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PRECLOSURE RADIOLOGICAL SAFETY ANALYSIS FOR
ACCIDENT CONDITIONS OF THE POTENTIAL YUCCA MOUNTAIN REPOSITORY:
UNDERGROUND FACILITIES

by

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ABSTRACT

This preliminary preclosure radiological safety analysis assesses the scenarios, probabilities, and potential radiological consequences associated with postulated accidents in the underground facility of the potential Yucca Mountain repository. The analysis follows a probabilistic-risk-assessment approach. Twenty-one event trees resulting in 129 accident scenarios are developed. Most of the scenarios have estimated annual probabilities ranging from 10^{-11} /yr to 10^{-5} /yr. The study identifies 33 scenarios that could result in offsite doses over 50 mrem and that have annual probabilities greater than 10^{-9} /yr. The largest offsite dose is calculated to be 220 mrem, which is less than the 500 mrem value used to define items important to safety in 10 CFR 60. The study does not address an estimate of uncertainties, therefore conclusions or decisions made as a result of this report should be made with caution.

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EXECUTIVE SUMMARY

This preliminary preclosure radiological safety analysis (PRSA) studies the scenarios, probabilities, and potential radiological consequences associated with postulated accidents in the underground facility of the potential Yucca Mountain repository. This report is a continuation of a previous PRSA study (MacDougall, 1987), which emphasized the surface facilities and was limited in its investigation of underground facilities. The analysis follows a probabilistic-risk-assessment approach at a general level commensurate with the available information and design details of the repository.

To develop the accident scenarios, the underground facility is divided into 14 compartment areas. Both internal and external events are investigated for each compartment. After the screening criteria have been applied, it is found that only accidents in 5 of the 14 compartments have a potential for credible and significant radionuclide releases. Event trees are developed for each of the initiating events that have survived the screening process. Twenty-one event trees resulting in 129 accident scenarios are developed.

The probabilities of the accident scenarios (including the initiating events and the intermediate events) are estimated using both historical data and engineering judgment. Most of the scenarios have estimated annual probabilities ranging from $10^{-11}/\text{yr}$ to $10^{-5}/\text{yr}$.

The radiological dose to a maximally exposed individual at the site boundary is calculated for each scenario. The calculations involve evaluating radioactive material source terms and the release, dispersion, and deposition of these radioactive materials.

Because accidental releases from spent fuel result in larger offsite doses than similar accidents with other waste forms at the repository, this study employs source terms associated with spent fuel to calculate dose consequences. Releases of Kr-85 gas, Cs in the fuel rod gap, and

respirable-size particles of spent fuel are assessed for each accident scenario using the methods and assumptions in MacDougall (1987).

Transport of airborne radioactivity to the site boundary is analyzed by means of an atmospheric dispersion model (MacDougall, 1987) that takes into account deposition of particles on the ground.

Accident doses are calculated for inhalation and immersion pathways using adult breathing rates and dose conversion factors from the previous PRSA.

Thirty-three scenarios with offsite doses larger than 50 mrem and with annual probabilities greater than 10^{-9} /yr are identified. The study determines the largest offsite dose to be 220 mrem, which is less than the 500 mrem value used to define items important to safety in 10 CFR 60 (NRC, 1986).

The study does not address an estimate of uncertainties therefore conclusions or decisions made as a result of this report should be made with caution.

1.0 INTRODUCTION

To determine that the underground facilities of the potential Yucca Mountain repository can be safely operated without undue risk to the public, a preliminary radiological safety analysis (PRSA) must be performed. This report describes and presents the results of such an analysis.

1.1 Purpose

The primary purpose of this PRSA study is to establish a base from which items important to safety can be identified (at a later time) for the underground facilities of the potential Yucca Mountain repository. Items important to safety would then be included in a Q-list, which identifies items that receive special attention during design, fabrication, and construction. This study is a continuation of a previous PRSA study (MacDougall, 1987), which emphasized the surface facilities, and uses the same approach as was used in that earlier effort. A probabilistic-risk-assessment (PRA) approach is employed to develop credible scenarios for site-specific and repository-design-specific accidents that could result in significant offsite releases of radioactive materials. The annual probabilities of these accident scenarios and the corresponding radiological doses at the site boundary are determined.

In addition to establishing a base from which a Q-list can be determined, the results of this study can be used to (1) recommend changes to the current repository design, (2) assist in establishing a set of design basis accidents for the repository, and (3) help define the design requirements and design classifications for the structures, systems, and components of the repository. Because the repository has very little regulatory guidance and no licensing precedent, subsequent use of the study results for establishing design basis accidents and design requirements is expected to be as important as their use in the development of a Q-list.

1.2 Scope

This study is limited to preclosure operations in the underground facilities; retrieval, closure, and criticality safety issues are not considered. The study addresses only offsite radiological exposures to the public during accidents; it does not address the question of worker exposure during accidents. To evaluate the potential offsite radiation doses caused by postulated accidents in the underground areas, a modified and simplified PRA-type approach (NRC, 1983) is developed here.

This study also includes a preliminary review of literature for available computer codes and analytical models for evaluating airborne radionuclide transport in the underground facilities (see Appendix A).

The main features of the study are as follows:

- o A systematic application of the PRA-type assessment methods to the potential repository underground facility design in MacDougall (1987)
- o An approach based on the engineering judgment of experienced engineers when data or design details have not yet been developed or are not available for this facility
- o Analyses that are specific to the Yucca Mountain site and the underground facility design
- o Interactions and discussions between the PRSA study team and underground facility designers

1.3 Report Organization and Approach

This report consists of nine chapters and four appendices.

Section 1.0 is an introduction.

Section 2.0 presents the study bases.

Section 3.0 describes the development of accident scenarios as well as the event tree analyses.

Section 4.0 gives the assessments of annual probabilities for the developed event trees.

Sections 5.0 and 6.0 present the modeling for radiological release and transport, respectively.

Section 7.0 describes the dose analysis.

Section 8.0 discusses and summarizes the results of this study.

Section 9.0 presents the references used in this study.

Appendices are included at the end of this report. Specifically, Appendix A gives a review of transport mechanisms that are anticipated in the underground facility. Several available computer codes are also briefly described. Appendix B presents the interaction matrices that are used to identify the initiating events of accidents in the underground facilities. Appendix C gives the fault diagrams for the intermediate events. Information used from or that should be included in the RIB or SEPDB is discussed in Appendix D.

2.0 BASES FOR STUDY

2.1 Reference Facility Description and Operations

The reference facility design for the potential Yucca Mountain Nuclear Waste Repository used in this PRSA study corresponds to the Site Characterization Plan-Conceptual Design Report (SCP-CDR) by MacDougall (1987). Because this design is conceptual, detailed information to support the analyses is often absent or sparse. A summary of the repository design is given in this section.

