 2\cdot UO_2 + 7\cdot H_2 \]

• Reactions in the presence of oxygen:

\[ U + O_2 \rightarrow UO_2 \]
\[ 4\cdot UH_3 + 7\cdot O_2 \rightarrow 4\cdot UO_2 + 6\cdot H_2O \]
\[ 2\cdot UH_3 + 2\cdot O_2 \rightarrow 2\cdot UO_2 + 3\cdot H_2 \text{ (weak)} \]

Note that when uranium hydride reacts with oxygen, it is more likely to produce water than hydrogen.

B1.1 HYDROGEN GENERATION WITHOUT OXYGEN PRESENT

The oxygen-free corrosion rate in the absence of uranium hydrides is shown in the equations below (HNF-SD-SNF-TI-015). The fuel temperature in all cases is less than 100°C. Equation B-1 describes corrosion of uranium immersed in water.

\[
\log(K_{\text{WET}}) = 7.634 - 3016/T_{\text{FUEL}}
\] (B-1)

and Equation B-2 describes corrosion of uranium immersed in oxygen-free, moist gases

\[
\log(K_{\text{MOIST}}) = 4.33 - 2144/T_{\text{FUEL}} + 0.5\cdot\log(P_{\text{SAT}}) \] (B-2)
\[
\log(P_{\text{SAT}}) = 7.07406 - 1657.46/(T_{\text{GAS}} - 46.11)
\]

where

\[ K_{\text{WET}} = \text{weight gain resulting from oxygen-free corrosion in saturated conditions} \]
\[ (\text{mg/h/cm}^2) \]

\[ K_{\text{MOIST}} = \text{weight gain resulting from oxygen-free corrosion under unsaturated conditions} \]
\[ (\text{mg/h/cm}^2) \]

\[ T_{\text{FUEL}} = \text{temperature of the uranium metal (Kelvin)} \]

\[ T_{\text{GAS}} = \text{average temperature of the gases in the MCO (Kelvin)} \]

\[ P_{\text{SAT}} = \text{saturated vapor pressure of water at the temperature of the gas (kPa)} \]

\[ H = \text{relative humidity of the water vapor (fraction)} \]
The method shown to approximate the saturation vapor pressure of water ($P_{\text{sat}}$) comes from *Chemical Process Safety Fundamentals with Applications* (Crowl and Louvari 1990).

Weight gain formulas are equivalent to hydrogen generation rates because each mole of oxygen is accompanied by the liberation of a certain number of moles of hydrogen gas. The bounding MCO with two scrap baskets has 120,000 cm$^2$ of exposed surface area (HNF-SD-SNF-TI-015). Fuel reaction area enhancement factors are included in the weight gain formulas to account for the increased surface area caused by corrosion as well as the increased reaction rate caused by radiation effects and uranium hydride reactions. Without the uranium hydrides participating in the reaction, the enhancement factor is 10 (HNF-SD-SNF-TI-015). Note that 2 gmoles of hydrogen gas are liberated for every 32 g of oxide weight gain (0.0625 gmoles H$_2$ per gram weight gain). The overall bounding rate at which hydrogen is liberated in the absence of hydride reactions (in gmoles per hour) is shown in Equation B-3. The only reaction that is limited by not having hydride reactions is the wet corrosion reaction.

$$\text{Rate}_{\text{WET}} = (K_{\text{WET}})(120,000 \text{ cm}^2)(10)(0.0625 \text{ gmoles H}_2 \text{ per g gain}). \quad (B-3)$$

When uranium hydride is included, the bounding weight gain formula is unchanged, but the enhancement factor increases from 10 to 22. The increase of 12 is attributed to uranium hydride reactions. Uranium hydride reactions with water liberate 3.5 gmoles of hydrogen for every 29 g of weight gain. This 29 g comes from the difference in formula weights between UO$_2$ and UH$_3$. Thus the weighted average when hydride reactions are included is 0.094 gmoles of hydrogen liberated per gram of weight gain. The average calculation is shown below.

$$\frac{(10) \left( \frac{2 \text{ gmoles}}{32 \text{ g}} \right) + (12) \left( \frac{3.5 \text{ gmoles}}{29 \text{ g}} \right)}{10 + 12} = 0.094 \text{ gmoles H}_2 \text{ per gram gain}.$$  

The overall bounding rate at which hydrogen is liberated, including the hydride reaction, is shown in Equation B-4.

$$\text{Rate}_{\text{MOIST}} = (K_{\text{MOIST}})(120,000 \text{ cm}^2)(22)(0.094 \text{ gmoles H}_2 \text{ per g gain}). \quad (B-4)$$

Three examples illustrate how these formulas are used to estimate hydrogen generation at the CVDF. The first example is an estimate of the total amount of hydrogen generated in a bounding MCO during shipment from K Basins to the CVDF on a hot day. The second is an estimate of hydrogen generation during draining of the MCO. The third is an estimate of hydrogen generation rates in the MCO during drying operations.
B1.1.1 Hydrogen Generated during Shipment from the K Basins

Temperatures in the MCO during shipment from the K Basins to the CVDF depend on the time elapsed (HNF-SD-TP-SARF-017). This temperature-versus-time is also used to derive an estimate of the amount of particulate that forms after washing at K Basins (HNF-SD-W441-CN-001). The temperatures used are shown in Table B-1. Also shown in Table B-1 is the total number of moles of hydrogen that accumulate in the void space during shipment. Equations B-1 and B-3 have been used to calculate the values in Table B-1.

Table B-1. Bounding Hydrogen Generated During Shipment to the Cold Vacuum Drying Facility.

<table>
<thead>
<tr>
<th>Elapsed time (hours)</th>
<th>Fuel temperature (°C)</th>
<th>$K_{WET}$ (µg/cm²/h)</th>
<th>Hydrogen generated (gmoles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>15</td>
<td>1.47</td>
<td>0.22</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>1.60</td>
<td>0.58</td>
</tr>
<tr>
<td>8</td>
<td>17</td>
<td>1.74</td>
<td>0.97</td>
</tr>
<tr>
<td>11</td>
<td>23</td>
<td>2.82</td>
<td>1.60</td>
</tr>
<tr>
<td>14</td>
<td>29</td>
<td>4.49</td>
<td>2.61</td>
</tr>
<tr>
<td>17</td>
<td>35</td>
<td>7.02</td>
<td>4.20</td>
</tr>
<tr>
<td>21</td>
<td>36</td>
<td>7.55</td>
<td>6.46</td>
</tr>
<tr>
<td>24</td>
<td>37</td>
<td>8.12</td>
<td>8.29</td>
</tr>
</tbody>
</table>

The bounding shipment is a multi-canister overpack with two scrap baskets on a hot day with a reaction enhancement factor of 10. Hydride decomposition is not included.

B1.1.2 Hydrogen Generated during Multi-Canister Overpack Draining

While the fuel is covered with water, the hydrogen generation rate is based on $K_{WET}$. To simplify modeling of the hydrogen generation, it is assumed that no hydrides can react to form additional hydrogen while the MCO is full of water. The reaction forming hydrides dominates over the reaction decomposing them. The enhancement factor is therefore 10. Once the fuel is uncovered, the reaction rate is based on the water vapor in the helium blanketing the MCO, and uranium hydride reactions that liberate hydrogen gas are allowed. Equation B-5 represents the total hydrogen generated inside the MCO during draining. It is derived by summing the time-integrals of the hydrogen generation rates for corrosion in water and water vapor. It is assumed that water is removed from the MCO at a constant rate during draining.

$$\text{Total } H_2 = (t)(\text{Rate}_{WET}) + (\text{Rate}_{MOIST} - \text{Rate}_{WET})(0.5)(t^2)/(t_{drain}) \quad (B-5)$$
where

\[
\text{Total } H_2 = \text{ total hydrogen generated inside the MCO during draining} \\
\text{t} = \text{ elapsed time since the start of draining (hours)} \\
\text{Rate}_{\text{WET}} = \text{ rate at which corrosion occurs when liquid water is in contact with the SNF (2.86 gmole/h, } T_{\text{FUEL}} = 60 ^\circ \text{C)} \\
\text{Rate}_{\text{MOIST}} = \text{ rate at which corrosion occurs when water vapor is in contact with the SNF (6.86 gmole/h, } T_{\text{GAS}} = 50 ^\circ \text{C with 100% relative humidity)} \\
\text{t}_{\text{drain}} = \text{ time required to remove most water from the MCO (0.5 hours).}
\]

Table B-2 shows the bounding hydrogen concentration in the MCO during draining. It is assumed that the gas pressure during draining is 4 lb/in\(^2\) gauge and that the initial gas volume of the MCO is 21.9 L. After the water is drained, the gas volume of the MCO is 500 L. The fuel temperature is 50 ^\circ \text{C and the gas temperature is 50 ^\circ \text{C during draining.}

<table>
<thead>
<tr>
<th>Elapsed time (hours)</th>
<th>MCO contents (liters)</th>
<th>Amount of each gas (gmoles)</th>
<th>Hydrogen concentration (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water</td>
<td>Gas</td>
<td>H(_2)</td>
</tr>
<tr>
<td>0.0</td>
<td>500.0</td>
<td>21.9</td>
<td>0.52</td>
</tr>
<tr>
<td>0.1</td>
<td>404.4</td>
<td>117.5</td>
<td>0.70</td>
</tr>
<tr>
<td>0.2</td>
<td>308.8</td>
<td>213.1</td>
<td>0.94</td>
</tr>
<tr>
<td>0.3</td>
<td>213.1</td>
<td>308.8</td>
<td>1.23</td>
</tr>
<tr>
<td>0.4</td>
<td>117.5</td>
<td>404.4</td>
<td>1.58</td>
</tr>
<tr>
<td>0.5</td>
<td>21.9</td>
<td>500.0</td>
<td>1.98</td>
</tr>
</tbody>
</table>

The assumed fuel temperature is 50 ^\circ \text{C. The assumed MCO gas temperature is 50 ^\circ \text{C. The relative humidity in the MCO is 100%. MCO pressure is maintained at 4 lb/in\(^2\) gauge. MCO gas volume is assumed to be 21.9 L initially and 500 L at the conclusion. The hydrogen concentration at the start of draining is assumed to be 50%.

MCO = multi-canister overpack.
Note that the initial hydrogen concentration in the MCO at the start of draining is 50%. This assumption is necessary because the predrain purge of the MCO may not be effective at reducing hydrogen in the MCO. The predrain purge of the MCO uses a 20% variation in absolute pressure (1 lb/in² gauge to 4 lb/in² gauge). In addition, the line volume is similar to the 21.9-L MCO volume. Thus the gas moving into the MCO during the predrain purge is not pure helium.

To illustrate the effect of various initial concentrations of hydrogen on the concentration during draining, the calculations used for Table B-2 were repeated at other initial MCO hydrogen concentrations. Results are shown in Table B-3. Note that the number of moles of helium is much larger than the number of moles of hydrogen. Consequently, the hydrogen concentrations at the end of draining are within 4% of each other.

<table>
<thead>
<tr>
<th>Elapsed time (hours)</th>
<th>Starting hydrogen concentration after pre-drain purge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>0.0</td>
<td>10.0%</td>
</tr>
<tr>
<td>0.1</td>
<td>5.0%</td>
</tr>
<tr>
<td>0.2</td>
<td>5.1%</td>
</tr>
<tr>
<td>0.3</td>
<td>5.5%</td>
</tr>
<tr>
<td>0.4</td>
<td>6.0%</td>
</tr>
<tr>
<td>0.5</td>
<td>6.5%</td>
</tr>
</tbody>
</table>

The fuel and gas temperatures are both assumed to 50 °C. The pressure in the multi-canister overpack is maintained at 4 lb/in² gauge during draining.

B1.1.3 Hydrogen Generated during Vacuum Drying

It is assumed that during vacuum drying the average MCO fuel temperature is 60°C and the average MCO gas temperature is 50°C. At that gas temperature, the water vapor pressure at 100% humidity (saturation) is 12.3 kPa. Assuming the relative humidity in the MCO is 50%, the weight gain formula (Equation B-2) predicts that $K = 19.5 \mu g/cm^2/h$. From the hydrogen generation rate formula that includes hydride reactions (Equation B-4), the total hydrogen generation rate is 4.85 gmoles $H_2$ per hour. At 10% and 100% relative humidities, the hydrogen generation rates are 2.17 gmoles $H_2$ per hour and 6.86 gmoles $H$ per hour, respectively.

The volume or pressure of a quantity of gas is computed using the ideal gas law, shown below. This formula shows the simple relationship between the pressure, volume, and temperature of a given number of moles of the gas.

\[(P)(V) = (n)(R)(T)\]
where

\[ P = \text{pressure of the gas (atm } [1 \text{ atm} = 101.325 \text{ kPa}]) \]
\[ V = \text{volume of the gas (liters)} \]
\[ n = \text{number of moles of the gas (gmoles)} \]
\[ R = \text{gas constant } (0.082057 \text{ L.atm/gmole/K}) \]
\[ T = \text{temperature of the gas (Kelvin)}. \]

**B1.2 HYDROGEN GENERATION RATES WITH OXYGEN PRESENT**

The presence of oxygen slows the corrosion rates of uranium and uranium hydride. Moist air (i.e., with oxygen) corrosion rates in the absence of uranium hydrides are shown in the equations below. The fuel temperature in all cases is less than 100 °C. Equation B-6 describes corrosion of uranium for most relative humidities, while Equation B-7 describes corrosion of uranium under conditions of 100% relative humidity.

\[
\log(K_{\text{AIR}}) = 13.8808 - 5769.9/T_{\text{FUEL}} \tag{B-6}
\]

\[
\log(K_{\text{HUMID}}) = 8.333 - 3730/T_{\text{FUEL}} \tag{B-7}
\]

where

\[ K_{\text{AIR}} = \text{weight gain due to moist air corrosion when the relative humidity is between 11\% and 75\% (mg/h/cm}^2) \]
\[ K_{\text{HUMID}} = \text{weight gain due to moist air corrosion when the relative humidity is 100\% (mg/h/cm}^2) \]
\[ T_{\text{FUEL}} = \text{temperature of the uranium metal (Kelvin)}. \]

The moist air weight gain formulas (Equations B-6 and B-7) represent essentially no hydrogen generation. As before, the enhancement factor is 10 (HNF-SD-SNF-TI-015) in the absence of uranium hydrides. Note that no hydrogen gas is liberated along with the oxide weight gain (see the chemical equations in Section B1.0). When the uranium hydride is included, the weight gain formula is unchanged, but the enhancement factor increases from 10 to 22. The increase of 12 is attributed to uranium hydride reactions. The hydrogen-producing chemical reaction is weak, as noted in the chemical equations in Section 1.0. To quantify the term “weak”, it can be argued on the basis of free energy (SNF-3650, Section 3.3) that about 15\% of the hydride molecules react with oxygen to form hydrogen. The other 85\% of the uranium hydride and oxygen reactions produce water vapor. Thus, the average uranium hydride reaction with oxygen liberates 0.225 gmoles of hydrogen for every 29 grams of weight gain. Equivalently, the hydrogen production rate is 0.0078 gmoles of hydrogen liberated per gram of weight gain.
The overall rate at which hydrogen is liberated (in gmole per hour) is shown in the equations below. Equation B-8 applies to ordinary corrosion of uranium without hydride reactions. Equation B-9 includes the hydride reaction in a long-term average.

\[
\text{Rate}(\text{H}_2, \text{no hydride}) = 0 \text{ gmole H}_2 \text{per gram gain} \quad (B-8)
\]

\[
\text{Rate}(\text{H}_2, \text{total}) = (K)(120,000 \text{ cm}^2)(12)(0.0078 \text{ gmole H}_2 \text{per gram gain}) \quad (B-9)
\]

As an example, consider hydrogen generation rates during vacuum drying operations if there were significant air in the MCO. It is assumed that the average MCO fuel temperature is 60°C. Assuming the relative humidity in the MCO is 100%, the weight gain formula (Equation B-7) predicts that \( K = 1.37 \mu\text{g/cm}^2/\text{h} \). From the hydrogen generation rate formula that includes hydride reactions (Equation B-9), the total hydrogen generation rate is 0.015 gmoles \( \text{H}_2 \) per hour. Note that this is 460 times smaller than the hydrogen produced in the absence of oxygen at 100% relative humidity (i.e., 6.86 gmoles \( \text{H}_2 \) per hour). If an accident allows oxygen into the MCO, additional hydrogen generation is effectively halted.