2.1.1 Repository Design Summary

The potential repository site is located at Yucca Mountain in Nye County, Nevada, about 85 miles northwest of Las Vegas. The overall site is composed of surface and underground facilities linked by a combination of shafts and ramps, as shown in the perspective sketch and overall site plan in Figures 2-1 and 2-2, respectively.

The repository design is based on disposal of 3,000 MTU/yr spent fuel and 400 MTU/yr vitrified high-level waste (HLW). The spent fuel will be received as PWR and BWR fuel assemblies. The fuel assemblies will be consolidated at the repository, and the fuel rods will be placed in containers for disposal. The vitrified HLW will be received in canisters and overpacked in containers for disposal. Over the facility operating life, a total of up to 70,000 MTU spent fuel and vitrified HLW will be emplaced. Disposal will be in vertical boreholes located in the floor of emplacement drifts.

The underground facilities are located below the ridgeline of Yucca Mountain. A ramp is used for transporting waste from the surface to the underground disposal area. Another ramp is used to convey mined tuff to the surface. Four vertical shafts (two exploratory shafts, an emplacement exhaust shaft, and a men and materials shaft) are located near the northeast boundary of

CENTRAL SURFACE FACILITIES

Figure 2-1
Tuff Repository Perspective Sketch

the underground waste emplacement or disposal area. The shafts, shown in Figures 2-1 and 2-2, are used for underground ventilation and for access of personnel, supplies, and equipment. During repository operations, mining development areas are separated from the underground emplacement areas (where radioactive materials are handled) by partitions. These partitions serve as ventilation and access barriers. No radioactive materials are permitted in the underground mining development area.

2.1.2 Underground Development

Underground development includes mining, installation of ground support (e.g., rock bolts), excavation of emplacement boreholes, installation of utilities, and construction of support facilities such as shops, warehouses, and offices. The major elements are listed in Table 2-1.

2.1.3 Underground Facilities Accesses

Two ramps and four shafts provide access to the underground facility. These ramps and shafts are designed to permit sealing and backfilling to the extent necessary for decommissioning the repository.

These accesses also provide routes for air intake and exhaust. The ventilation system design uses the shafts and ramps in a way that separates the ventilation for the waste emplacement area from the ventilation for the development area.

The waste ramp includes a paved roadway suitable for the waste transporter to safely move the waste from the waste-handling buildings to the emplacement area. In sections of the waste ramp that are longer than 400 ft, the slope is less than 10 percent. Current design criteria allow grades of up to 15 percent in

Table 2-1

MAJOR ELEMENTS OF THE UNDERGROUND FACILITIES

Element	Functions
Shafts and ramps	
Waste ramp	Provides sole access for the waste transporter. Serves as the ventilation intake for the waste emplacement areas
Tuff ramp	Serves as the primary haulageway for excavated tuff and as the primary exhaust airway for the development area
Men-and-materials shaft	Provides transportation for personnel and materials. Serves as the main utilities route and as the ventilation intake for the development area
Emplacement area exhaust shaft	Carries exhaust air from the waste emplacement area
Exploratory shaft 1 (ES-1)	Serves as the primary intake of ventilation air for the waste emplacement area
Exploratory shaft 2 (ES-2)	Serves as the secondary intake of ventilation air for the waste emplacement area
Access mains	
Waste main	Connects waste ramp with access drifts. Serves as the sole access to the panels for the waste transporter and as the ventilation intake for the waste emplacement area
Tuff main	Serves as the main haulageway for excavated tuff. Carries exhaust air from the development area
Service main	Provides access from the men-and-materials shaft to the development area for personnel, supplies, and machinery. Carries ventilation air to the development area.
Drifts	
Panel access drifts	Provide access to the emplacement drifts
Emplacement drifts	Contain emplacement boreholes
Perimeter drift	Serves as an exhaust airway from the waste emplacement area to the waste emplacement area exhaust shaft
Other facilities	
Development area shops	Supports development operations
Waste emplacement area shops	Supports waste emplacement operations
Training area	Provides space in the waste emplacement area for the training of personnel who perform emplacement and retrieval operations
Performance confirmation area	Consists of one or more areas that are highly instrumented and monitored to collect data for the performance confirmation program
Exploratory shaft facility	An area designated for obtaining data on site characteristics, mining, opening stability, and other information important to the design and to predicting repository performance

segments less than 400 ft. The ramp is ventilated by an approximate maximum of 300,000 ft³/min of fresh air to dilute fumes generated by the transporters operating on the ramp and to supply a part of the intake air for the waste emplacement area. A large turning radius at the base of the ramp facilitates entry into the underground facility.

The men-and-materials shaft affords access for men and materials and serves as an air intake for the development area. An approximate maximum of 410,000 ft³/min of air enters the repository through this shaft. The shaft furnishes convenient access to the development area shops as well as to the remainder of the underground facilities. This shaft is equipped with a large men-and-materials cage, a small service elevator (for four to six people), and an access for utilities.

The exhaust shaft for the waste emplacement area is near the first panels east of the perimeter drift. This location facilitates the use of the shaft as an exhaust pathway. The maximum flow of air through this shaft is 840,000 ft³/min. The surface location is suitable for the exhaust filtration facilities.

The tuff ramp is used for removing excavated tuff and ventilation exhaust from the development area. An approximate maximum of 350,000 ft³/min of exhaust air travels up the ramp in the vertical emplacement configuration. The ramp is large enough to provide limited access for large machinery during construction and operation of the subsurface facility.

The site characterization program specified in 10 CFR 60.10 (NRC, 1986) includes construction of a shaft to permit testing at the depths at which waste will be emplaced. At Yucca Mountain, the exploratory shafts include a main 12 ft dia. shaft (ES-1) and a 6 ft dia. shaft (ES-2). The two exploratory shafts serve as air intakes for the waste emplacement area during the emplacement phase. The shafts bring a maximum of approximately 480,000 ft³/min

of air into the waste emplacement area, the emplacement area shops, and the underground decontamination facility.

Additional design information and details of the underground facilities accesses are found in MacDougall (1987).

2.1.4 Underground Facilities

In the reference design of the underground repository, containers are placed in vertical boreholes in the floor of each emplacement drift. The subsurface facility access and emplacement drifts for the vertical configuration are shown in Figure 2-3.

The layout boundary for underground facilities encompasses over 2,000 acres, which exceeds the approximately 1,400 acres required for disposal of the total waste receipts of 70,000 MTU.

The underground repository is divided by three main drifts - the waste main, the tuff main, and the service main. A perimeter drift encircles the repository. Each emplacement panel is bounded by parallel panel access drifts, the perimeter drift, and one of the main drifts. Parallel emplacement drifts, containing the emplaced waste, run perpendicular to the access drifts and equally spaced for the length of the panel. Vertical emplacement layout and panel layout are shown in Figures 2-4 and 2-5, respectively.

Other areas in the underground facility include emplacement service shops, development service shops, training areas, a decontamination area, and a performance confirmation area.

Ventilation barriers and access controls are provided between the waste emplacement area and the development area. To prevent leakage of potential radioactive contamination, ventilation air in the emplacement area is maintained at a lower pressure than ventilation in the development area.

Figure 2-3
Subsurface Facility Access and Emplacement Drifts

DETAIL 1 OF
VERTICAL EMPLACEMENT OF
COMMINGLED WASTE

WASTE MAIN
25' DIA.

TUFF MAIN
19'H X 25'W

SERVICE MAIN
15'H X 25'W

23' DIA
PERIMETER DRIFT

Figure 2-4
Vertical Emplacement Layout

Figure 2-5
Panel Layout

Figure 2-6 illustrates the material handling and unit operations associated with the emplacement of spent fuel and DHLW.

The basic operations required to emplace a waste package include the following:

- o Install a temporary shielding mechanism around the waste emplacement borehole
- o Load the waste package into a shielded cask or underground transporter at the surface storage vault
- o Move the loaded transporter underground through the waste ramp, waste main, panel access drift, and emplacement drift to the vertical emplacement borehole
- o Lower the waste package through the temporary shielding mechanism into the borehole
- o Install a shielding device above the emplaced waste package
- o Remove the temporary shielding mechanism
- o Install a plug (cover) on the borehole

Site-generated wastes packaged in drums or boxes will be shipped off site for disposal, rather than emplaced in the underground repository.

2.2 PRSA Methodology

This study of underground accidents is a continuation of the preclosure radiological safety analysis (PRSA) performed for the repository surface facilities (MacDougall, 1987), and follows the same approach as that previous study.

Figure 3-14.

Because of the lack of available design details for the repository underground design, this study uses a modified level 3 PRA-type analysis (such as that performed in MacDougall (1987)). The method and the sequence used in this phase of the PRSA study is schematically described in Figure 2-7. Initiating events, both internal and external, are first identified and screened on the basis of their potential contribution to credible and significant offsite releases of radioactive materials during the preclosure period. Event-tree analysis is used to develop accident scenarios for those initiating events surviving the screening criteria.

The key issue for developing event trees is identifying and defining the intermediate events (event tree headings). Because the repository design is in the conceptual stage, the event trees are constructed to a level of detail commensurate with the available design information. For example, some intermediate events involve combinations of failures of more than one system or component.

When the event trees are developed, the associated probabilities and consequences are then quantified. For each initiating event, the study estimates the probability that the event will occur in a given time period (e.g., 1 yr). Also, the conditional probabilities of each intermediate event are evaluated. (These probabilities of intermediate events are based on the condition that the initiating event occurs.) The probabilities are determined using historical data and engineering judgment. The consequence analyses involve the development of models and estimates of the release, dispersion, and transport of radionuclides in the environment as well as calculations of radiological doses.

Figure 2-7
Preclosure Radiological Safety Analysis (PRSA) Method

Based on the results of the event tree quantifications, the dominant or most important scenarios are selected as the reference accident scenarios. These reference accident scenarios are those that result in radiological doses of more than 0.05 rem at the site boundary with probabilities of more than 10^{-9} in a given year. The reference scenarios will need to be further evaluated to determine if any structures, systems, or components in the underground facilities should be on the initial Q-list, as discussed in MacDougall (1987).

2.3 Major Assumptions

The major assumptions and methods used in this study are consistent with those in the initial PRSA in Appendix F of MacDougall (1987). A brief summary of these assumptions follows:

- o The SCP-CDR conceptual design (two-stage facility with consolidation) is used as the reference configuration.
- o Site-generated wastes are shipped off site for disposal.
- o Emplacement containers involved in the underground accident scenarios contain consolidated fuel rods from six PWR fuel assemblies. This is a typical container loading (some containers hold slightly more and some contain less MTU).
- o If a container accidentally drops, airborne particles will be generated. The same fraction of airborne fuel particles will be generated for all scenarios involving severe impact on the fuel. This fraction of 2×10^{-4} is taken from Appendix F of MacDougall (1987).
- o Depletion of airborne radionuclides in the underground facility due to gravitational settling and other deposition mechanisms is neglected. This introduces conservatism in the calculations because some respirable particles would actually be deposited on the underground surfaces rather than be released to the atmosphere as assumed here.

The above assumptions are consistent with those in MacDougall (1987). The following two assumptions are specifically introduced for this study:

- o This study uses spent fuel radionuclide inventories specified by Roddy (1986). The previous PRSA (MacDougall, 1987) used inventories specified by Alexander (1977). These two inventories result in a difference in dose calculations of a few percent.
- o Sr-90 is not considered in the gap releases in this study. This is considered to be more realistic than the analysis in MacDougall (1987), which included releases of Sr-90 from the fuel rod gap. Strontium has a high vapor pressure (Weast, 1984) and therefore would not be volatile at the normal temperatures in the underground facility. Gap releases would include only gases and volatile or semivolatile materials in the space between the fuel rods and cladding.

3.0 DEVELOPMENT OF ACCIDENT SCENARIOS

This section consists of three subsections:

- o Subsection 3.1 Compartment Modeling
- o Subsection 3.2 Identification and Screening of Initiating Events
- o Subsection 3.3 Development of Event Trees

3.1 Compartment Modeling

In developing accident scenarios, it is useful to divide the underground repository into different areas. This procedure, called "compartment modeling," facilitates the safety assessment and focuses attention on all major parts of the underground facility. In this study, activities within each compartment and interactions between compartments are considered.

The underground facility includes two major areas: (1) a waste emplacement area, where the radioactive waste is handled and emplaced, and (2) a mining and development area, where no waste is handled. Even though no waste is handled there, the mining and development area is considered in this report because accidents in that area may affect the waste in the emplacement area. These two major areas are subdivided into eight and six compartments, respectively, as shown in Figure 3-1.

Each compartment is evaluated to identify the key factors essential to the comprehensive development of accident scenarios, such as the associated waste forms, equipment, operations, and functions. These evaluations were performed by mining experts and experienced safety analysts. Table 3-1 describes the key factors for each compartment of the underground facilities.