**B2.0 FLAMMABILITY LIMITS FOR MIXTURES OF HYDROGEN AND HELIUM IN AIR**

In all postulated accident sequences involving flammable concentrations of hydrogen, hydrogen has accumulated because of processing delays, equipment malfunctions, or catastrophic events. The three conditions necessary for this accumulation in a reasonable time frame are uranium metal, water, and elevated temperatures: the uranium and water are reactants, and the elevated temperature speeds the reaction. The combustion sequence begins when enough hydrogen has accumulated. Next, the accumulated hydrogen mixes with oxygen (usually in air) to form a combustible mixture of hydrogen and air. Finally, this mixture is ignited. Since 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 within ventilation ducting, a small particle of uranium hydride, static electricity in spray nozzles, or other sources.

One method used at CVDF for preventing flammable mixtures of hydrogen and oxygen is to dilute the hydrogen with helium to reduce the hydrogen concentration in the gaseous mixture. When the helium and hydrogen mix with air, the concentration of the hydrogen is reduced to the point that the gas is not flammable. The upper and lower limits of flammability, as reported in *Limits of Flammability of Gases and Vapors* (Coward and Jones 1952), are shown in Table B-4. The last line on Table B-4 shows the lowest concentration of hydrogen in helium that can burn is 8.7%. This hydrogen–helium mixture needs to be added to air in large amounts (69.8% \( \text{H}_2 \) and helium, 30.2% air) to be combustible. If the hydrogen concentration is less than 8.7%, the hydrogen–helium mixture will not burn when mixed with air regardless of how much is added.
Table B-4. Flammability Limits for Mixtures of Hydrogen and Helium in Air.

<table>
<thead>
<tr>
<th>Gas mixture</th>
<th>Flammability of mix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>Hydrogen 100.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>58.1%</td>
<td>41.9%</td>
</tr>
<tr>
<td>27.9%</td>
<td>72.1%</td>
</tr>
<tr>
<td>19.3%</td>
<td>80.7%</td>
</tr>
<tr>
<td>10.7%</td>
<td>89.3%</td>
</tr>
<tr>
<td>8.7%</td>
<td>91.3%</td>
</tr>
</tbody>
</table>

Values shown for gases at atmospheric pressure are from Coward, H. F., and G. W. Jones, 1952, Limits of Flammability of Gases and Vapors, Bulletin 503, U.S. Bureau of Mines, Washington, D.C. The first two columns show the relative amounts of hydrogen and helium and sum to 100%. The last two columns show how much of this mixture must be added to air to be combustible.

The concentration of each gas in a flammable mixture can be computed assuming that air is composed of 20.8% oxygen and 79.2% nitrogen. These compositions are shown in Table B-5. From Table B-5 it is clear that low hydrogen concentrations require high oxygen concentrations to burn. Similarly, large hydrogen concentrations will burn with very little oxygen. Table B-5 defines the minimum concentrations of hydrogen and oxygen that will burn. Note that the smallest values for either hydrogen or oxygen are about 4%. When both the oxygen and hydrogen concentrations are small at the same time, the minimum is around 6%. The values shown in Table B-5 are plotted in Figure B-1.

**B3.0 TEMPERATURES AND PRESSURES CAUSED BY HYDROGEN DEFLAGRATION**

Mixtures of hydrogen in air are flammable in the range of 4% to 72% hydrogen by volume at atmospheric pressure and room temperature (see Table B-5). Higher pressures and temperatures change the flammable concentration range slightly, but the concentration limits at standard temperature and pressure are assumed for simplicity. Very damaging shock waves may be produced if the hydrogen concentration is between 18% and 58% in air (NUREG/CR-2726). The chemical equation describing the combustion of hydrogen and oxygen mixtures is shown below.

\[ 2 \cdot \text{H}_2 + \text{O}_2 \rightarrow 2 \cdot \text{H}_2\text{O}. \]
Table B-5. Flammable Concentrations After Mixing.

<table>
<thead>
<tr>
<th>Hydrogen</th>
<th>Oxygen</th>
<th>Nitrogen</th>
<th>Helium</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.20%</td>
<td>19.93%</td>
<td>75.87%</td>
<td>0.00%</td>
</tr>
<tr>
<td>4.13%</td>
<td>19.32%</td>
<td>73.58%</td>
<td>2.97%</td>
</tr>
<tr>
<td>4.69%</td>
<td>17.31%</td>
<td>65.89%</td>
<td>12.11%</td>
</tr>
<tr>
<td>4.81%</td>
<td>15.62%</td>
<td>59.48%</td>
<td>20.09%</td>
</tr>
<tr>
<td>5.49%</td>
<td>10.13%</td>
<td>38.57%</td>
<td>45.81%</td>
</tr>
<tr>
<td>6.07%</td>
<td>6.28%</td>
<td>23.92%</td>
<td>63.73%</td>
</tr>
<tr>
<td>8.59%</td>
<td>4.10%</td>
<td>15.60%</td>
<td>71.71%</td>
</tr>
<tr>
<td>15.67%</td>
<td>3.91%</td>
<td>14.89%</td>
<td>65.53%</td>
</tr>
<tr>
<td>22.10%</td>
<td>4.33%</td>
<td>16.47%</td>
<td>57.10%</td>
</tr>
<tr>
<td>44.27%</td>
<td>4.95%</td>
<td>18.85%</td>
<td>31.93%</td>
</tr>
<tr>
<td>71.50%</td>
<td>5.93%</td>
<td>22.57%</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

It is assumed that air is composed of 20.8% oxygen and 79.2% nitrogen. The minor components of air have been ignored.

The stoichiometric ratio (2 moles hydrogen per 1 mole of oxygen) corresponds to 29.4% 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 22.7%.

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 caused by 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. If the concentration of hydrogen or oxygen is low (near the minimum flammable), the efficiency is reduced. The heat capacity of various gases is calculated from the quadratic formula using the parameters listed in Table B-6.
Table B-6. Method to Calculate Heat Capacities of Gases.

<table>
<thead>
<tr>
<th>Gas</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>4.959</td>
<td>-1.96 E-04</td>
<td>4.76 E-07</td>
</tr>
<tr>
<td>N₂</td>
<td>4.470</td>
<td>1.39 E-03</td>
<td>-6.90 E-08</td>
</tr>
<tr>
<td>O₂</td>
<td>4.130</td>
<td>3.17 E-03</td>
<td>-1.01 E-06</td>
</tr>
<tr>
<td>H₂O</td>
<td>5.149</td>
<td>2.64 E-03</td>
<td>4.59 E-08</td>
</tr>
<tr>
<td>He</td>
<td>3.020</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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, J. C., and R. K. 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 for hydrogen, nitrogen, and water vapor are overestimated and the final temperature and pressure are underestimated. The opposite is true for oxygen heat capacities.

The final temperature of the gas mixture is found using Equation B-10. 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.

\[
\frac{T_f}{T_o} = \int \left[ \sum (C_{v,x})(N_x) \right] (dT)
\]

where

\( \epsilon \) = combustion efficiency, the fraction of the limiting reactant (hydrogen or oxygen) that actually reacts

\( H_F \) = 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; either the number of moles of hydrogen or twice the number of moles of oxygen, whichever is smaller (before combustion)

\( T_o \) = temperature of the gas mixture before combustion, (Kelvin)
\[ T_f = \text{temperature of the gas mixture after combustion (Kelvin)} \]

\[ C_{VX} = \text{heat capacity at constant volume of gas "X" (depends on the temperature of the gas represented as a quadratic equation)} \]

\[ N_x = \text{number of moles of gas "X" after the oxygen and hydrogen react} \]

\[ dT = \text{temperature increment used in the integral (Kelvin).} \]

An example calculation is provided in Section B10.0 for a free-air explosion following a sudden release of hydrogen gas into the process bay.

The hydrogen combustion descriptions found in NUREG/CR-2726, *Light Water Reactor Hydrogen Manual* (1983) provide additional insight into potential combustion effects at concentrations that barely burn, and at concentrations that produce shock waves. These observations are summarized below.

1. Below 8% hydrogen in air, the combustion is incomplete. In addition, the flame speed is low enough that heat transfer reduces the gas temperature. Both effects lead to smaller pressure increases. (pages 2-42 and 2-45).

2. For detonations, the dimensions of the combustion volume may prevent the formation of detonation shock waves (pages 2-51 to 2-54). Propagation down a tube requires that the tube diameter be greater than 1/3 "cell width". Detonation propagation from a tube or duct into a larger volume requires the tube have a diameter greater than 13 "cell widths" and the duct greater than 11 "cell widths" (square) or 3 "cell widths" (wide duct). A graph of cell widths for various hydrogen concentrations in air is given on page 2-52 of NUREG/CR-2726. Near stoichiometric (30% hydrogen) mixtures have a cell width of about 0.6 inch.

3. "The detonation wave is composed of unsteady oblique shock waves moving in an ever changing cellular structure (characterized by it transverse dimension), a 'foamy' detonation front." In addition, reflections from hard surfaces lead to considerable time dependence for the pressure.

4. NUREG/CR-2726 is concerned with detonations inside reactor containment structures, which offer considerably more open volume and larger dimensions than an MCO loaded with baskets of SNF. Homogeneous mixtures and normally incident shock waves are used for the detonation pressure graphs on pages 2-56 and 2-57.

In the case of hydrogen combustion within an MCO, the time interval between formation of a combustible gas mixture and its ignition allows diffusion and mixing of the gases to produce a homogeneous mixture. However, the MCO has little free space for detonation waves to form, propagate, and damage the confinement boundary. The bottom scrap basket has copper fins which are approximately 0.25 inch from the MCO wall. The bottom of the bottom scrap basket is
within an inch from the MCO bottom plate. The fuel baskets have aluminum walls for the lower 1/3 of the distance between baskets, and are filled with fuel, which occupies most of the remaining space. The top of the MCO is protected by a stainless steel guard plate. Thus, a detonable mixture of hydrogen and oxygen in the MCO cannot form shock waves over the entire surface of the MCO. In those places where reflected shock waves exist, the peak pressure listed in NUREG/CR-2726 (37 atm, or 529 lb/in² gauge) could be reached. However, the MCO can withstand pressures to 39 atm (562 lb/in² gauge) (see HNF-SD-SNF-SARR-005, Section 2.2.6.2).

B4.0 PROBABILITY OF HARM TO NEARBY PERSONNEL

Considerable uncertainty is inherent in predicting the degree to which an individual is harmed by a nearby explosion. Response-versus-dose relationships exist for a variety of hazards, including pressure, heat, impact, and sound. The "probit" method is used here. "Probit" comes from "probability unit". The probit variable (Y) is related to the probability variable (P) by the following formula (Crowl and Louvar 1990):

\[
P = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\infty} \exp(-u^2/2) \, (du)
\]

\[
Y = k_1 + (k_2)(\ln V)
\]

where

- \( P \) = probability that a particular hazard (e.g., death) will be realized from the exposure, V
- \( Y \) = probit variable for a particular hazard (mean value of 5 and a standard deviation of 1)
- \( k_1, k_2 \) = constant parameters for a particular hazard (as shown on Table B-7)
- \( u \) = integration variable.

Examples for three hazards are given in Table B-7. The first two (death from lung hemorrhage and eardrum rupture) depend on the peak pressure at the location of the individual (pascal [V]). The third example (death by impact) depends on the impulse per unit area imparted to the individual (in pascal-seconds).
The calculation of peak pressure and impulse per unit area are typically done using a scaled distance approach that begins with an estimate of trinitrotoluene (TNT) equivalence for the explosion. The adiabatic temperature and pressure from the combustion apply to the burning gas mixture itself. It is assumed that the nearest individual is a few feet from the burning gas. The actual steps in the calculation are as follows (Crowl and Louvar 1990, page 185):

1. Compute the energy liberated by the combustion
2. Convert the energy to an equivalent amount of TNT
3. Use the scaled distance to estimate pressure
4. Use the scaled distance to estimate impulse per unit area
5. Use the probit method to estimate likely effects.

Energy Liberated by Combustion. The energy liberated by the combustion is based on the number of moles of hydrogen and oxygen that burn and the heat of formation of water vapor (57,800 cal/mole).

Equivalent Amount of Trinitrotoluene. The conversion to TNT begins with the simple thermal equivalent for TNT (i.e., 1,120 cal/g TNT). It then adds an efficiency factor to include differences between TNT and flammable gas clouds. When TNT explodes, essentially 100% of the material is consumed. However, when mixtures of gases burn, less than 100% is consumed simply because the concentration is not uniform throughout the cloud. A portion of the mixture is below the flammable limit. An additional difference between TNT and gas mixtures is that the TNT burns much faster. A review of analytical methods by the Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs (Center for Chemical Process Safety 1994), suggests that a conservative value for TNT equivalency is 20%.

Pressure at the Location of the Receptor. The pressure at the location of the individual is estimated using the scaled distance. The scaled distance is computed as the effective distance of the individual from the explosion divided by the cube root of the equivalent mass of TNT. The distance from the explosion is the distance from a point source. Since a cloud of gas is not a point source, the distance from the blast is taken to be the sum of the radius of a spherical volume of
gas plus the distance from the outside of the sphere to the individual. A spherical shape is assumed to simplify modeling and to represent the bounding case shape. More realistic shapes could be expected to exhibit lower burning efficiencies because the relative concentrations of hydrogen and oxygen would vary from place to place in the plume. As a result, the combustion would react less than 100% of the available hydrogen and oxygen. Thus a spherical shape is likely to be bounding.

Scaled distance, \( D_s = \text{(distance from blast)}/(\text{mass TNT})^{1/3} \).

Pressures are estimated using empirically based graphs (Crowl and Louvar 1990, page 185). The graph, in metric units, is represented with the fourth-order polynomial shown below.

\[
\ln(P_{\text{over}}) = (a)[\ln(D_s)]^4 + (b)[\ln(D_s)]^3 + (c)[\ln(D_s)]^2 + (d)[\ln(D_s)] + (e)
\]

where

- \( P_{\text{over}} \) = peak pressure (kPa gauge)
- \( D_s \) = scaled distance (m/kg\(^{1/3}\))
- \( a, b, c, d, e \) = constants to represent the graph in Crowl and Louvar (1990, page 185)
  - \( a = -0.048076 \)
  - \( b = 0.293691 \)
  - \( c = -0.199471 \)
  - \( d = -2.42227 \)
  - \( e = 6.68589 \)

**Impulse per Unit Area at the Location of the Receptor.** This impulse is an indicator of harm since it represents a transfer of momentum from the pressure wave to the individual. If enough momentum is transferred, the individual can be killed. The impulse, or momentum, imparted to the individual affected by the pressure pulse is computed as the time-integral of the force acting on the person. The force applied to the person is the pressure times the area is applied to. As a simple approximation, the pressure is assumed to rise linearly to the peak and then fall linearly back to where it started. An estimate of how long the force exists can be obtained from the formula shown below for the rate of pressure increase (SFPE 1992).

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

where

- \( (dP/dt)_{\text{max}} \) = 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 burning gases (m\(^3\)).
Dividing the overall 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 can be multiplied by the peak force applied to an individual to estimate the total impulse. The impulse per unit area is the total impulse divided by the area used.

\[ J = (1,000 \text{ Pa/kPa})(P_{\text{over}})^2(V^{1/3})/(K_G) \]

where

- \( J \) = impulse imparted to an individual per unit area (Pa·s)
- \( P_{\text{over}} \) = peak pressure (kPa gauge)
- \( K_G \) = parameter measured for explosions in spherical containers (for hydrogen this is 66,000 kPa·m/s [SFPE 1992])
- \( V \) = volume of the flammable gas mixture before combustion (m³).

**Probit Variable for Likely Effect.** The final step is to calculate the probit variable for the biological effect of interest and convert this to a probability. The formula and parameters for this calculation were shown above. Note that for lung hemorrhage and eardrum rupture, the dose variable \( V \) must have units of pascals. Thus, for these indicators, the dose variable is computed as \( J = (1,000 \text{ Pa/kPa})(P_{\text{over}}) \). For death from impact, the dose variable \( V \) must have units of pascal-seconds. Thus for this indicator, the dose variable equals the impulse per unit area, \( V = J \).

Conversion of the probit variable to probability uses Equation B-11. A convenient formula to approximate the integral from \(-\infty\) is shown below (Abramowitz and Stegun 1965).

\[ P = (X)(a + (X)(b + (X)(c))(2\pi)^{1/2}\text{Exp}[-(Y-5)^2/2] \]

If \( Y < 5 \) then \( X = [1 - (d)(Y-5)]^{-1} \) and \( P = F(X) \)

If \( Y > 5 \) then \( X = [1 + (d)(Y-5)]^{-1} \) and \( P = 1 - F(X) \)

where

- \( P \) = probability of a particular biological effect associated with the probit variable \( Y \)
- \( Y \) = probit variable for a particular hazard (described above)
- \( a, b, c, d \) = constants to represent the integral of the gaussian distribution
  - \( a = 0.4361836 \)
  - \( b = -0.1201676 \)
  - \( c = 0.937298 \)
  - \( d = 0.33267 \)
An example calculation is provided in Section B10.0 for a free-air explosion following a sudden release of hydrogen gas into the process bay.

### B5.0 MULTI-CANISTER OVERPACK PARTICULATE INVENTORY AND RELEASE FACTORS

The bounding amount of radioactive particulate in an MCO with two scrap baskets leaving K Basins is estimated to be 30 kg as uranium dioxide and other ingredients (HNF-SD-SNF-TI-015). This particulate is initially tightly bound to the fuel and scrap or is inaccessible to the washing process. As time goes on, this particulate is slowly replaced with newly formed particulate. The process of forming new particulate has the effect of loosening the existing particulate. It is assumed that the bounding MCO at CVDF contains 15 kg of loose particulate before draining and 25 kg during vacuum drying (HNF-SD-SNF-TI-015). This particulate is available for resuspension and release by hydrogen explosions inside the MCO. Another 30 kg is assumed to be tightly adhering or partially contained in crevices so it cannot be released from the MCO as respirable particles.

The unit dose factor for calculating doses from airborne emissions of SNF has units of rem per gram of radioactive material inhaled. Since virtually all of the mass of SNF is uranium metal while the SNF particulate matter is predominantly uranium dioxide, it is assumed that the fraction of particulate mass that is radioactive material is $\frac{238}{270} = 0.8815$. Thus 15 kg of particulate corresponds to 13.2 kg of radioactive material, and 25 kg corresponds to 22.0 kg respirable radioactive material.

The initial effect of an explosion inside an MCO is to resuspend loose particulate. Any loss of confinement associated with the explosion provides a path for the pressurized gases to escape the MCO. For most leaks, the escape path is tortuous. The pressurized gas must pass through the four 1-in.-diameter holes in the guard plate, through the holes in the metal HEPA filter tube, through the HEPA filter, up the passage through the MCO shield plug, and out of the MCO. However, if the leak is in the long process tube lines the escape path is more direct. The pressurized gas travels down to the bottom of the MCO, then up the long process tube, makes two 90° turns and exits the MCO.

A release factor has been selected from DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions/Rates for Nonreactor Nuclear Facilities*, Section 4.4.2.3.2, which described pressurized releases through powders. In the experiments described in DOE-HDBK-3010-94, air at a pressure less than 170 kPa was forced through a cup of uranium dioxide powder at high velocity. The bounding release factor was 0.005, with a respirable fraction of 0.4. The overall respirable release fraction is, therefore, 0.002. The release factor selected appears to be bounding for at least two reasons. First, the tortuous path the gases and suspended particulate must take leaving the MCO would produce impaction losses. Second, the MCO particulate is not directly affected by the high-speed air flow used in the pressurized...
release experiments. The MCO particulate is primarily located on scrap and fuel, and the gas flowing from the MCO is not moving very fast through these regions because of the larger cross-sectional area.

The mass of respirable radioactive material released as the result of an accident can be calculated using the following formula:

\[ M = MAR \times ARF \times RF \]

where

- \( M \) = radioactive material that becomes airborne as respirable particles (g)
- \( MAR \) = radioactive material at risk for release (g)
- \( ARF \) = airborne release fraction
- \( RF \) = respirable fraction.

The mass of respirable radioactive material made airborne by a pressurized release near the end of draining is calculated as follows:

\[ (13.2 \text{ kg}) (1,000 \text{ g/kg})(0.005)(0.4) = 26 \text{ g respirable radioactive material.} \]

The mass of respirable radioactive material made airborne by a pressurized release during vacuum drying is calculated as follows:

\[ (22 \text{ kg})(1,000 \text{ g/kg})(0.005)(0.4) = 44 \text{ g respirable radioactive material.} \]

### B6.0 MULTI-CANISTER OVERPACK VOID SPACE PARTICULATE INVENTORY AND RELEASE FACTORS

Before the MCO is drained, a small gas space exists at the top of the MCO. At the K Basins, this space is filled with helium at a pressure of about 3 lb/in\(^2\) gauge before the MCO is shipped to the CVDF. During shipment a portion of the loose particulate on the scrap and fuel will be dislodged by motion of the water and carried to all surfaces inside the MCO, including the underside of the MCO guard plate, which is located on the underside of the MCO shield plug and may be in contact with the MCO water. Thus any pressurized release from the MCO may entrain some of this particulate and carry it outside the MCO. The purpose of this section is to provide a bounding estimate of the size of this release.

The void space in the cask–MCO during shipment is estimated to be 41.2 L. This is based on the following volumes:

- A layer 4.25 in. thick and 20 in. in diameter at the top of the MCO
• A layer 0.6 in. thick between the outside of the MCO and the inside of the cask (this layer is treated as a circular cylindrical shell 16 in. tall with a diameter of 24 in.)

• A space between the top of the cask and the top of the MCO (this space is represented as a cylinder 1 in. tall with a diameter of 24 in.).

The exact dimensions and volume of the void space are not necessary to the conclusions of the accident analyses. This volume could be slightly larger or smaller without changing the accidents because other parameters can be adjusted to make up for the difference.

To estimate the potential surface contamination on the underside of the MCO guard plate, consider first how it becomes contaminated. A clean MCO shield plug assembly is placed on the MCO at K Basins. As the MCO is transported to CVDF, the water inside sloshes and carries particulate from the surfaces on which it forms to any other surface in the MCO. The ratio of guard plate surface area to the entire surface area in the MCO is 0.34%, as shown on Table B-8. Note that the total surface area shown on Table B-8 is intended to underestimate rather than overestimate.

An additional consideration is the small free volume inside the MCO. The baskets and their contents act as baffles that greatly reduce the velocity of the water, leading to less relocation to the guard plate. Also, because of the wet conditions, the resuspension factor for powders is reduced. A factor of 10 is used to account for these two effects (baffling and wet conditions). Thus, the fraction of the 15 kg loose particulate in the MCO that is attached to the underside of the MCO guard plate is 0.034%, or 4.44 g. This is the material at risk. The mass released as respirable particles is calculated as shown below.

\[
(4.44 \text{ g})(0.005)(0.4) = 0.0089 \text{ g respirable radioactive material.}
\]

**B7.0 HIGH-EFFICIENCY PARTICULATE AIR FILTER PARTICULATE INVENTORY ANDRELEASE FACTORS**

For hydrogen explosions outside the MCO, the HEPA filters represent a concentration of radioactive particulate matter that could be resuspended and released from the building by an explosion. This section develops a value for the fraction of SNF on the HEPA filters that could be released into the air as respirable-sized particles by an explosion impacting the filter media and rupturing the ventilation ductwork.

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). This release fraction is based on tests on standard 2-ft by 2-ft by 12-in.-thick HEPA filters. The average breaking pressure for these filters is 16.3 kPa.
Table B-8. Multi-Canister Overpack Interior Surface Area.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCO lid area</td>
<td>0.27 m²</td>
</tr>
<tr>
<td>MCO tube area</td>
<td>6.90 m²</td>
</tr>
<tr>
<td>Basket surface area</td>
<td>13.80 m²</td>
</tr>
<tr>
<td>Total MCO inside area</td>
<td>21.23 m²</td>
</tr>
<tr>
<td>Mark IV canister</td>
<td>3,060 cm²</td>
</tr>
<tr>
<td>Canisters per basket</td>
<td>54</td>
</tr>
<tr>
<td>Fuel baskets per MCO</td>
<td>3</td>
</tr>
<tr>
<td>Total canister area</td>
<td>49.57 m²</td>
</tr>
<tr>
<td>Total scrap area</td>
<td>9.00 m²</td>
</tr>
<tr>
<td>Total fuel and scrap area</td>
<td>58.57 m²</td>
</tr>
<tr>
<td>Total exposed area</td>
<td>79.81 m²</td>
</tr>
<tr>
<td>Lid underside fraction</td>
<td>0.34%</td>
</tr>
</tbody>
</table>

The MCO has an inside diameter of about 23 in. and an inside length of about 148 in. The surface area of all five baskets is assumed to be about twice the internal surface area of the MCO vessel. Scrap surface area is the value for two scrap baskets given in HNF-SD-SNF-TI-015, 1998, *Spent Nuclear Fuel Technical Databook*, Rev. 6, Fluor Daniel Hanford, Incorporated, Richland, Washington.

MCO = multi-canister overpack.

Three HEPA filter units are of interest. The first is located on the process bay local exhaust heating, ventilation, and air conditioning (HVAC) and process vent system. It is an array of 2-ft by 2-ft by 12-in.-thick HEPA filters that is three filters high and two filters wide. The second is located on the CVDF general supply/exhaust HVAC system. It is an array of 2-ft by 2-ft by 12-in.-thick HEPA filters that is four filters high and three filters wide. The third HEPA filter is a smaller unit located on the PWC storage tank. This HEPA filter is 1 ft by 1 ft by 11.5 in. thick.

The dose rates near the three filters were estimated using the safety/regulatory basis spent fuel composition from HNF-SD-SNF-TI-015, *Spent Nuclear Fuel Technical Databook*, and ISO-PC software Version 1.6 (WHC-SD-SQA-CSWD-303). While this is not the current version of ISO-PC, it does have a document describing the verification and validation tests that were completed. The program revisions since then have little effect on the computed dose rates for this geometry and shield thicknesses.

The HVAC filter units (local and general exhausts) have a prefilter and a HEPA filter separated by a 2-ft gap. The prefilter efficiency is assumed to be about 25%, so the total activity
on the prefilter is about one-fourth the total activity on the HEPA filter array. Since the dose rate is directly proportional to the filter loading, the filter loading can be adjusted up or down to obtain the desired dose rate. In addition, the exposure rate near the filter indicates the total activity on the filter.

As input to the ISO-PC program, it was assumed that both the prefilter and HEPA held a total of 1 g of SNF. The dose rates were combined so that the entire unit had a 1 g SNF total. The filter medium was homogenized throughout its volume at a density of 0.16 g/cm³, corresponding to a 2-ft by 2-ft by 12-in. filter weight of 18.1 kg (40 lb). Concrete was used to represent the medium. The prefilters were modeled using the same material except they were modeled as 6 in. thick. The dose points for all three filters were 2 in. to the side of the HEPA filter, corresponding to a likely dose rate measurement point for weekly surveys by radiation protection technicians. Dose rates are measured with an ion chamber instrument that reads out in units of milli-roentgen per hour (mR/h). Hence the calculated values are in milli-roentgen per hour also. The prefilters were modeled using virtual sources to represent the partially face-on orientation at the dose rate measurement point. The ISO-PC results are shown on Table B-9. The actual ISO-PC output file is listed in Attachment B1 at the end of this appendix.

<table>
<thead>
<tr>
<th>Filter</th>
<th>ISO-PC result with 1 g SNF (mR/h)</th>
<th>Minimum filter exposure rates (mR/h) to exceed the onsite risk evaluation guideline for unlikely events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process bay local exhaust HVAC and process vent system</td>
<td>8.8</td>
<td>82</td>
</tr>
<tr>
<td>CVDF general supply/exhaust HVAC system</td>
<td>5.0</td>
<td>47</td>
</tr>
<tr>
<td>PWC storage tank exhaust filter</td>
<td>81</td>
<td>760</td>
</tr>
</tbody>
</table>

Minimum filter loadings are based on an accident release fraction of 1% and a cesium depletion factor of 10. All of the amount that becomes airborne is assumed to be respirable-sized particles. The minimum HEPA filter loadings are based on a minimum airborne emission from CVDF of 0.94 g SNF for unlikely events (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).