Table 3-1

KEY FACTORS ASSOCIATED WITH EACH COMPARTMENT

<u>Compartment</u>	<u>Waste Form</u>	<u>Equipment</u>	<u>Operations/Functions</u>
1. Waste ramp	Container (spent fuel or DHLW) in transporter cask Outgoing site-generated waste from decontamination activities	Transporter and cask Spent fuel container DHLW container Utility trucks Electrical cables	Loaded and empty transporters, trucks, or vans drive down/up waste ramp Ventilation intake for the waste emplacement areas One-way traffic only
2. Performance confirmation area	Container (spent fuel or DHLW) in transporter cask Container in borehole with shield plug off Container in sealed (plugged) borehole	Monitoring and testing instrumentation Transporter and cask Shield plugs Shielding closures Plug installer Spent fuel container DHLW container Shielded forklift Electrical lines Air doors	Emplace/remove waste containers Install/remove shielding closure Install/remove shielding plugs Monitoring and testing
3. Waste emplacement area shops	None	Refueling tanks and equipment Welding equipment Hydraulic fluids & lubricants Bulkheads Automotive parts Machine shop equipment Electrical instrumentation Fire truck Ambulance Utility systems Air compressors	Supports waste emplacement operations Equipment maintenance (repairs, oil changes, refueling) Equipment fabrication Emergency medical operations QA check
4. Waste main	Container (spent fuel or DHLW) in transporter cask	Transporter and cask Spent fuel container DHLW container Bulkheads Forklifts Utility vehicles Personnel transporters	Moving transporter, truck, van, or forklift Moving empty transporter Ventilation intake for waste emplacement area Connects waste ramp with panel access drifts Two-way traffic

Table 3-1 (Cont'd)

<u>Compartment</u>	<u>Waste Form</u>	<u>Equipment</u>	<u>Operations/Functions</u>
5. Panel access drift	Container (spent fuel or DHLW) in transporter cask	Transporter & cask Bulkheads & doors Spent fuel containers DHLW containers Forklifts Utility vehicles Utility lines	Moving loaded transporter Moving empty transporter Provide access to emplacement drifts Two-way traffic
6. Emplacement drift	Container (spent fuel or DHLW) in transporter cask Container in borehole with shield plug off Container in sealed (plugged) borehold	Transporter and cask Shield plugs Shielding closures Plug installer Spent fuel container DHLW container Shielded forklift Electrical lines Air doors Radiological monitors	Emplace/remove waste containers Install/remove shielding closure Install/remove shield plugs Traffic
7. Emplacement exhaust shaft	None	Inspection/escape hoist Radiological monitors HEPA filters (part of associated surface facility)	Ventilation exhaust for emplacement area
8. Decontamination facility	Contaminated equipment Transporter Forklift Shield plug Shielding closure Contaminated waste Rags, paper, clothing Water/detergents Grease/oils Solvents	Ambulance Transporter Forklifts Radcon/transfer casks Movable shields Tow vehicles Utility vehicles Front-end loader Radiation detectors Portable electrical generators Fire suppression equipment Remote manipulation equipment	Decontamination of equipment Cleanup following underground radiological accident Emergency medical treatment Sign-in/sign-out register Dosimetry control

Table 3-1 (Cont'd)

<u>Compartment</u>	<u>Waste Form</u>	<u>Equipment</u>	<u>Operations/Functions</u>
9. Mains (waste, tuff, service) under development	None	Tunnel boring machine Explosive loader Explosives Roof bolter Bulkheads Load-haul-dump (LHD) machines Belt drives and conveyors Transfer points Jumbo drills Personnel transporter Utility vehicles	Drilling and blasting Tunnel boring Installing ground control Tuff main carries exhaust air from development area Service main carries ventilation air to development area Tuff main used for removing excavated tuff
10. Drifts (emplacement panel access perimeter) under development	None	Tunnel boring machine Pilot hole drill Reamer drill Bulkheads Explosives Roof bolter Explosives loader Load-haul-dump (LHD) machines Belt conveyors and crushers Jumbo drills	Drilling and blasting Tunnel boring Installing ground control Borehole drilling/lining Perimeter drift exhausts air from development area
11. Development area shop	None	Electrical substations Diesel fuel and oil Hydraulic fluids Tires Batteries Welding gases Bulkheads Fire suppression General warehouse	Support development operations Equipment repair/maintenance Welding operations (blowing fans)
12. Men-and-materials shafts	None	Elevators Hoisting cages Utility lines	Provides transportation for personnel and materials (including explosives) Main utilities route Ventilation intake for development area

Table 3-1 (Cont'd)

<u>Compartment</u>	<u>Waste Form</u>	<u>Equipment</u>	<u>Operations/Functions</u>
13. Exploratory shafts	None	Inspection/escape hoist	Ventilation intake for emplacement area
14. Tuff ramp	None	Belt conveyor Belt drives Utility vehicles Load-haul-dump (LHD) machines Jumbo drills Utility lines	Excavated tuff removed Alternative access for equipment and supplies Ventilation exhaust for development area

3.2 Identification and Screening of Initiating Events

The flow diagram in Figure 3-2 depicts the general approach for identifying and screening initiating events. This approach results in a logical, systematic, and comprehensive analysis of the underground facilities.

Both external and internal initiating events are evaluated. External events are those caused by natural phenomena or human activities external to the repository. Internal events are those caused by failures or operator activities at the repository.

3.2.1 External Events

External initiating events that may cause significant radiological releases from the underground facility to the environment are identified and screened. The methodology follows that of MacDougall (1987). A comprehensive checklist for external initiating events, including both natural phenomena and human activities, is taken from MacDougall (1987), as shown in Table 3-2. The checklist was distributed to a panel of experienced engineers to eliminate some of the external events from further analysis. External events were eliminated if they met one or more of the following criteria:

- o The external event is either not applicable to the Yucca Mountain site or not credible.
- o The external event will not cause any significant radiological releases to the environment.
- o The external event is beyond the scope of this study.
- o The effect of the external event has been considered within the design basis of the repository. (The repository is designed to withstand the effects of the event.)

IDENTIFICATION AND SCREENING OF INITIATING EVENTS

Figure 3-2

Flow Diagram for Identifying and Screening
Initiating Events

Table 3-2

CHECKLIST OF EXTERNAL INITIATING EVENTS

Seismic activity (faulting, shear zone)	Coastal erosion
Flooding (storm, river diversion)	High tide, high lake level, or high river stage
Lightning	Hurricane
Volcanic activity	Low lake or river water level
Weather fluctuations and extremes (fog, frost, hail, drought, high temperature, low temperature, rapid thaws, ice cover, snow, etc.)	Meteorite impact
Chemical effects (release of chemicals stored on site, e.g., toxic gas)	Seiche
Sandstorm	Tsunami
Tornado	Dam failure
Extreme wind	Waves
Industrial activity induced accident	Undetected features and processes (breccia pipes, lava tubes, gas or brine pockets, etc.)
Military accident (weapons testing, aircraft impacts, bombing range)	Sedimentation
Crash of a commercial aircraft (helicopter, passenger planes, etc.)	Subsidence
Undetected past intrusion (undiscovered boreholes or mine shafts)	Landslide
Sabotage	Uplifting
Fire (forest fire)	Thermal loading (differential elastic response, nonelastic response, fluid pressure changes, fluid migration, canister migration, etc.)
Pipeline accident (gas, etc.)	Geochemical alterations
Loss of offsite power	Waste and rock interactions
Improper design/operation (shaft seal failure, improper waste emplacement, etc.)	Rock deformation
Perturbation of groundwater system (establishment of population center, reservoirs, irrigation, intentional artificial recharge, etc.)	Glaciation
Avalanche	Dissolution
Static fracturing (surficial fissuring, impact fracturing, hydraulic fracturing)	Epeirogenic displacement (igneous emplacement, isostasy)
Denudation and stream erosion	Orogenic diastrophism (near-field faulting, far-field faulting, diapirism, diagenesis)
Magmatic activity (extrusive, intrusive)	Rockburst

The results of the screening for the underground facility are shown in Table 3-3. Only seismic activities are selected for further analysis.