CVDF = Cold Vacuum Drying Facility.
HEPA = high-efficiency particulate air (filter).
HVAC = heating, ventilation, and air conditioning.
PWC = process water conditioning.
SNF = spent nuclear fuel.
Also shown on Table B-9 is the minimum filter loading needed to exceed the risk evaluation guidelines for "unlikely" accidents. These minimum filter exposure rates were computed using the formula below.

\[
R_{\text{MIN}} = \frac{(R_{\text{ISO-PC}})(M_{\text{MIN}})}{(\text{ARF})(\text{RF})(\text{CRF})}
\]

(B-12)

where

- \(R_{\text{MIN}}\) = minimum exposure rate on a filter unit that would exceed the risk evaluation guideline (mR/h)
- \(R_{\text{ISO-PC}}\) = exposure rate computed by ISO-PC at the side of a HEPA filter with 1 g SNF uniformly distributed over the entire unit (mR/h per g SNF from Table B-9)
- \(M_{\text{MIN}}\) = minimum mass of SNF that would have to be released into the air as respirable particles to exceed the risk evaluation guideline at the onsite receptor location, which is the most limiting location (0.94 g SNF for unlikely events [HNF-SD-SNF-TI-059])
- \(\text{ARF}\) = airborne release fraction, which is the fraction of SNF accumulated on the filter unit that becomes airborne because of an explosion (0.01 [DOE-HDBK-3010-94])
- \(\text{RF}\) = respirable fraction, which is the fraction of SNF released into the air that is respirable-sized particles (1.0 [DOE-HDBK-3010-94]).
- \(\text{CRF}\) = cesium removal factor, which is the ratio of cesium originally present in the fuel to cesium actually present in the fuel (10 [HNF-1777 Appendix B]).

From a practical standpoint, it is not possible to work around a filter unit reading more than 100 mR/h. Thus, only the ventilation system HEPA filter arrays may require administrative controls to limit the activity.

One major assumption regarding filter loading is that the relative amounts of gamma-emitting and alpha-emitting nuclides are not the same on the filters as they are in the fuel. The gamma-emitting nuclides (e.g., \(^{137}\text{Cs}\)) give essentially all of the measurable dose rate on the filters while the alpha-emitting nuclides (e.g., \(^{241}\text{Am}\)) give essentially all of the internal dose when released into the environment. Radioactive decay decreases the amount of cesium faster than the amount of alpha-emitters. In addition, it may be that the cesium dissolves more readily in water than the alpha emitters. Based on the measured sludge compositions in K basins as well as calculated fuel compositions, it is concluded in HNF-1777, \textit{K West Basin Integrated Water Treatment System Annular Filter Vessel Accident Calculations} (Appendix B), that a factor of 10 will bound the observed cesium depletion factors. Table B-9 uses this factor, and in effect uses 10 times more fuel in the filter enclosure as a result.
**B8.0 ACTIVITY IN PROCESS WATER CONDITIONING TANKS**

The amount of radioactive material that might be present in the PWC receiver tanks as a result of completed drain operations is used in the analysis of the spray leak and the external hydrogen explosion. This quantity affects the potential dose rates in the drain line and in the PWC tank room. It is likely that dose rates near the PWC tanks in excess of 100 mR/h would be unacceptable from ALARA (as low as reasonably achievable) considerations.

In recent experiments at the CVDF prototype (HNF-4057 Section 3.4), cerium oxide powder (representing uranium oxide) was spread over the bottom of the MCO to indicate the amount of particulate carryover during draining. The density of cerium oxide is 6.9 kg/L, which is high enough to represent uranium oxide. In addition, the cerium oxide particle diameters were distributed in the range from 0 to 10 µm, consistent with SNF particulate. Drain operations at up to twice the normal flow rate resulted in the transfer of at most 7% of the cerium oxide. In an MCO loaded with fuel, the SNF particulate would be located primarily in the fuel and scrap baskets with a portion settled to the bottom of each basket and the floor of the MCO. When the water drains from the MCO, some particulate will be carried through the holes in the baskets to the drain tube. Since the SNF particulate has very small diameters, most of this waterborne material would be carried from the MCO without settling out. Assuming a 7% release from a fuel or scrap basket leads to a 7% overall release during draining.

A representative, bounding fraction of 10% is used to estimate particulate carryover from the MCO to the PWC tanks during draining. This fraction applies only to the loose particulate in the MCO. As listed in Table 1-3, there is 21 kg of particulate that is considered tightly adhering because it survives the washing at K basins. This will not contribute to the carryover. Only the 15 kg of loose particulate that forms after washing at K basins will be considered free enough to be carried out of the MCO during the drain operation. Thus the MCO drain operation is assumed to carry over just 1.5 kg of particulate, or 1.32 kg radioactive material (SNF).

The ISO-PC Version 1.6 software (WHC-SD-SQA-CSWD-303) was used to estimate dose rates near the MCO drain line and the PWC receiver tanks for a 1.5 kg transfer. Results are given in Table B-10. The current version of ISO-PC (i.e. Version 2.1) lacks documentation for the testing that has been carried out. Version 1.6 was the last version fully documented. Numerous errors in ISO-PC have been corrected since then. For example, it is possible to generate negative dose rates with the spherical geometry. In these calculations, the only revision that affects the results is the method for calculating the attenuation coefficients. The attenuation coefficients calculated for iron in Version 1.6 are smaller than in Version 2.1. However, the attenuation coefficients for concrete are larger. The result is that Version 1.6 underestimates the dose rates outside the PWC room (last line in Table B-10) by 26%, and overestimates the other doses by 25 to 45%.
The safety basis fuel composition used was from 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. The mass of particulate suspended in the water is 1.5 kg. The drain line is 20-ft-long, 1-in.-diameter schedule 40 pipe. The PWC receiver tanks are assumed to be 2 ft in diameter and 4 ft tall. Exposure rates were computed using the ISO-PC software (Version 1.6).

PWC = process water conditioning.

The safety basis source composition (HNF-SD-SNF-TI-015) was used to represent the bounding particulate suspended in the water. Note that the cesium removal factor of 10 was not used in these calculations. Initially, the particulate is suspended in 490 L of water, representing the MCO water. In the PWC room, the MCO water is added to a minimum PWC receiver tank inventory of 160 L to give a total for the PWC room of 650 L of water.

To estimate dose rates near the drain line, the drain line was modeled as a 1-in.-diameter, schedule 40 pipe with a length of 20 ft. The pipe wall was modeled as iron with a density of 7.86 kg/L. The ISO-PC material selected for calculation of exposure buildup was air. The density of the MCO water was adjusted for the presence of the particulate using the dry density of an SNF particle, 5.0 kg/L. Figure B-2 shows the particle suspended in the drain water. The masses and volumes of the water and solids are labeled. Note that the solid particle is actually regarded as a porous solid with water filling the empty spaces. Some formulas and definitions are listed below.

Water density $\rho_{\text{WATER}} = \frac{M_a}{V_a} = \frac{M_b}{V_b}$

Solids density $\rho_{\text{SOLIDS}} = \frac{M_c}{V_c}$

Dry particle density $\rho_{\text{PART,DRY}} = \frac{M_c}{(V_b + V_c)}$

Wet particle density $\rho_{\text{PART,WET}} = \frac{(M_b + M_c)}{(V_b + V_c)}$

Drain water density $\rho_{\text{TOT}} = \frac{M_{\text{TOT}}}{V_{\text{TOT}}}$

$\rho_{\text{TOT}} = \rho_{\text{WATER}} + \left(\frac{M_c}{V_{\text{TOT}}}\right)(1 - \rho_{\text{WATER}}/\rho_{\text{SOLIDS}})$

<table>
<thead>
<tr>
<th>Location</th>
<th>Exposure rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above drain line (1 m)</td>
<td>10.8 mR/h</td>
</tr>
<tr>
<td>Below drain line (3 m)</td>
<td>2.3 mR/h</td>
</tr>
<tr>
<td>Near PWC receiver tank (1 m)</td>
<td>1,980 mR/h</td>
</tr>
<tr>
<td>Near PWC receiver tank (3 m)</td>
<td>320 mR/h</td>
</tr>
<tr>
<td>Wall outside PWC tank room</td>
<td>6.7 mR/h</td>
</tr>
</tbody>
</table>

Table B-10. Exposure Rates during Multi-Canister Overpack Draining.
where

\[ \begin{align*}
Ma &= \text{mass of the water surrounding the suspended particle (kg)} \\
Va &= \text{volume of the water surrounding the suspended particle (L)} \\
Mb &= \text{mass of the water stored in pores of the suspended particle (kg)} \\
Vb &= \text{volume of the water stored in pores of the suspended particle (L)} \\
Mc &= \text{mass of the solid material inside the particulate (kg)} \\
Vc &= \text{volume of the solid material inside the particulate (L)} \\
\rho_{\text{WATER}} &= \text{density of pure water (1.0 kg/L)} \\
\rho_{\text{SOLIDS}} &= \text{density of the solid portion of the particulate (10 kg/L)} \\
\rho_{\text{PART,DRY}} &= \text{density of the dry, porous particulate matter (5.0 kg/L)} \\
\rho_{\text{PART,WET}} &= \text{density of the particle after the porous portion is filled with water (kg/L)} \\
M_{\text{TOT}} &= Ma + Mb + Mc \\
V_{\text{TOT}} &= Va + Vb + Vc \\
\rho_{\text{TOT}} &= \text{density of the MCO drain water with suspended particulate (kg/L)}.
\end{align*} \]

For SNF particles, the solid density \( \rho_{\text{SOLIDS}} \) is 10 kg/L, while the dry particle density \( \rho_{\text{PART,DRY}} \) is 5 kg/L. To obtain the drain water density, the 1.5 kg of particulate \( M_c \) are present in the water. During transfer from the MCO, the particulate is suspended in 490 L total \( V_{\text{TOT}} \). The drain water density during transfer from the MCO is therefore calculated as follows:

\[ \rho_{\text{TOT}} = \left(1.0\ \text{kg/L}\right) + \frac{1.5\ \text{kg}}{490\ \text{L}} \left[1 - \frac{1.0\ \text{kg/L}}{10\ \text{kg/L}}\right] \]

\[ \rho_{\text{TOT}} = 1.0028\ \text{kg/L}. \]

The density of the wet particles can be derived from the above equations and definitions. The resulting formula is shown below. Inserting values gives a wet particle density of 5.50 kg/L.

\[ \rho_{\text{PART,WET}} = (\rho_{\text{WATER}}) + (\rho_{\text{PART,DRY}}) - (\rho_{\text{WATER}})(\rho_{\text{PART,DRY}})/(\rho_{\text{SOLIDS}}). \]

Note that after mixing with water already present in the PWC receiver tanks, the particulate is suspended in 650 L water. The drain water density is reduced slightly to 1.00208 kg/L.

Exposure rates were calculated at distances of 1 m and 3 m from the drain line. The 1-m distance represents a person standing on the mezzanine directly over the drain line. The 3-m distance represents a person standing on the floor under the drain line. Results are shown in Table B-10. The ISO-PC output for these calculations is listed in the Attachment B2.

To estimate dose rates near the PWC receiver tanks, the tanks were modeled as cylinders 2 ft in diameter and 4 ft tall. Each cylinder has a total volume of 350 L. Rather than model two cylinders (each with half the total activity), the PWC receiver tanks were represented as a single tank with all the activity. In the simple models afforded by ISO-PC, this is adequate accuracy. The exposure rates near the PWC receiver tanks are listed in Table B-10.
Because the exposure rates inside the PWC tank room would be high, an additional case was prepared to estimate dose rates just outside the nearest 10-in. concrete wall of the PWC tank room. The distance from the tank to the wall is 3 m. The dose rate is shown in Table B-10.

For routine processing and maintenance activities to be carried out in the PWC tank room, the bounding mass of particulate in the PWC receiver tanks could not differ greatly from the 1.5 kg assumed.

**B9.0 MATHEMATICAL MODELS FOR GAS CONCENTRATIONS IN THE PROCESS WATER CONDITIONING RECEIVER TANKS**

**B9.1 GAS CONCENTRATIONS DURING HELIUM PURGE PRIOR TO MULTI-CANISTER OVERPACK DRAINING**

This section derives the formulas used to represent the helium purge of the PWC receiver tanks prior to MCO draining. The model includes the possibility that gases introduced into the tanks may not mix very well with gases already in the tanks before leaving the tank. The objective is to provide the mathematical basis for determining the effectiveness of the helium purge.

The two PWC receiver tanks are assumed to be at atmospheric pressure and at the same temperature. The tanks are linked in a chain (see Figure B-3). The first tank receives material from an infinite source at a concentration Cx. As gas is added to the first tank, it is simultaneously removed, so the pressure and volume of the first tank remain constant. Gases are transferred from the first tank to the second tank at the same rate at which they are added to the first tank. Gases flow from the second tank to the ventilation system. It is assumed that the concentration being added (Cx) remains constant. Formulas for the concentrations in the first and second tanks, along with the concentration of gas entering the ventilation system, are desired.

The equations derived here use a mixing factor to account for less than perfect mixing in one tank before the gases are transferred to the next tank. The helium purge operation brings helium into the first receiver tank mixed with water flowing through the air ejector (PWC-EJR-4031). This leads to good mixing in the first tank because the falling droplets stir the added gas into whatever is currently in the tank vapor space. However, the second tank is expected to exhibit poor mixing because (1) both the inlet and outlet pipes are attached to the top of the tank, (2) the tank is tall and slender, and (3) there is no design or operating feature that enhances mixing.

The concentration and volume of the first tank (tank A) are Ca and Va, and the mixing ratio is Ka. Mixing ratios specify how well the gases introduced into a tank mix with the gas already in the tank before they are discharged to the next tank. Good mixing means the mixing ratio is nearly one. Poor mixing means that much of the introduced gas goes unmixed to the discharge port. In effect, when a small volume (dV) is added to tank A, the volume of added gas
that mixes in tank A is $K_a \cdot dV$. This same volume of gas is removed and goes into the second
tank. The remaining volume, $(1 - K_a) \cdot dV$, is the portion of the added gases that passes to the next
tank in the chain. The mass balance for the first tank is shown in the Equation B-12.

$$V_a \cdot dC_a = (C_x - C_a) \cdot K_a \cdot dV$$  \hspace{1cm} (B-12)

where

- $V_a$ = volume of the first tank, tank A
- $dC_a$ = change in concentration of the gas in the tank A due to the added gas
- $C_x$ = concentration of the gas being added to tank A
- $C_a$ = concentration of the gas in tank A
- $K_a$ = mixing ratio for tank A: the fraction of gas that is added to tank A that remains in
the tank rather than passing to the next tank in the chain
- $dV$ = small increment of volume of gas at concentration $C_x$ that is added to tank A and
also passed from tank A to tank B.