3.2.2 Internal Events

Internal initiating events that have the potential of causing significant radiological releases from the underground facility to the environment are also identified and screened. The methodology also follows that described in MacDougall (1987).

3.2.2.1 Identification of Initiating Events

Two different methods are used to establish a comprehensive set of site-specific and underground-design-specific initiating events (MacDougall, 1987). In one method, a standardized accident scenario survey form is developed. In the other method, interaction matrices for all underground compartments are developed.

Survey Form Method. An example of the survey form is given in Figure 3-3. This form includes such items as a description of the initiating event (cause of failure), the annual probability of the event, and the possible consequence. The probability ranking system is taken from MacDougall (1987) and is shown in Table 3-4. The survey form was distributed to a panel of experienced underground design engineers, who completed the survey form for each underground compartment based on the information in Table 3-1.

Interaction Matrices Method. In this method, the key factors shown in Table 3-1 are used to identify major structures, systems, and equipment in each compartment. These items are then included in the rows and columns of an interaction matrix. Each row in

Table 3-3

EXTERNAL INITIATING EVENT SCREENING

<u>Events Selected for Consideration</u>	<u>Events with Insignificant Radiological Consequences</u>
Seismic activity	Loss of offsite power
<u>Events Not Applicable to Yucca Mountain or Not Credible</u>	Flooding
Volcanic activity	Undetected geologic features (joints)(a)
Aircraft crash (commercial)	Weather fluctuations and extremes
Undetected past intrusion	Extreme wind
Inadvertent intrusion	Sandstorm
Forest fire	Lighting
Pipeline accident	<u>Events Beyond this Study Scope</u>
Groundwater perturbation	Military accident (including aircraft impacts)
Avalanche	Sabotage
Coastal erosion	Orogenic diastrophism
High tide	<u>Events with Impact Considered within the Design Basis</u>
Hurricane	Thermal loading(b)
Low lake level	Waste and rock interaction
Meteorite impact	Rock deformation
Seiche	Geochemical alteration
Tsunami	
Dam failure	
Waves	
Sedimentation	
Subsidence	
Uplifting	
Glaciation	
Dissolution	
Static fracturing	
Stream erosion	
Magmatic activity	
Epeirogenic displacement	
Intentional intrusion (drilling)	
Tornado	
Landslide	
Undetected features and processes (breccia pipes, lava tubes, gas or brine pockets)	
Chemical effects	
Industrial activity accident	

(a) Undetected features (joints) include the formation of movable blocks that slide into boreholes.

(b) The heat generated by the waste forms will not rupture or crack the containers.

Compartment	Waste Present (Y or N)	Initiating Event (Cause of Failure)	Possible Effects and Consequences	Frequency (per year) ^a (1,2,3, or 4)	Consequence Category ^b (1,2, and/or 3)	Summary of Scenarios

- a) Frequency Categories:
1. Anticipated
 2. Unlikely
 3. Very Unlikely
 4. Incredible
- b) Consequence Categories:
1. Radiological Exposure
 2. Occupational Injury
 3. Cost Production/Schedule

Figure 3-3
Accident Survey Form

Table 3-4
PROBABILITY RANKING SYSTEM

Category	Type of Event		Range of Expected Occurrences for Repository	
	Reference	Possible Alternatives	Possible Alternatives	Numerical per Year
1	Anticipated	Expected	Yes, during lifetime	Once per year to once per 10 years ~10 ⁻¹
2	Unlikely	Infrequent	Maybe, during lifetime	One per 10 years to once per facility lifetime ~10 ⁻²
3	Very unlikely	Design bases	No, during lifetime	Once per facility lifetime to will not happen ~10 ⁻⁴
4	Not credible		Do not need to consider	Will not happen at the site <10 ⁻⁶

each matrix is analyzed on a column-by-column basis to identify possible interactions between items. The interaction matrices for each compartment are included in Appendix B.

The results of the survey and those of the interaction matrices are then compared, and a checklist of internal initiating events is compiled. The list, presented on a compartment-by-compartment basis, is shown in Table 3-5.

3.2.2.2 Screening of Initiating Events

The comprehensive checklist is screened to eliminate the internal events that do not require further analysis. Internal events are eliminated if they meet any of the following criteria:

- o The probability of the internal initiating event is sufficiently small that the event is not credible.
- o The internal initiating event will not cause any significant radiological releases to the environment.
- o The internal initiating event is beyond the scope of this study.
- o Because of similar consequences or similar accident scenarios, the internal initiating event can be combined with other internal initiating events.

The results of the screening are shown in Table 3-6. The 16 internal initiating events surviving the screening process and the one external event (earthquake) are listed in Table 3-7. These events and various intermediate events are discussed in Section 4.0.

On the basis of the above screening, no internal initiating events in the mining and development area could threaten the integrity of

Table 3-5

CHECKLIST OF INTERNAL INITIATING EVENTS

<u>Compartment #1: Waste Ramp</u>	<u>Compartment #5: Panel Access Drift</u>
Transporter collision with structure or stationary object Transporter collision with moving object Runaway (uncontrolled) transporter accident Drift collapse	Transporter collision with structure or stationary object Transporter collision with moving object Runaway (uncontrolled) transporter accident Drift collapse
<u>Compartment #2: Performance Confirmation Area</u>	<u>Compartment #6: Emplacement Drift</u>
Container failure due to overstress resulting from fabrication problem (e.g., failure of container pintle or container rupture), which may lead to container drop during emplacement or retrieval Transporter grapple or hoist failure, in which container is dropped into borehole Transporter collision with structure or stationary object Transporter collision with moving object Transporter slides during container handling (e.g., stabilizing jacks on transporter sink, slide, or fail during emplacement or retrieval) Explosion due to volatile gases in the underground Drift collapse Container damage during emplacement or removal of containers Failure of hydraulic lifting system on transporter during lift Equipment malfunction of shield closure device during emplacement or retrieval	Container failure due to overstress resulting from fabrication problem (e.g., failure of container pintle or container rupture), which may lead to container drop during emplacement or retrieval Transporter grapple or hoist failure, in which container is dropped into borehole Transporter collision with structure or stationary object Transporter collision with moving object Transporter slides during container handling (e.g., stabilizing jacks on transporter sink, slide, or fail during emplacement or retrieval) Explosion due to volatile gases in the underground Drift collapse Container damage during removal or emplacement of container Failure of hydraulic lifting system on transporter during lift Equipment malfunction of shield closure device during emplacement or retrieval
<u>Compartment #3: Waste Emplacement Area Shops</u>	<u>Compartment #7: Emplacement Exhaust Shaft</u>
Explosion/fire at diesel fuel refueling stations Fire resulting from used oil collection processes Explosion resulting from pressurized gases in welding shop	Collision of waste transporter and explosives truck near base of shaft
<u>Compartment #4: Waste Main</u>	<u>Compartment #8: Decontamination Facility</u>
Transporter collision with structure or stationary object Transporter collision with moving object Runaway (uncontrolled) transporter accident Drift collapse	Mechanical failure of containment system for contaminated water
	<u>Compartment #9: Mains (Waste, Tuff, Service) Under Development</u> Accidents due to use of explosives