The solution to the differential equation for tank A is shown in Equation B-13.

$$C_a = C_x + (C_{ao} - C_x) \cdot \text{Exp}(-V \cdot K_a / V_a)$$  \hspace{1cm} (B-13)

where

- $C_{ao}$ = initial concentration of the gas in tank A
- $V$ = total volume of gas at concentration $C_x$ added to tank A.

Before any gas is added ($V = 0$), the concentration in tank A is the initial concentration
($C_{ao}$). After a considerable volume of gas has been added, the concentration in Tank A is the
same as that of the added gas ($C_x$). If the mixing ratio is far less than one, the volume of gas
needed to reach the concentration of the added gas is greater than if the mixing ratio is closer to
one. A graph of Equation B-13 is shown in Figure B-4. It is assumed that the gas volume of the
first tank ($V_a$) is 19 ft$^3$. Two mixing factors are shown on the graph. A value of 0.9 was chosen
to represent good mixing, and a value of 0.5 was chosen to represent poor mixing.

During the helium purge, $C_x$ would be 100% helium. Because tank A is initially filled with
air, $C_{ao}$ would be 100% air (i.e., 20.8% oxygen and 79.2% nitrogen). Figure B-4 shows how
these concentrations decrease as helium is added to the tank. The figure also illustrates that a
tank with a low mixing factor requires more helium to reduce the oxygen concentration below the
minimum needed to support combustion (5%). The oxygen concentration is not shown but is
proportional to the nitrogen concentration. The oxygen concentration is $0.208/0.792 = 0.263$
times the nitrogen concentration. To ensure any added hydrogen will not form a combustible mixture, the oxygen concentration should be kept below 4%. Since the nitrogen concentration is proportional to the oxygen concentration, the nitrogen concentration needs to be kept below 15%. From Figure B-4, the minimum purge to accomplish this is about 35 ft$^3$ with good mixing ($Ka = 0.9$) and 63 ft$^3$ with poor mixing ($Ka = 0.5$).

The concentration and volume of the second tank (tank B) are $Cb$ and $Vb$, and the mixing ratio for tank B is $Kb$. The mass balance for Tank B includes the portion added to tank A that does not mix in tank A but passes directly to tank B. This is shown in Figure B-5 and in Equation B-14.

$$Vb \cdot dCb = [Cx \cdot (1 - Ka) + Ca \cdot Ka - Cb] \cdot Kb \cdot dV$$  \hspace{1cm} (B-14)

where

- $Vb$ = volume of second tank, tank B
- $dCb$ = change in concentration of the gas in tank B due to the added gas
- $Cx$ = concentration of the gas being added to tank A
- $Ka$ = mixing ratio for tank A: the fraction of gas that is added to tank A that remains in the tank rather than passing to the next tank in the chain, tank B
- $Ca$ = concentration of the gas in tank A
- $Cb$ = concentration of the gas in tank B
- $Kb$ = mixing ratio for the second tank: the fraction of gas that is added to tank B that remains in the tank rather than passing on to the next tank in the chain, tank C
- $dV$ = small increment of volume transferred from tank A into tank B, as well as the volume transferred from tank B to tank C.

The solution to the differential equation for tank B is shown in Equation B-15. At this point it is assumed that the ratio ($Ka/Va$) does not equal the ratio ($Kb/Vb$).

$$Cb = Cx + A \cdot \text{Exp}(-V \cdot Ka/Va) + B \cdot \text{Exp}(-V \cdot Kb/Vb)$$  \hspace{1cm} (B-15)

where

- $A = (Cao - Cx) \cdot Ka \cdot Rab$
- $Cao$ = initial concentration of the gas in tank A
- $Rab = Kb \cdot Va/(Kb \cdot Va - Ka \cdot Vb)$
Before any gas is added ($V = 0$), the concentration in tank B is the initial concentration ($C_{bo}$). After a considerable volume of gas has been added, the concentration in tank B is the same as that of the added gas, $C_x$. If the mixing ratios for tank A and tank B are far less than one, the transition to $C_x$ requires that more gas be added than if the mixing ratio is closer to one.

If the ratio $(K_a/V_a)$ equals $(K_b/V_b)$, a different equation applies because the term $R_{ab}$ is undefined. The solution for this case is shown in Equation B-16.

$$C_b = C_x + \left(A + B_e\right)\exp(-V\cdot K_a/V_a) \tag{B-16}$$

where

$$A_e = \frac{(C_{ao} - C_x) \cdot K_a^2}{V_a}$$
$$B_e = C_{bo} - C_x.$$

During the initial helium purge, the gas flowing into tank B is a mixture of air and helium, with the helium fraction steadily increasing. Figure B-5 illustrates that a tank with a low mixing factor requires more helium to reduce the air concentration. Comparing Figure B-4 with Figure B-5, it is apparent that air concentrations are higher in tank B at all purge volumes because tank A receives pure helium while tank B receives a mixture of helium and air. The oxygen concentration is not shown, but is proportional to the nitrogen concentration. The oxygen concentration is $0.208/0.792 = 0.263$ times the nitrogen concentration. To ensure any added hydrogen will not form a combustible mixture, the oxygen concentration should be kept below 4%. Since the nitrogen concentration is proportional to the oxygen concentration, the nitrogen concentration needs to be kept below 15%. From Figure B-4, the minimum purge to accomplish this is about 90 ft$^3$ with good mixing ($K_b = 0.5$), and 180 ft$^3$ with poor mixing ($K_b = 0.2$).
The concentration of the gas leaving the second tank and entering the ventilation system is shown on Figure B-6 and repeated in Equation B-17.

\[ C_{\text{VENT}} = (1 - K_b)[(1-K_a)C_x + K_a C_a] + K_b C_b \]  

(B-17)

where

\[ C_{\text{VENT}} = \text{gas concentration leaving the second tank and entering the ventilation system.} \]

The gas concentrations entering the ventilation system during the helium purge are shown in Figure B-6. This figure illustrates the fact that oxygen concentrations fall more rapidly in the outlet from tank B than inside tank B. The poor mixing characteristics of this tank make this possible.

**B9.2 GAS CONCENTRATIONS DURING MULTI-CANISTER OVERPACK DRAINING**

While the MCO is being drained, the water levels in the first two tanks increase, thus the tank volumes (\( V_a \) and \( V_b \)) decrease. To facilitate modeling the hydrogen addition, the concentrations in the two tanks need to be derived for this different situation.

Figure B-7 shows the situation during draining. It differs from Figure B-3 in that no gas is being added to tank A (\( C_x = 0 \)) and no mixing takes place in tank A (\( K_a = 0 \)). No gases are added to tank A, but whatever mixture is present in this tank is transferred to tank B. Transfer of gas from tank B to the ventilation system is at twice the rate of the transfer from tank A to tank B. The mass balance for tank B is shown in Equation B-18.

\[ (V+dV)\cdot C_b = C_{b0}\cdot V + K_b\cdot C_a\cdot(-dV) - K_b\cdot C_b\cdot(-dV) - C_b\cdot(-dV) \]

or

\[ V\cdot dC_b = (C_b-C_a)\cdot K_b\cdot dV \]  

(B-18)

where

\[ V = \text{instantaneous volume of tank B, which decreases from } V_b \text{ to smaller values} \]

\[ dV = \text{small increment of volume that is added to tank B; an amount that is twice this volume is transferred from tank B to tank C} \]

\[ C_b = \text{concentration of the gas in tank B} \]

\[ C_{b0} = \text{the initial concentration of the gas in tank B} \]
Kb = mixing ratio for tank B: the fraction of gas that is added to tank B that remains in the tank

Ca = concentration of the gas in tank A; this is what is added to tank B

dCb = change in concentration of the gas in tank B due to the added gas

The solution to the differential equation for tank B is shown in Equation B-19.

\[ C_b = C_{ao} + (C_{bo} - C_{ao}) \cdot \frac{V}{V_b} K_b \]  
(B-19)

where

Cao = the initial concentration of the gas in tank A (same as Ca, because gas is not added to tank A)

V = total volume of tank B, decreases from \( V_b \) to smaller values.

Before any gas is added (\( V = V_b \)), the concentration in tank B is the initial concentration (\( C_{bo} \)). As gas is transferred from tank A to tank B, the concentration in tank B becomes more like the concentration in tank A. The effect on concentrations in the second receiver tank is small, as illustrated in Figure B-8. The concentration of the gas leaving the second tank and entering the ventilation system is shown in Equation B-20.

\[ C_{vent} = \frac{[(1 - K_b) \cdot C_a + (1 + K_b) \cdot C_b]}{2} \]  
(B-20)

The gas concentrations entering the ventilation system are also shown in Figure B-8. With poor mixing in the second tank, the nitrogen and oxygen concentrations are lower in the outlet from tank B than they are inside tank B. The poor mixing characteristics of this tank cause most of the helium from the first tank to bypass the second tank.

**B9.3 CONCENTRATIONS DURING MULTI-CANISTER OVERPACK GAS BREAKTHROUGH**

After the liquid has been drained from the MCO, the gas in the MCO is rapidly transferred to the PWC receiver tanks. The MCO and the two receiver tanks are assumed to be at atmospheric pressure and at the same temperature (50 °C). The MCO and the tanks are linked in a chain (in Figure B-9 the MCO is tank A, and the two receiver tanks are tank B and tank C). The first tank (in this case, the first tank is the MCO) receives helium from an infinite source at a concentration \( C_x \) (100% helium). As gas is added to the first tank (the MCO, or tank A), it is simultaneously removed, so the pressure and volume of the first tank remain constant. Gases are transferred from the first tank to the second tank (the first receiver tank) at the same rate at which they are added to the first tank. In a similar fashion, gases flow from the second tank (the first receiver tank) to the third tank (second receiver tank) and then out to the ventilation system.
A special feature of tank A (the MCO) is that a portion of the contents is transferred undiluted by the added helium. The undiluted fraction is identified as "fa" in Figure B-9. The remainder (1-fa) is diluted by the added helium. This detail is included so that the hydrogen concentrations in the first receiver tank (tank B in Figure B-9) are not underestimated.

The equations derived in this section use mixing factors for each tank to account for less than perfect mixing in one tank before the gases are transferred to the next tank. The MCO (tank A) is assumed to have relatively good mixing because of the number of baffles and flow channels. Good mixing in tank A also maximizes the hydrogen concentrations in tanks B and C (the PWC receiver tanks). The operation of the air ejector produces good mixing in tank B (the first receiver tank). Tank C (the second receiver tank) is expected to exhibit poor mixing because both the inlet and outlet pipes are attached to the top of the tank.

The derivation of formulas to represent the gas concentrations as a function of volume transferred from the MCO are similar to those derived for the helium purge of the PWC receiver tanks. One important change is that the flow from the MCO (tank A) is divided into two cases: undiluted flow \([0 < V < (fa \cdot Va)]\) and diluted flow \([(fa \cdot Va) < V < 2 \cdot Va]\). The concentrations transferred under these two assumptions are shown in Table B-11.

### Table B-11. Concentrations Transferred from Tank to Tank.

<table>
<thead>
<tr>
<th>Category</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0 &lt; V &lt; (fa \cdot Va))</td>
<td>(C_{ao})</td>
<td>((1-Kb) \cdot C_{1} + Kb \cdot C_{b})</td>
<td>((1-Kc) \cdot C_{2} + Kc \cdot C_{c})</td>
</tr>
<tr>
<td>((fa \cdot Va) &lt; V &lt; 2 \cdot Va)</td>
<td>((1-Ka) \cdot C_{a} + Ka \cdot C_{c})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where

- \(V\) = volume of gas added to tank A.
- \(Va, Vb, Vc\) = gas volume of tanks A, B, and C.
- \(fa\) = fraction of the gas volume of tank A which is transferred undiluted to tank B.
- \(Ka, Kb, Kc\) = mixing fractions for each tank.
- \(C_{x}\) = concentration of the gas added to tank A.
- \(C_{ao}, C_{bo}, C_{co}\) = initial concentrations in tanks A, B, and C.
- \(C_{a}, C_{b}, C_{c}\) = current concentration in tanks A, B, and C (after a volume \(V\) is added to tank A).

The concentration in tank A (MCO) along with the differential equations used to derive the concentration are shown below. Note that the concentration shown is the average (i.e., the total amount in the tank divided by the volume of the tank).

For \(0 < V < (fa \cdot Va)\):

- differential equation: \(V_{a} \cdot dC_{a} = (C_{x} - C_{ao}) \cdot dV\)
- solution equation: \(C_{a} = C_{ao} - (C_{ao} - C_{x}) \cdot V/V_{a}\)

For \(V > (fa \cdot Va)\):

- differential equation: \(V_{a} \cdot dC_{a} = (C_{x} - C_{a}) \cdot Ka \cdot dV\)
- solution equation: \(C_{a} = C_{x} + Y \cdot \exp(-V \cdot Ka/V_{a})\)
  \[Y = (1 - fa) \cdot (C_{ao} - C_{x}) \cdot \exp(fa \cdot Ka)\]
The concentration in tank B (first PWC receiver tank) along with the differential equations used to derive the concentration are shown below. The special case where the term Rab is undefined is not considered. It is assumed that \((K_b \cdot V_a)\) is never equal to \((K_a \cdot V_b)\).

**differential equation:** \(V_b \cdot dC_b = (C_1 - C_b) \cdot K_b \cdot dV\)

\[
\begin{align*}
V < (fa \cdot Va) & \quad C_b = C_a + (C_b_o - C_a) \cdot \text{Exp}(-V \cdot K_b/V_b) \\
V > (fa \cdot Va) & \quad C_b = C_x + A \cdot \text{Exp}(-V \cdot K_a/V_a) + B \cdot \text{Exp}(-V \cdot K_b/V_b) \\
A &= Y \cdot K_a \cdot R_b_c \\
R_b_c &= K_b \cdot V_a/(K_b \cdot V_a - K_a \cdot V_b) \\
B &= C_b_o - C_a + \\
& \quad [C_a - C_x - A \cdot \text{Exp}(-K_a \cdot fa)] \cdot \text{Exp}(K_b \cdot f_a \cdot V_a/V_b)
\end{align*}
\]

The concentration in tank C (second PWC receiver tank) along with the differential equations used to derive the concentration are shown below. The three special cases where the terms Rab, Rbc, or Rac are undefined are not considered.