Table 3-5 (Cont'd)

<u>Compartment #10: Drifts (Emplacement, Panel Access, Perimeter) Under Development</u>	<u>Compartment #12: Men-and-Materials Shaft</u>
Drift collapse	Rupture of fuel pipeline
Accidents due to use of explosives	Rupture of water line
	Explosions due to commercial explosives and pressurized gases
<u>Compartment #11: Development Area Shops</u>	<u>Compartment #13: Exploratory Shafts</u>
Explosion/fire at diesel fuel refueling station	None
Fire resulting from used oil collection	<u>Compartment #14: Tuff Ramp</u>
Accidental detonation of commercial explosives	None
Explosion resulting from pressurized gases in welding shop	

Table 3-6

INTERNAL INITIATING EVENT SCREENING

Events Selected for Consideration

Transporter collision

Runaway (uncontrolled) transporter accident

Container failure

Transporter grapple or hoist failure

Transporter slide

Drift collapse

Events That Are Not Credible

Explosion due to volatile gases in the underground

Collision of waste transporter and explosives truck near base of shaft

Events with Insignificant Radiological Consequences

Failure of hydraulic lifting system on transporter during lift

Explosion/fire at diesel fuel refueling stations

Fire resulting from used oil collection processes

Explosion resulting from pressurized gases in welding shop

Mechanical failure of containment system for contaminated water

Accidents due to use of explosives

Rupture of fuel pipe

Rupture of water pipe

Events Combined with Other Initiating Events

Transporter collision with structure or stationary object and transporter collision with moving object (combined into one event, called transporter collision)

Container damage during emplacement or removal of containers (combined with container failure)

Equipment malfunction of shield closure device during emplacement or retrieval (combined with transporter slide)

Table 3-7

FINAL LIST OF UNDERGROUND INITIATING EVENTS

<u>Compartment #1: Waste Ramp</u>	<u>Compartment #4: Waste Main (Cont'd)</u>
<u>Internal Initiating Events:</u>	<u>External Initiating Events:</u>
Transporter collision	Earthquake
Runaway (uncontrolled) transporter accident	
<u>External Initiating Events:</u>	<u>Compartment #5: Panel Access Drift</u>
Earthquake	<u>Internal Initiating Events:</u>
	Transporter collision
	Runaway transporter
<u>Compartment #2: Performance Confirmation Area</u>	<u>External Initiating Events:</u>
<u>Internal Initiating Events:</u>	Earthquake
Container failure due to overstress resulting from fabrication problem (e.g., pintle failure or container rupture)	<u>Compartment #6: Emplacement Drift</u>
Transporter grapple or hoist failure, container is dropped into borehole, damaging containment	<u>Internal Initiating Events:</u>
Transporter collision	Container failure due to overstress resulting from fabrication problem (e.g., pintle failure or container rupture)
Transporter slides during container handling	Transporter grapple or hoist failure, container is dropped into borehole, damaging containment
Drift collapse during emplacement or removal of containers	Transporter collision
<u>External Initiating Events:</u>	Drift collapse during emplacement or removal of containers
Earthquake	Transporter slides during container handling
<u>Compartment #3: Waste Emplacement Area Shops</u>	<u>External Initiating Events:</u>
None	Earthquake
<u>Compartment #4: Waste Main</u>	<u>Compartment #7 through #14</u>
<u>Internal Initiating Events:</u>	None
Transporter collision	
Runaway transporter	

the waste forms in the emplacement area. Thus, no initiating event (internal or external) in the mining and development area requires further study.

3.3 Development of Event Trees

This study uses event-tree analysis to further evaluate the initiating events identified in Subsection 3.2. Event trees logically and systematically depict the various accident scenarios that could develop through the occurrence of different intermediate events following a single initiating event.

In developing the event trees, failures of radioactive release barriers (e.g., casks, cladding, and containers) and mitigators (e.g., HVAC filtration systems and monitors) were considered, along with the effects of release promoters (e.g., fires) to identify potential intermediate events. The scenarios developed by event-tree analysis for the internal and external initiating events are described below. All event trees for the underground facility are shown in Section 8.0.

Preliminary fault diagrams are given in Appendix C. These fault diagrams are introduced to describe in more detail the interpretation of the events. The current lack of design details and data prevents a quantitative fault-tree analysis at this time. In later phases of the PRSA study, the development of these preliminary fault diagrams will be continued, and detailed fault-tree analyses will be performed.

3.3.1 Compartment #1: Waste Ramp

The initiating events that may occur in the waste ramp include the following:

- o A transporter collision that involves two transporters colliding, a transporter running into the ramp wall or other stationary structures, or a transporter colliding with another moving vehicle
- o A runaway transporter caused by a loss of control leading to a full-speed collision with the rock walls at the bottom of the waste ramp
- o An earthquake resulting in a severe ramp collapse or a transporter collision into the ramp wall

Intermediate events considered in developing the event trees include breach of the waste containers, failure of the airborne radioactivity monitoring system (including failure to activate the ventilation bypass HEPA filter system), and failure of the ventilation system (defined as the failure to exhaust through filters or the possible reversal of airflow).

3.3.2 Compartment #2: Performance Confirmation Area

The initiating events that may occur in the performance confirmation area include:

- o Spontaneous failure of a waste container (e.g., pintle failure or container rupture) during handling due to stress, or fabrication error leading to the drop of spent fuel rods or HLW glass matrix
- o Failure of the transporter grapple or hoist during container emplacement or removal leading to a drop of the container

- o A transporter collision in this area with another vehicle or with a structure
- o A lateral slide of the transporter caused by something running into the transporter during emplacement or retrieval, resulting in a shear of the container and fuel rods
- o A severe drift collapse onto a loaded transporter during emplacement or retrieval of containers (the impact may result in container drop or transporter slide)
- o An earthquake leading to a severe drift collapse or a transporter slide during emplacement or retrieval

Intermediate events considered in the development of the event trees include breach of the waste container, rupture of cladding, failure of the airborne radioactivity alarm, and failure of the ventilation system.