**differential equation:** \(V_c \cdot dC_c = (C_2 - C_c) \cdot K_c \cdot dV\)

\[
\begin{align*}
V < (fa \cdot Va) & \quad C_c = C_a + E \cdot \text{Exp}(-V \cdot K_b/V_b) + F \cdot \text{Exp}(-V \cdot K_c/V_c) \\
E &= (C_b_o - C_a) \cdot K_b \cdot R_b_c \\
R_b_c &= K_c \cdot V_b/(K_c \cdot V_b - K_b \cdot V_c) \\
F &= C_c_o - C_a - E \\
V > (fa \cdot Va) & \quad C_c = C_x + G \cdot \text{Exp}(-V \cdot K_a/V_a) + H \cdot \text{Exp}(-V \cdot K_b/V_b) + K \cdot \text{Exp}(-V \cdot K_c/V_c) \\
G &= [Y \cdot K_a \cdot (1 - K_b) + K_b \cdot A] \cdot R_ac \\
R_ac &= K_c \cdot V_a/(K_c \cdot V_a - K_a \cdot V_c) \\
H &= B \cdot K_b \cdot R_b_c \\
K &= F + G \cdot \text{Exp}(-K_a \cdot fa) + \\
& \quad [C_a - C_x + (E - H) \cdot \text{Exp}(-K_b \cdot f_a \cdot V_a/V_b)] \cdot \text{Exp}(K_c \cdot f_a \cdot V_a/V_c)
\end{align*}
\]

**B10.0 EXAMPLE FREE-AIR HYDROGEN EXPLOSION CALCULATION**

In this example, 900 g of hydrogen gas are released into the process bay, mix with air to form a flammable mixture, and then ignite. The methods presented in Sections B3.0 and B4.0 will be used to calculate the combustion temperature, pressure and probability of harm to an individual nearby. The detailed calculations presented here illustrate the calculation methods followed for all hydrogen explosion cases.

The 900 g hydrogen is 446.5 gmole \(H_2\), based on an atomic weight of 2.0159. A small amount of helium accompanies this discharge. The discharged gas is assumed to be 96%
hydrogen and 4% helium based on the HANSF output. The small amount of water vapor is ignored. Thus the total discharge is 465.1 gmole, including 18.6 gmole of helium.

The gas temperature is assumed to be 27 °C (300.15 K). At atmospheric pressure this gas occupies a volume given by the ideal gas law to be 11,460 L, as shown below.

\[ V(H_2) = (465.1 \text{ gmole})(0.082058 \text{ L·atm/gmole/K})(300.15 \text{ K})/(1 \text{ atm}) = 11,460 \text{ L} \]

Two hydrogen combustion calculations will be described first. These are the calculation of peak pressure in the flammable gas plume and the average pressure in the process bay. The first situation illustrates the method used for hydrogen explosions inside the MCO or inside ventilation ducts. The second illustrates the method used to evaluate possible structural damage to the process bay following a sudden hydrogen gas release.

It is assumed, for the sake of illustration, that the discharged MCO gas mixes with a volume of air that is 3 times greater. The air volume is therefore 34,380 L. From the ideal gas law, there are a total of 1395.3 gmoles of air.

Dry air is assumed to be 20.8% oxygen and 79.2% nitrogen, because the small components of air (argon and carbon dioxide) are included in the nitrogen percentage. Adding water vapor lowers these percents. The composition of moist air begins with the calculation of the water vapor content using the formula for \( P_{\text{SAT}} \) found in Equation B-2. This calculation is shown below for an air temperature of 27 °C (300.15 K).

\[
\log(P_{\text{SAT}}) = 7.07406 - 1657.46/(300.15 - 46.11) = 0.549654
\]

\[ P_{\text{SAT}} = 3.545 \text{ kPa} \]

Because the assumed pressure is 1 atm (101.325 kPa), the condition of 100% relative humidity at 27 °C means the air is 3.5% water vapor. For these calculations, a representative relative humidity 10% is assumed. The water vapor is 0.35% of the air. The small percentage indicates that water vapor is not important to the final temperature. The number of moles of water in the air before combustion is therefore \((0.0035)(1395.3 \text{ g mole}) = 4.9 \text{ g mole water}.\) The remaining moles of air are divided between the oxygen and nitrogen. Table B-12 summarizes the assumed composition of the flammable gas cloud prior to combustion.

The final composition of the gas plume after combustion is based on the assumption of 100% combustion efficiency. In this example, the limiting reactant is hydrogen. All 446.5 g mole hydrogen are assumed to react with 223.25 g mole oxygen to form 446.5 g mole water vapor when the mixture burns. This is very conservative, since the gas concentrations vary from the center of the plume to the edge. A portion of the hydrogen will not react simply because it is below the lower flammable limit. The energy liberated by this reaction is calculated as shown below.

\[ H(\text{Total}) = (446.5 \text{ g mole water})(57,800 \text{ cal/g mole}) = 2.58 \times 10^7 \text{ cal} \]
Table B-12. Gas Composition Before and After Combustion.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Pre-combustion</th>
<th>Post-combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inventory (gmoles)</td>
<td>Concentration (percent)</td>
</tr>
<tr>
<td>H₂</td>
<td>446.50</td>
<td>24.00%</td>
</tr>
<tr>
<td>He</td>
<td>18.60</td>
<td>1.00%</td>
</tr>
<tr>
<td>H₂O</td>
<td>4.90</td>
<td>0.26%</td>
</tr>
<tr>
<td>N₂</td>
<td>1101.20</td>
<td>59.19%</td>
</tr>
<tr>
<td>O₂</td>
<td>289.20</td>
<td>15.55%</td>
</tr>
<tr>
<td>Total:</td>
<td>1860.40</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

To estimate the temperature rise of the final mixture, it is necessary to calculate the heat energy absorbed by each component of the gas mixture as it heats from the initial temperature to some undetermined final temperature. The formula for this calculation was given in Section B3.0 and Table B-6. Since the increase of heat capacity with temperature is represented by a quadratic formula, the integral of the heat capacity shown in Equation B-10 can be solved for each gas. This is shown below.

\[
H(X) = [A(T_f - T_o) + B(T_f^2 - T_o^2)/2 + C(T_f^3 - T_o^3)/3] \cdot N_x
\]

where

- \( H(X) \) = heat energy added to gas "X", cal
- \( A, B, C \) = constants for each gas from Table B-6
- \( T_o \) = initial gas temperature (before combustion), 300.15 K
- \( T_f \) = final gas temperature (after combustion), K
- \( N_x \) = number of moles of gas "X" in the post-combustion mixture.

The heat energies added to each component of the final gas mixture are summed for comparison with the heat energy released by the combustion reaction \((2.58 \times 10^7 \text{ cal})\). The determination of final gas temperature \((T_f)\) is carried out by successive guesses until a final temperature is found such that the energy liberated by combustion matches the energy absorbed by the gas. Three iterations of \( T_f \) assumptions are shown in Table B-13. The third case is close enough to be considered the solution. An illustration of how the absorbed energy is calculated for one gas (nitrogen) is shown below.
Energy = [(4.470)(2553 - 300.15) + (0.00139)(2553² - 300.15²)/2 + (-6.90E-08)(2553³ - 300.15³)/3](1101.2 gmoles)

= [(10,070) + (4,467) + (-382)](1101.2)

= (14,152)(1101.2) = 1.558 x 10⁷ cal

The heat capacity quadratic approximation formula is valid up to 1500 K, but the final temperature is considerably greater, 2553 K. The extrapolation is still accurate because the mixture includes both overestimates and underestimates of energy absorbed, which tend to cancel out the departures from the true heat capacities. The individual differences are all less than 10%. Hence, the final temperature of the post-combustion gas mixture is 2553 K.

From the ideal gas law, the final pressure of the gas mixture is 7.48 atm (95.3 lb/in² gauge) as shown below.

\[ P_f = (1637.15 \text{ gmoles})(0.082058 \text{ L·atm/gmole/K})(2553 \text{ K})/(45,840 \text{ L}) \]

\[ = 7.48 \text{ atm} \]

<table>
<thead>
<tr>
<th>Gas</th>
<th>Stored heat energy (cal) for various Tf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tf= 2500 K</td>
</tr>
<tr>
<td>H₂</td>
<td>0.0</td>
</tr>
<tr>
<td>He</td>
<td>1.236E+05</td>
</tr>
<tr>
<td>H₂O</td>
<td>8.891E+06</td>
</tr>
<tr>
<td>N₂</td>
<td>1.514E+07</td>
</tr>
<tr>
<td>O₂</td>
<td>8.978E+05</td>
</tr>
<tr>
<td>Total:</td>
<td>2.506E+07</td>
</tr>
</tbody>
</table>

The above result for peak pressure in the plume illustrates calculations for the process bay local exhaust system and inside the MCO. As a further example, consider the average effect on the entire process bay. The average pressure is needed to evaluate possible structural damage to the process bay walls and ceiling. For this calculation, the final temperature is based on all the air in the process bay, 1600 m³. This volume is derived from the approximate dimensions of a process bay, 30 ft wide, 60 ft long, and 32 ft to the ceiling. The total number of moles of gas in this volume is calculated from the ideal gas law to be 64,960 gmoles. Assuming 10% relative humidity means the gas composition is as shown in Table B-14.
Table B-14. Process Bay Average Gas Composition.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Pre-combustion</th>
<th>Post-combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inventory (gmoles)</td>
<td>Concentration (percent)</td>
</tr>
<tr>
<td>H₂</td>
<td>446.5</td>
<td>0.60</td>
</tr>
<tr>
<td>He</td>
<td>18.6</td>
<td>0.03</td>
</tr>
<tr>
<td>H₂O</td>
<td>227.3</td>
<td>0.35</td>
</tr>
<tr>
<td>N₂</td>
<td>51,269.9</td>
<td>78.36</td>
</tr>
<tr>
<td>O₂</td>
<td>13,464.8</td>
<td>20.58</td>
</tr>
<tr>
<td>Total:</td>
<td>65,427.1</td>
<td>100.00</td>
</tr>
</tbody>
</table>

All the hydrogen is assumed to react, so the energy liberated is the same as before. However, the final temperature of this gas mixture is much lower than before due to the large number of moles present. The final temperature is determined using the same approach, and turns out to be 379.7 K. The calculation is summarized in Table B-15.

Table B-15. Final Temperature in a Process Bay.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Stored heat energy (cal) for various Tf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tf= 400 K</td>
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<tr>
<td>H₂</td>
<td>0.0</td>
</tr>
<tr>
<td>He</td>
<td>5.608E+03</td>
</tr>
<tr>
<td>H₂O</td>
<td>4.090E+05</td>
</tr>
<tr>
<td>N₂</td>
<td>2.533E+07</td>
</tr>
<tr>
<td>O₂</td>
<td>6.762E+06</td>
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<tr>
<td>Total:</td>
<td>3.250E+07</td>
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</tbody>
</table>

From the ideal gas law, the final pressure of the gas mixture averaged over the process bay is 1.261 atm (3.83 lb/in², or 552 lb/ft² gauge) as shown below. This pressure should be used to evaluate potential damage to the process bay walls and ceiling.

\[
Pf = (65,203.85 \text{ gmoles})(0.082058 \text{ L-atm/gmole/K})(379.7 \text{ K})/(1,611,460 \text{ L})
= 1.261 \text{ atm}
\]
Neither of the above pressures are used to determine the potential injury to an individual nearby. Instead, the equivalent amount of TNT is used to estimate the probability of harm, as discussed in Section B4.0. In this example, the probability of harm at a distance of 4.3 m (14 ft) from the center of the plume will be calculated.

The first step in the procedure described in Section B4.0 is to compute the energy liberated by the combustion of the flammable gas mixture. This is 2.581E+07 cal, assuming that 100% of the hydrogen burns.

The second step is to calculate the equivalent amount of TNT. Because TNT liberates 1,120 cal/g TNT, the thermal equivalent is 23 kg TNT. However, the TNT is assumed to be only 20% as effective. Thus the equivalent amount of TNT is 4.6 kg, as shown below.

\[
\text{Equivalent TNT} = \frac{(2.581E+07 \text{ cal})}{(1120 \text{ cal/g TNT})}/(1000 \text{ g/kg})(0.20) = 4.6 \text{ kg TNT}
\]

The third step is to calculate the scaled distance \(D_s\) and convert this to a pressure. The scaled distance is the distance from the center of the plume to the worker location divided by the cube root of the mass of TNT. It will assumed that the individual is 4.3 m (14 ft) from the center of the plume. The scaled distance is shown below.

\[
D_s = \frac{(4.3 \text{ m})}{(4.6 \text{ kg})}^{1/3} = 2.5855 \text{ m/kg}^{1/3}
\]

This distance is used to determine the blast pressure \(P_{\text{OVER}}\) at the worker location using either a graph or the formula in Section B4.0. To use the formula, the natural logarithm of 2.5855 is 0.94992. Using the formula gives a blast pressure of 14.8 lb/in² at the chosen distance (4.3 m), as shown below.

\[
\ln(P_{\text{OVER}}) = (-0.048076)(0.94992)^4 + (0.293691)(0.94992)^3 \\
+ (-0.199471)(0.94992)^2 + (-2.42227)(0.94992) + (6.68589) = 4.6175
\]

\[
P_{\text{OVER}} = \exp(4.6175) = 101.24 \text{ kPa}
\]

The fourth step is to calculate the values of the probit variable \(Y\) for death by lung hemorrhage and eardrum rupture. This is shown below. Note that \(P_{\text{OVER}}\) has been converted to units of pascal.

\[
Y_{\text{DEATH}} = (-77.1) + (6.91)[\ln(101,240)] = 2.5395
\]

\[
Y_{\text{EAR}} = (-15.6) + (1.93)[\ln(101,240)] = 6.6437
\]

The final step is to convert this to a probability using the integral approximation used to convert the probit variable to a probability (see Section B4.0). The calculation for probability of
death by lung hemorrhage is shown below. The eardrum rupture probability is computed in a
similar manner and turns out to be 95.0%.

\[ X = \left[1 - (0.33267)(2.5395 - 5)\right]^4 = 0.5499 \]

Probability of death = \((0.5499)\left((0.4361836) + (0.5499)(-0.1201676) + (0.5499)(0.937298)\right)/(2.506628)\cdot \exp\left[-(-2.4605)^2/2\right]

\[ = 0.0069 = 0.69\% \]

A small decrease in distance increases this probability of death dramatically. For example, it can be shown that for a distance of 4.0 m (13 ft) from the center of the plume, the probability of death is 8.66%.

The calculations in the section illustrate how the hydrogen calculations in this document were performed.

B11.0 REFERENCES

Abramowitz, M., and I. A. Stegun, 1965, Handbook of Mathematical Functions, Dover

Coward, H. F., and G. W. Jones, 1952, Limits of Flammability of Gases and Vapors,


Center for Chemical Process Safety, 1994, Guidelines for Evaluating the Characteristics of
Vapor Cloud Explosions, Flash Fires, and BLEVEs, American Institute of Chemical
Engineers, New York.


HNF-1777, 1999, K West Basin Integrated Water Treatment System Annular Filter Vessel

HNF-4057, 1999, Cold Vacuum Drying Proof of Performance (First Article Testing) Test
Results, Rev. 0, Numatec Hanford Corporation, Richland, Washington.

HNF-SD-TP-SARP-017, 1998, Safety Analysis Report for Packaging (Onsite) Multi-Canister
Overpack Cask, Rev. 1, Fluor Daniel Hanford, Incorporated, Richland, Washington.


Figure B-1. Lower Flammable limits for Mixtures of Hydrogen, Helium, and Air.
Figure B-2. Multi-Canister Overpack Drain Water Composition.
Figure B-3. Schematic for the Process Water Conditioning Helium Purge Model.

\[(1 - Ka)Cx + KaCa + KbCb\]

\[(1 - Kb)[(1 - Ka)Cx + KaCa]\]

Tank A

Tank B
Figure B-4. Gas Concentrations in Tank A During the Helium Purge.
Figure B-5. Gas Concentrations in Tank B During the Helium Purge.
Figure B-6. Concentration Added to Ventilation System During the Helium Purge.

- **Helium**
  - Smooth Curves: $K_a = 0.5$ & $K_b = 0.5$
  - Rough Curves: $K_a = 0.9$ & $K_b = 0.2$

**Volume of Helium Added, cu.ft**

**Gas Concentration Entering HVAC**

- **Nitrogen**
- **Helium**
Figure B-7. Schematic for the Multi-Canister Overpack Draining Model.

\[
\frac{[(1-Ka)Ca + (1+Ka)Cb]}{2}
\]
Figure B-8. Concentrations in Tank B and Entering the Ventilation System.

- Helium to HVAC
- 75 cu.ft He Purge
- $K_a = 0.9$
- $K_b = 0.2$
- Helium in PWC-2
- Nitrogen in PWC-2
- Nitrogen to HVAC

Volume of Water Drained, cu.ft

SNF-2770 APB

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Figure B-9. Schematic for the Multi-Canister Overpack Breakthrough Model.
ATTACHMENT B1: ISO-PC Output for
High-Efficiency Particulate Air Filters

Start run at 09:37:08 09/28/99

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<tr>
<td>for IBM &amp; Compatible Personal Computers</td>
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<tr>
<td>Nuclear Safety &amp; Radiological Analysis</td>
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<tr>
<td>Westinghouse Hanford Company</td>
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<tr>
<td>Richland, WA  99352</td>
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CVDF HVAC Filters with 1 g SNF Fuel (Safety Source)

Table of Source Activity:

Scale Factor = 1.000E-06

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<th>Isotope</th>
<th>Initial Values</th>
<th>Final Curies</th>
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<td>SR-90</td>
<td>6.93E+03</td>
<td>6.930E-03</td>
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<tr>
<td>Y-90</td>
<td>6.93E+03</td>
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<tr>
<td>CD-113M</td>
<td>2.78E+00</td>
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<td>CS-134</td>
<td>6.47E+00</td>
<td>6.470E-06</td>
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Shield Composition, g/cc

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<tr>
<th>Shield 1</th>
<th>Shield 2</th>
<th>Shield 3</th>
<th>Shield 4</th>
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Local Exhaust HEPA Array -- 3 high & 2 wide

Source Shields
Slab Slab
Thickness = 1.200E+02 cm Height = 1.800E+02 cm Width = 3.000E+01 cm
Volume = 6.480E+05 cc
Integration Specs: NTHETA = 19 NPSI = 59 DELR = 2.000E+00 cm
Total Intervals: 6.726E+04

Shield Thickness, cm 1.200E+02 2.540E+00 1.000E-01
Taylor Buildup Data for Shield 2 with Effective Atomic Number 7.0
Source Scale Factor was 1.000E-06

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<th>Source Total photons/sec</th>
<th>Energy Flux Mev/sq.cm/sec</th>
<th>Dose Rate R/hr</th>
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<tr>
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General Exhaust HEPA Array -- 4 high and 3 wide

Source Slab Shields Distance to Detector, $X = 1.877E+02$ cm
Slab Thickness = 1.800E+02 cm Volume = 1.296E+06 cc
Slab Height = 2.400E+02 cm Width = 3.000E+01 cm
Integration Specs: $N_{THETA} = 19$ $N_{PSI} = 65$ $DEL_R = 2.000E+00$ cm
Total Intervals: 1.111E+05

Shield Thickness, cm 1.800E+02 2.540E+00 1.000E-01
Taylor Buildup Data for Shield 2 with Effective Atomic Number 7.0

Source Scale Factor was 1.000E-06

<table>
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<th>Dose Rate R/hr</th>
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Note that 1.072E-02 R/hr = 7.605E-10 amp/kg
### Raw Text

#### Table

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<th>Group</th>
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**Note that 5.964E-03 R/hr = 4.274E-10 amp/kg**

#### Text

PWC Storage Tank HEPA -- 1 ft by 1 ft by 11.5 in thick

Source Shields Distance to Detector, X = 3.772E+01 cm

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<tr>
<th>Slab</th>
<th>Slab Volume = 2.628E+04 cc</th>
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<td>Thickness = 3.000E+01 cm</td>
<td>Height = 3.000E+01 cm</td>
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<td>Width = 2.920E+01 cm</td>
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</table>

Integration Specs: NTHETA = 19 NPSI = 19 DELR = 1.000E+00 cm

Total Intervals: 1.083E+04

Shield Thickness, cm: 3.000E+01 2.540E+00 1.000E-01

Taylor Buildup Data for Shield 2 with Effective Atomic Number 7.0

Source Scale Factor was 1.000E-06

---

SNF-2770 APB B-53

October 1999
Local Exhaust Prefilter -- Including Virtual Half

Source Shields | Distance to Detector, X = 9.100E+01 cm
Slab Slab Volume = 6.89E+05 cc
Thicknes = 1.500E+01 cm | Height = 1.800E+02 cm | Width = 2.554E+02 cm
Integration Specs: NTHETA = 65 | NPSI = 59 | DELR = 1.000E+00 cm
Total Intervals: 5.752E+04

Shield Thickness, cm 1.500E+01 2.540E+00 1.000E-01
Taylor Buildup Data for Shield 2 with Effective Atomic Number 7.0

Source Scale Factor was 1.060E-06

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### Local Exhaust Prefilter -- Excess Virtual Piece

Source Slab Shields Distance to Detector, $X = 9.100E+01$ cm

<table>
<thead>
<tr>
<th>Source Slab Thickness</th>
<th>1.500E+01 cm</th>
<th>Height</th>
<th>1.800E+02 cm</th>
<th>Width</th>
<th>1.544E+01 cm</th>
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<td>NPSI</td>
<td>59</td>
<td>DELR</td>
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Total Intervals: 1.681E+04

Shield Thickness, cm | 1.500E+01 | 2.540E+00 | 1.000E-01

Taylor Buildup Data for Shield 2 with Effective Atomic Number 7.0

Source Scale Factor was 6.044E-08

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<th>Group</th>
<th>Average Energy, Mev</th>
<th>Bremsstr. photons/sec</th>
<th>Source Total photons/sec</th>
<th>Energy Flux Mev/sq.cm/sec</th>
<th>Dose Rate R/hr</th>
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Note that 2.560E-04 R/hr = 1.835E-11 amp/kg

General Exhaust Prefilter -- Including Virtual Half

Shield Thickness, cm 1.500E+01 2.540E+00 1.000E-01

Taylor Buildup Data for Shield 2 with Effective Atomic Number 7.0

Source Scale Factor was 1.041E-06

<table>
<thead>
<tr>
<th>Group</th>
<th>Average Energy, Mev</th>
<th>Bremsstr. photon/sec</th>
<th>Source Total photon/sec</th>
<th>Energy Flux Mev/sq.cm/sec</th>
<th>Dose Rate R/hr</th>
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General Exhaust Prefilter -- Excess Virtual Piece

Source Shields Distance to Detector, $X = 9.100 \times 10^1$ cm
Slab Slab Volume = $5.558 \times 10^4$ cc
Thickness = $1.500 \times 10^1$ cm Height = $2.400 \times 10^2$ cm Width = $1.544 \times 10^1$ cm
Integration Specs: NTHETA = 19 NPSI = 65 DELR = $1.000 \times 10^0$ cm
Total Intervals: $1.852 \times 10^4$

Shield Thickness, cm

$1.500 \times 10^1$  $2.540 \times 10^0$  $1.000 \times 10^{-1}$

Taylor Buildup Data for Shield 2 with Effective Atomic Number 7.0
Source Scale Factor was $4.112 \times 10^{-8}$

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<th>Source Total photons/sec</th>
<th>Energy Flux Mev/sq.cm/sec</th>
<th>Dose Rate R/hr</th>
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TOTALS $1.305 \times 10^6$  $1.516 \times 10^7$  $7.396 \times 10^1$  $1.535 \times 10^{-04}$

Note that $1.535 \times 10^{-04}$ R/hr = $1.100 \times 10^{-11}$ amp/kg
***> This is the End of the CVDF HVAC Cases!!

Finish run at 09:38:49 09/28/99

Contents of Input file, HEPA-CVD.

0 2 CVDF HVAC Filters with 1 g SNF Fuel (Safety Source)
Local Exhaust HEPA Array -- 3 high & 2 wide
&Input 1Geom= 10, SLTH= 30, Y= 180, T= 120,2.54,0.1, X= 127.72,
NShld= 3, JBuf= 2, NTheta= 19, NPsi= 59, DelR= 2.0,
SFact= 1.0E-6, Weight(472)= 2.09, Next= 1,
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 16 0.16
air 3 0.0012
1 duct 9 7.86
General Exhaust HEPA Array -- 4 high and 3 wide
&Input SLTH= 30, Y= 240, T= 180, X= 187.72, Next= 4,
NTheta= 19, NPsi= 65, DelR= 2 &
PWC Storage Tank HEPA -- 1 ft by 1 ft by 11.5 in thick
&Input SLTH= 29.2, Y= 30, T= 30, X= 37.72,
NTheta= 19, NPsi= 19, DelR= 1 &
Local Exhaust Prefilter -- Including Virtual Half
&Input SLTH= 255.44, Y= 180, T= 15, X= 91,
NTheta= 65, NPsi= 59, DelR= 1, SFACT= 1.060445E-6 &
Local Exhaust Prefilter -- Excess Virtual Piece
&Input SLTH= 15.44,
NTheta= 19, SFACT= 6.0445E-8 &
General Exhaust Prefilter -- Including Virtual Half
&Input SLTH= 375.44, Y= 240,
NTheta= 75, NPsi= 65, SFACT= 1.041125E-6 &
General Exhaust Prefilter -- Excess Virtual Piece
&Input SLTH= 15.44,
NTheta= 19, SFACT= 4.1125E-8 &
This is the End of the CVDF HVAC Cases!!
&Input Next= 6 &

Notes:
There is a 1 inch gap between the filter and the housing.
The housing is represented using a 1 mm iron thickness.
It is assumed that 1 ft = 30 cm for the filter dimensions.
The prefilters are computed using virtual image filters and
removing a piece from the middle.
SFACl is increased to include the piece in the middle.
The unit dose rate for the prefilter/HEPA is given by
UDR = (HEPA DR)(F) + (Prefilter - Virtual)(1 - F)
where F is the fraction of activity on the HEPA.
ATTACHMENT B2: ISO-PC Output for Drained Particulate

Start run at 10:03:01 09/28/99

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<td>for IBM &amp; Compatible Personal Computers</td>
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<tr>
<td>Nuclear Safety &amp; Radiological Analysis</td>
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<tr>
<td>Westinghouse Hanford Company</td>
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<td>Richland, WA 99352</td>
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PWC Tank (2' Diameter) with 1.32 kg SNF Fuel

Table of Source Activity:

Scale Factor = 2.694E-03

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<th>Initial Values</th>
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Shield Composition, g/cc

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<th>Shield 3</th>
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### Group Linear Attenuation Coefficients (last region is air)

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Near 1 inch Drain Line: 1 meter away

Source Shields Distance to Detector, $X = 1.017E+02$ cm

Cylindrical Cylindrical Volume = $2.053E+03$ cc

Source Length = $6.100E+02$ cm Distance Along Cylinder, $Y = 3.050E+02$ cm

Integration Specs: NTHETA = 21 NPSI = 55 DELR = $6.088E-02$ cm

Total Intervals: $1.963E+04$

Shield Thickness, cm 1.035E+00 6.350E-01

Taylor Buildup Data for Shield 3 with Effective Atomic Number 0.0

WARNING: Buildup Factors for photons < 0.1 Mev use an Effective Atomic Number of 4.0

Source activity is interpreted as uCi/cc

Source Scale Factor was 2.694E-03

Average Bremsstr. Source Total Energy Flux Dose Rate

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<th>photons/sec</th>
<th>Mev/sq.cm/sec</th>
<th>R/hr</th>
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TOTALS 1.755E+08 2.039E+09 5.224E+03 1.084E-02

Note that 1.084E-02 R/hr = 7.768E-10 amp/kg

Near 1 inch Drain Line: 3 meters away

Source Cylindrical  Cylindrical Volume = 2.053E+03 cc
Source Length = 6.100E+02 cm Distance Along Cylinder, Y = 3.050E+02 cm
Integration Specs: NTHETA = 21 NPSI = 55 OELR = 6.088E-02 cm
Total Intervals: 1.963E+04

Shield Thickness, cm 1.035E+00 6.350E-01
Taylor Buildup Data for Shield 3 with Effective Atomic Number 0.0

WARNING: Buildup Factors for photons < 0.1 Mev use an Effective Atomic Number of 4.0
Source activity is interpreted as uCi/cc
Source Scale Factor was 2.694E-03

SNF-2770 APB  B-61  October 1999
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**Table of Source Activity:**

Scale Factor = 1.320E-03

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**Note that 2.348E-03 R/hr = 1.683E-10 amp/kg**

---

**Shield Composition, g/cc**

SNF-2770 APB

B-62

October 1999
### Shield 1 | Shield 2 | Shield 3 | Shield 4 | Shield 5
---|---|---|---|---
H2O & 9.998E-01 & 0.000E+00 & & &
AIR & 3.000E-04 & 0.000E+00 & & &
URANIUM & 2.000E-03 & 0.000E+00 & & &
IRON & 0.000E+00 & 7.860E+00 & & &

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<th>(last region is air)</th>
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Near PWC Receiver Tank: 1 meter away

Source Shields Distance to Detector, X = 1.310E+02 cm
Cylindrical Cylindrical Volume = 3.534E+05 cc
Source Length = 1.220E+02 cm Distance Along Cylinder, Y = 6.100E+01 cm
Integration Specs: NTHETA = 31 NPSI = 35 DELR = 1.002E-01 cm
Total Intervals: 3.288E+05

Shield Thickness, cm 3.036E+01 6.350E-01
Taylor Buildup Data for Shield 3 with Effective Atomic Number 0.0

WARNING: Buildup Factors for photons < 0.1 Mev use an Effective Atomic Number of 4.0
Source Scale Factor was 1.320E-03

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<th>Group</th>
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<th>Bremsstr. photons/sec</th>
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<th>Energy Flux Mev/sq.cm/sec</th>
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TOTALS 4.188E+10 4.866E+11 9.558E+05 1.984E+00