3.3.3 Compartment # 4: Waste Main

The initiating events that may occur in the waste main include:

- o A transporter collision with the drift wall or other stationary structures, any moving vehicle, or another transporter
- o A runaway transporter caused by a loss of control leading to a full-speed collision at the bottom of the waste main
- o An earthquake resulting in a severe drift collapse on the loaded transporter, or a transporter collision into the drift wall

Intermediate events considered in the development of event trees include breach of the waste container, failure of the airborne radioactivity alarm, and failure of the ventilation system.

3.3.4 Compartment #5: Panel Access Drift

The initiating and intermediate events in this area are the same as those in Compartment #4. Thus, the scenarios and event trees developed for this compartment are similar to those in Compartment #4.

3.3.5 Compartment #6: Emplacement Drift

The initiating and intermediate events in this compartment are the same as those in Compartment #2. Thus, the scenarios and event trees developed for this compartment are similar to those in Compartment #2.

4.0 EVENT TREE PROBABILITY ANALYSIS

In quantifying accident scenarios, this study estimates the probability of each scenario and calculates the radiological doses. In this section, the probabilities of the initiating and intermediate events are determined. The probability of each scenario is the product of the probabilities of each event in the scenario.

4.1 Methodology

Probability assessments are based on historical data and the engineering judgment of a panel of experienced engineers who are involved with the underground facility design and are familiar with nuclear facilities and nuclear materials handling. To form their judgments, these engineers made use of (1) their knowledge of the functions of each system, component, and structure in the repository and (2) conceptual design drawings and limited operational plans.

The panel of engineers judged the probabilities of all initiating events and intermediate events using the ranking system shown in Table 3-4 in Subsection 3.2. Discussions were held among the members of the panel, each of whom provided individual estimates of the probabilities of each event. The average value of these estimated probabilities was assigned to each event.

The above methodology for probability assessment is appropriate for the present phase of design. Because structures, systems, and components involved in the underground accident scenarios are not yet designed in detail, failure rate data are generally not available. A list of some data is given in Table 4-1. Estimated probabilities of events may be modified in later studies when design and operational details become available.

Table 4-1
SURVEY OF FAILURE RATE DATA

<u>Component or Type of Failure</u>	<u>Failure Rate</u>	<u>Source</u>
Brakes	1×10^{-6} /actuation	NRC, 1975
Overhead cranes	5×10^{-5} /hr	NRC, 1975
Overhead bridge cranes (10 ton)	1.1×10^{-4} /hr	IEEE, 1984
Truck accident	2.5×10^{-6} accident/mi	Dennis, et al., 1978
Truck falls off bridge	1.8×10^{-8} /mi	Dennis, et al., 1978
Train accident	1×10^{-5} accident/mi	Dennis, et al., 1978
Train falls off bridge	1.96×10^{-11} /mi	Dennis, et al., 1978
Human error (without stress)	1×10^{-4} /action	NRC, 1975
Human error (with stress)	1×10^{-3} /action	NRC, 1975
Train impact with speed greater than 30 mph	3.7×10^{-8} /mi	Dennis, et al., 1978
Cask puncture (assume 2 in. mild steel)	2.31×10^{-5} /truck accident	Dennis, et al., 1978
Truck accident and fire	1.6×10^{-2} /truck accident	Dennis, et al., 1978
Train accident and fire	1×10^{-2} /train accident	Dennis, et al., 1978
Loss of offsite power	8.8×10^{-2} /site-yr	NRC, 1985
Radiation monitor sensors	5.1×10^{-6} /hr	IEEE, 1984
Diesel generator	2×10^{-2} /demand	NRC, 1985
HVAC system	No failure in 1,040,900 hr	NPRDS, 1985
Uninterruptible power supply	2×10^{-5} /hr	IEEE, 1984

4.2 Assessment of Event Probabilities

The probabilities of all events used in the event-tree analyses are discussed below. Table 4-2 presents these estimates on a compartment-by-compartment basis using the ranking system of Table 3-4.

The following guidelines and assumptions were used in the determining the probabilities:

- o The probability that an intermediate event will occur is contingent on the occurrence of the associated initiating event. (Conditional probabilities are used for intermediate events.)
- o The probability of fire is defined as the probability that a fire occurs and will not be extinguished in a 30 min time period.
- o Radioactivity alarm failure includes both the failure of monitors and the failure to automatically activate the ventilation filtration system upon demand.
- o Ventilation system failure includes the failure or bypass of HEPA filters and reversal of ventilation flow direction, resulting in no filtration of the exhaust air.
- o Container breach probability takes into account the penetration of all barriers, including the transporter cask.
- o The annual probabilities of transporter collision or a runaway transporter in a given compartment area is dependent on the frequency of transporter trips in that compartment area.

- o In this study, a drift collapse refers to a collapse of a drift roof area that is comparable to circle with diameter equal to half of the drift width. The annual probability of a drift collapse is estimated for a given length of drift (e.g., 1 mile).
- o The probability, P, of rocks falling on a transporter given a drift collapse is considered to be

$$P = R F$$

where R is the ratio of the length of the transporter cask (assumed to be 20 ft) to that of the drift (e.g., 1 mile), and F is the fraction of time that a transporter would be in that compartment area.*

- o About one container per month will be randomly removed from the repository for performance confirmation.

* For example, about 2,000 containers will be emplaced in the emplacement area per year, and each operation will last about 100 minutes (MacDougall, 1987). Thus, for the emplacement area, the probability of rocks falling on the transporter in a drift collapse may be determined as follows:

$$\begin{aligned} F &= (100 \text{ min/operation}) (2,000 \text{ operations/yr}) = 0.38 \\ R &= 20 \text{ ft/1 mile} = 0.0038 \\ P &= R F \approx 10^{-3} \end{aligned}$$