Note that 1.984E+00 R/hr = 1.422E-07 amp/kg

Near PWC Receiver Tank: 3 meters away

Source Shields Distance to Detector, X = 3.310E+02 cm

Cylindrical Cylindrical Volume = 3.534E+05 cc

Source Length = 1.220E+02 cm Distance Along Cylinder, Y = 6.100E+01 cm

Integration Specs: NTHETA = 31 NPSI = 35 DELR = 1.002E-01 cm

Total Intervals: 3.288E+05

Shield Thickness, cm 3.036E+01 6.350E-01

Taylor Buildup Data for Shield 3 with Effective Atomic Number 0.0

WARNING: Buildup Factors for photons < 0.1 Mev use an Effective Atomic Number of 4.0

Source Scale Factor was 1.320E-03
**Average Energy, MeV** | **Bremsstr. Source Total Energy Flux** | **Dose Rate R/hr**
---|---|---
1 1.500E-02 | 1.190E+10 | 1.200E+10 | 0.000E+00 | 0.000E+00
2 2.500E-02 | 6.714E+09 | 6.854E+09 | 1.500E-24 | 2.594E-29
3 3.500E-02 | 3.995E+09 | 3.651E+10 | 1.299E-08 | 8.251E-14
4 4.500E-02 | 2.708E+09 | 2.807E+09 | 5.679E-03 | 1.863E-08
5 5.500E-02 | 1.955E+09 | 1.955E+09 | 6.008E-01 | 1.376E-06
6 6.500E-02 | 1.639E+09 | 1.647E+09 | 3.347E+00 | 6.329E-06
7 7.500E-02 | 1.466E+09 | 1.466E+09 | 9.772E+00 | 1.675E-05
8 8.500E-02 | 1.305E+09 | 1.471E+09 | 2.290E+01 | 3.703E-05
9 9.500E-02 | 1.161E+09 | 1.161E+09 | 2.907E+01 | 4.659E-05
10 1.400E-01 | 5.229E+09 | 7.430E+09 | 3.674E+02 | 6.349E-04
11 2.800E-01 | 1.706E+09 | 2.092E+09 | 2.551E+02 | 4.999E-04
12 3.500E-01 | 8.286E+08 | 8.286E+08 | 1.762E+02 | 3.630E-04
13 4.750E-01 | 6.183E+08 | 6.560E+08 | 2.146E+02 | 4.378E-04
14 6.500E-01 | 3.665E+08 | 4.040E+11 | 1.486E+05 | 3.092E-01
15 8.250E-01 | 1.353E+08 | 1.332E+09 | 5.124E+02 | 1.025E-03
16 1.000E+00 | 9.112E+07 | 1.786E+09 | 7.547E+02 | 1.457E-03
17 1.225E+00 | 4.635E+07 | 2.359E+09 | 1.237E+03 | 2.277E-03
18 1.475E+00 | 1.518E+07 | 6.342E+07 | 4.310E+01 | 7.585E-05
19 1.700E+00 | 3.465E+06 | 1.110E+08 | 8.969E+01 | 1.534E-04
20 1.900E+00 | 7.252E+05 | 7.252E+05 | 6.604E-01 | 1.096E-06
21 2.100E+00 | 4.218E+04 | 5.160E+04 | 5.201E-01 | 8.321E-07
22 2.300E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00
23 2.500E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00
24 2.700E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00
25 3.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00

**TOTALS** 4.188E+10 4.866E+11 1.524E+05 3.162E-01

Note that 3.162E-01 R/hr = 2.266E-08 amp/kg

**Table of Source Activity:**

**Scale Factor = 1.320E-03**

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Shield Composition, g/cc

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Group Linear Attenuation Coefficients (last region is air)

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<th>Linear Attenuation Coefficients</th>
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</table>

Near PWC Tank Room: at 3 m through 10 in Concrete

Source Shields Distance to Detector, X = 3.310E+02 cm
Cylindrical Cyl. & Slab Volume = 3.534E+05 cc
Source Length = 1.220E+02 cm Distance Along Cylinder, Y = 6.100E+01 cm
Integration Specs: NTHETA = 31 NPSI = 35 DELR = 1.002E-01 cm
Total Intervals: 3.288E+05

Shield Thickness, cm 3.036E+01 6.350E-01 1.000E+02 2.540E+01

SNF-2770.APB B-66 October 1999
Taylor Buildup Data for Shield 4 with Effective Atomic Number 10.0

Source Scale Factor was 1.320E-03

<table>
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<tr>
<th>Group</th>
<th>Average Energy, Mev</th>
<th>Bremsstr. photons/sec</th>
<th>Source Total photons/sec</th>
<th>Energy Flux Mev/sq.cm/sec</th>
<th>Dose Rate R/hr</th>
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</table>

**TOTALS**

4.188E+10 4.866E+11 3.225E+03 6.674E-03

Note that 6.674E-03 R/hr = 4.783E-10 amp/kg

***> This is the End of the Tank Case!!

Finish run at 10:09:24 09/28/99

Contents of Input file, PWC

| 0 | 2 PWC Tank (2' Diameter) with 1.32 kg SNF Fuel Near 1 inch Drain Line: 1 meter away &Input Next= 1, IGeom= 7, SLTH= 610, Y= 305, T= 1,035,0.635 |
| 0 | NShld= 2, JBuf= 3, NTheta= 21, NPsi= 55, DelR= 0.06, X= 101.67, SFact= 0.002694, IConc= 1, 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 &
H2O 1 0.9997
Air 3 0.0004
U 15 0.0027
Fe 9 7.86
Near 1 inch Drain Line: 3 meters away
&Input Next = 4, X = 301.67 &
Near PWC Receiver Tank: 1 meter away
&Input SLTH = 122, Y = 61, T = 30.365, X = 131, Next = 1,
NTeta = 31, NPsi = 35, DelR = 0.1, SFact = 0.00132, IConc = 0 &
H2O 1 0.9998
Air 3 0.0003
U 15 0.0020
Fe 9 7.86
Near PWC Receiver Tank: 3 meters away
&Input Next = 4, X = 331 &
Near PWC Tank Room: at 3 m through 10 in Concrete
&Input Next = 1, IGeom = 11, T(3) = 100.25.4, X = 331,
NShld = 4, JBuf = 4 &
H2O 1 0.9998
Air 3 0.0003
U 15 0.0020
Fe 9 7.86
I Conc 16 2.35
This is the End of the Tank Case !
&Input Next = 6 &

Notes:
(1) Weight values have units of Ci/MTU. IConc = 1 expects µCi/cc or Ci/m^3
(2) Source composition during draining is the Safety Basis fuel suspended in 490 L water.
   SFact = (1000 L/m^3)(0.00132 MTU)/(490 L) = 0.02694
(3) Drain Line is 20 ft of 1 inch schedule 40 pipe.
(4) Source composition in the PWC tank room is the Safety Basis fuel suspended in 650 L water. The total activity is placed in one tank, rather than halving the activity and doubling the result.
(5) Tank is 4 ft tall, 2 ft diameter, and has a 1/4" wall (OD=62 cm; ID=60.72 cm).
APPENDIX C

SPRAY PROGRAM OUTPUT FOR
SPRAY LEAK BOUNDING CASE
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APPENDIX C

SPRAY PROGRAM OUTPUT FOR SPRAY LEAK BOUNDING CASE

SPRAY Version 3.0
May 3, 1994

Spray Leak Code
Produced by Radiological & Toxicological Analysis
Westinghouse Hanford Company

Run Date = 05/12/99/
Run Time = 13:23:47.54

INPUT ECHO:
c Spray Leak Bounding Case -- 1.5 kg Particulate (Aerodynamic Diameters)
c
C mode iflow iopt
1 0 T
C
C MODEL OPTIONS:
c mode = 1 orifice leak with friction assumed
C 2 slit leak with friction assumed
C iflow= 0 Reynold's number determines friction relation (laminar or turb.)
C 1 friction based on laminar relation
C 2 friction based on turbulent relation
C iopt = T optimal diameter search performed
C F search not performed
C
C PARAMETER INPUT:
c
C Slit Width or Orifice Diam. Slit Length Slit/Orifice
C (inch) (inch) (inch)
C -----------------  ---------  ----------
C 2.00000E-02 0.00000E+00 1.54000E-01
C
C Abs. Surface Contraction Coefficient Coefficient
C Roughness,in. Coefficient
C Pressure 0.00006 tube 0.61 and 0.98 sharp edge orifice
C Difference 0.0018 steel 1.00 and 0.98 rounded orifice
C (psi) 0.0102 iron 1.00 and 0.82 square edge orifice
C -----------------  ---------  --------------
C 6.00000E+01 1.80000E-03 6.10000E-01 9.80000E-01
C
C Fluid Specific Gravity is based on 1.5 kg of particulate matter
suspended in 650 L of solution.

Respirable Diameter is computed from \((4.22 \text{ \mu m}) \times [5(1-1/10)/0.00208]^{1/3}\)

which is the density-adjusted formula.

<table>
<thead>
<tr>
<th>Fluid Specific Gravity</th>
<th>Dynamic Viscosity (centi-poise)</th>
<th>Respirable Diameter (\mu m)</th>
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MESSAGES:
Orifice Model
Code search for optimal equivalent diameter.

OUTPUT:

Liquid Velocity = 7.54E+01 ft/s  2.30E+01 m/s
Reynolds Number = 2.51E+04 Turbulent Flow
Sauter Mean Diameter = 1.82E+02 \mu m
Optimum Diameter = 2.53E-02 in  6.42E-04 m
Respirable Fraction = 2.03E-02
Total Leak Rate = 7.19E-02 gpm  4.54E-06 m3/s  4.55E+00 g/s
Respirable Leak Rate = 1.46E-03 gpm  9.23E-08 m3/s  9.25E-02 g/s
APPENDIX D

PEER REVIEW CHECKLISTS
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CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-2770, Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation, Rev. 3

Scope of Review: Entire document, chapter integration and consistency

Yes No NA

[ ] [ ] [ ] * Previous reviews complete and cover analysis, up to scope of this review, with no gaps.

[ ] [ ] [ ] Problem completely defined.

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[ ] [ ] [ ] Software input correct and consistent with document reviewed.

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[ ] [ ] [ ] 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.

Mark A. Medsker
Reviewer (Printed Name and Signature)

10/18/99
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.

Notes: 1) HEPA filter loading in the unmitigated external hydrogen explosion source terms corresponds to a dose rate of 115 mSv/hr on the filter box (produces 14 mrem @ 100 m in the consequences analysis). HNF-8553. Annex B uses a value of 100 mSv/hr (instead of 115 mSv/hr) which is incorrect. However, there is no impact because the change in the number has no influence on results or conclusions. The SAR analysis is valid but the number should be updated at the earliest convenience.
CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-2770, Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation, Rev. 3, Chapter 2.0, “Calculations for Gaseous Release”

Scope of Review: Entire chapter

Author: P. D. Rittmann and S. D. Kopelic

Yes No NA

[ ] [ ] [ ] * Previous reviews complete and cover analysis, up to scope of this review, with no gaps.

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[ ] [ ] [ ] Document approved.

M. D. Rittmann

Reviewer (Printed Name and Signature)

10/13/99

Date

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CHECKLIST FOR PEER REVIEW

Documentation, Rev. 3, Chapter 3.0, "Calculations for Liquid Release"

Scope of Review: Entire chapter

Author: P. D. Rittmann and S. D. Kopelic

Yes No NA

[ ] [ ] [ ] * Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
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[ ] [ ] [ ] Document approved.

Reviewer (Printed Name and Signature)  

Date

10/13/99

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CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-2770, Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation, Rev. 3, Chapter 4.0, "Calculations for Hydrogen Explosions Outside the Multi-Canister Overpack"

Scope of Review: Entire chapter

Author: P. D. Rittmann

Yes No NA

[ ] [ ] Yes  Previous reviews complete and cover analysis, up to scope of this review, with no gaps.

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[ ] [ ] Yes  Accident scenarios developed in a clear and logical manner.

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[ ] [ ] Yes  Review calculations, comments, and/or notes are attached.

[ ] [ ] No  Document approved.

Reviewer (Printed Name and Signature)  10/13/99

Date

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CHECKLIST FOR PEER REVIEW


Scope of Review: Entire chapter

Author: P. D. Rittmann

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**CHECKLIST FOR PEER REVIEW**


Scope of Review: Entire chapter

Author: M. G. Piepho

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[ ] [ ] [x] Document approved.

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Reviewer (Printed Name and Signature)_________________________ Date 10-13-99
CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-2770, Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation, Rev. 3, Chapter 7.0, “Calculations for Multi-Canister Overpack Overpressurization”

Scope of Review: Entire chapter

Author: M. G. Piepho

Yea No NA
[X] [ ] [ ] * Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
[X] [ ] [ ] Problem completely defined.
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[X] [ ] [ ] Review calculations, comments, and/or notes are attached.

[X] [ ] [ ] Document approved.

Paul Ritterman 10-13-99
Reviewer (Printed Name and Signature) Date

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CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-2770, Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation, Rev. 3, Chapter 7.0, “Calculations for Multi-Canister Overpack Overpressurization”

Scope of Review: Entire chapter

Author: M. G. Piepho

Yes No NA
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[X] [ ] [ ] Document approved.

Paul Rittmann
Reviewer (Printed Name and Signature) 10-13-99

Date

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CHECKLIST FOR PEER REVIEW


Scope of Review: Entire appendix, changes to this revision

Author: T. B. Powers

Yes No NA
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[ ] [ ] [ ] Document approved.

Mark A. Medsker
Reviewer (Printed Name and Signature)

Mark A. Medsker
Date

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Document Reviewed: SNF-2770, Rev. 2, Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation, Appendix A, “Event Tree Analyses for Design Basis Accidents”

Scope of Review: Entire appendix

Author: T. B. Powers

Yes  No  NA
[ ] [ ] [ ] Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
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[ ] [ ] [ ] Document approved.

[ ] [ ] [ ]

Reviewer (Printed Name and Signature) Date

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Peer Review Comments SNF-2770, Rev 2.
Appendix A – Event Tree Analyses for Design Basis Accidents

This appendix was reviewed and comments were provided to the author. Comments were in three areas:

1. Minor editorial comments left to the author’s discretion.
2. Editorial comment on more clearly describing the thermal excursion scenarios that were included in addition to the thermal excursion design basis accident.
3. Technical comment on including operator error when quantifying connector leakage for external hydrogen explosion.

These items were addressed to the reviewer’s satisfaction and the peer review sheet was filled out and approved.

Reviewer (Printed Name and Signature) Date

[Signature]
6/14/99
CHECKLIST FOR PEER REVIEW

Document Reviewed: SNF-2770, Cold Vacuum Drying Facility Design Basis Accident Analysis Documentation, Rev. 3, Appendix B, "Calculations Supporting the Analysis of Hydrogen Explosions at the Cold Vacuum Drying Facility"

Scope of Review: Entire appendix

Author: P. D. Rittmann

Yes No NA
☑ [ ] [ ] * Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
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Melvin D. Pieglo 10/13/99
Reviewer (Printed Name and Signature) Date

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