Table 4-2

ESTIMATED PROBABILITIES
OF INITIATING AND INTERMEDIATE EVENTS

<u>Compartment #1: Waste Ramp</u>	<u>Event Category</u>	<u>Possibility</u>
1. Transporter Collision	1	$1 \times 10^{-1}/\text{yr}$
a. Container breach	3	$1 \times 10^{-4}/\text{event}$
b. Fire	2	$1 \times 10^{-2}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
2. Runaway Transporter	2	$1 \times 10^{-2}/\text{yr}$
a. Container breach	3	$1 \times 10^{-4}/\text{event}$
b. Fire	2	$1 \times 10^{-2}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
3. Earthquake	-	$5 \times 10^{-4}/\text{yr}$
a. Transporter collision with ramp wall	2	$1 \times 10^{-2}/\text{event}$
b. Container breach	3	$1 \times 10^{-4}/\text{event}$
c. Radiation alarm failure	1	$1 \times 10^{-1}/\text{event}$
d. Ventilation system failure	1	$1 \times 10^{-1}/\text{event}$
<u>Compartment #2: Performance Confirmation Area</u>		
1. Container Failure	2	$1 \times 10^{-2}/\text{yr}$
a. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
b. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
2. Grapple/Hoist Failure	2.5	$1 \times 10^{-3}/\text{yr}$
a. Container breach	2	$1 \times 10^{-2}/\text{event}$
b. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
c. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
3. Transporter Collision	2.5	$1 \times 10^{-3}/\text{yr}$
a. Container breach	3	$1 \times 10^{-4}/\text{event}$
b. Fire	2	$1 \times 10^{-2}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$

Table 4-2 (Cont'd)

<u>Compartment #2 (Continued)</u>	<u>Event Category</u>	<u>Probability</u>
4. Transporter Slide	3	$1 \times 10^{-4}/\text{yr}$
a. Container breach	2	$1 \times 10^{-2}/\text{event}$
b. Fire	3	$1 \times 10^{-4}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
5. Drift Collapse	2.5	$1 \times 10^{-3}/\text{yr-mile}$
a. Rocks fall on transporter	3	$1 \times 10^{-4}/\text{event}$
b. Container breach	2	$1 \times 10^{-2}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
6. Earthquake	-	$5 \times 10^{-4}/\text{yr}$
a. Drift collapse	2	$1 \times 10^{-2}/\text{event-mile}$
b. Rocks fall on transporter	3	$1 \times 10^{-4}/\text{event}$
c. Transporter slide	2.5	$1 \times 10^{-3}/\text{event}$
d. Container breach	2	$1 \times 10^{-2}/\text{event}$
e. Radiation alarm failure	1	$1 \times 10^{-1}/\text{event}$
f. Ventilation system failure	1	$1 \times 10^{-1}/\text{event}$
<u>Compartment #4: Waste Main</u>		
1. Transporter Collision	1	$1 \times 10^{-1}/\text{yr}$
a. Container breach	3	$1 \times 10^{-4}/\text{event}$
b. Fire	2	$1 \times 10^{-2}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
2. Runaway Transporter	2	$1 \times 10^{-2}/\text{yr}$
a. Container breach	3	$1 \times 10^{-4}/\text{event}$
b. Fire	2	$1 \times 10^{-2}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
3. Earthquake	-	$5 \times 10^{-4}/\text{yr}$
a. Transporter collision with wall	2	$1 \times 10^{-2}/\text{event}$
b. Container breach	3	$1 \times 10^{-4}/\text{event}$
c. Radiation alarm failure	1	$1 \times 10^{-1}/\text{event}$
d. Ventilation system failure	1	$1 \times 10^{-1}/\text{event}$

Table 4-2 (Cont'd)

<u>Compartment #5: Panel Access Drift</u>	<u>Event Category</u>	<u>Probability</u>
1. Transporter Collision	1	$1 \times 10^{-1}/\text{yr}$
a. Container breach	3	$1 \times 10^{-4}/\text{event}$
b. Fire	2	$1 \times 10^{-2}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
2. Runaway Transporter	2	$1 \times 10^{-2}/\text{yr}$
a. Container breach	3	$1 \times 10^{-4}/\text{event}$
b. Fire	2	$1 \times 10^{-4}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
3. Earthquake	-	$5 \times 10^{-4}/\text{yr}$
a. Transporter collision with wall	2	$1 \times 10^{-2}/\text{event}$
b. Container breach	3	$1 \times 10^{-4}/\text{event}$
c. Radiation alarm failure	1	$1 \times 10^{-1}/\text{event}$
d. Ventilation system failure	1	$1 \times 10^{-1}/\text{event}$
<u>Compartment #6: Emplacement Drift</u>		
1. Container Failure	2	$1 \times 10^{-2}/\text{yr}$
a. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
b. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
2. Grapple/Hoist Failure	1.5	$5 \times 10^{-2}/\text{yr}$
a. Container breach	2	$1 \times 10^{-2}/\text{event}$
b. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
c. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
3. Transporter Collision	1	$1 \times 10^{-1}/\text{yr}$
a. Container breach	3	$1 \times 10^{-4}/\text{event}$
b. Fire	2	$1 \times 10^{-2}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$

Table 4-2 (Cont'd)

<u>Compartment #6 (Continued)</u>	<u>Event Category</u>	<u>Probability</u>
4. Transporter Slide	2	$1 \times 10^{-2}/\text{yr}$
a. Container breach	2	$1 \times 10^{-2}/\text{event}$
b. Fire	3	$1 \times 10^{-4}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
5. Drift Collapse	2.5	$1 \times 10^{-3}/\text{yr-mile}$
a. Rocks fall on transporter	2.5	$1 \times 10^{-3}/\text{event}$
b. Container breach	2	$1 \times 10^{-2}/\text{event}$
c. Radiation alarm failure	1.5	$5 \times 10^{-2}/\text{event}$
d. Ventilation system failure	2.5	$1 \times 10^{-3}/\text{event}$
6. Earthquake	-	$5 \times 10^{-4}/\text{yr}$
a. Drift collapse	2	$1 \times 10^{-2}/\text{event-mile}$
b. Rocks fall on transporter	2.5	$1 \times 10^{-3}/\text{event}$
c. Transporter slide	1	$1 \times 10^{-1}/\text{event}$
d. Container breach	2	$1 \times 10^{-2}/\text{event}$
e. Radiation alarm failure	1	$1 \times 10^{-1}/\text{event}$
f. Ventilation system failure	1	$1 \times 10^{-1}/\text{event}$

5.0 ACCIDENT SCENARIO RELEASE MODELING

The potential releases of radionuclides due to postulated accident scenarios in the underground are discussed in this section. The approach of this section generally follows that of Appendix F of MacDougall (1987).

Spent fuel accidents can result in releases of three types of radioactive material that are potentially significant to offsite radiation doses: (1) Kr-85 releases, (2) gaseous radioactivity releases that include Cs, and (3) releases of respirable-size particles (less than 10-micron diameter) of spent fuel. The source terms and release mechanisms are briefly summarized in this section. Additional details of the calculational methods, assumptions, and derivations can be found in MacDougall (1987).

5.1 Source Terms

The source terms for the spent fuel used in this study are discussed below. Receipt rates for spent fuel in the underground facilities are also included. Because the offsite doses from spent fuel accidents are greater than those from defense high-level waste (DHLW) accidents (MacDougall, 1987), only spent fuel accidents are considered. For comparison purposes and for potential use in future studies, the source terms and receipt rates for DHLW are also included in the following subsections.

5.1.1 Spent Fuel

Most waste to be emplaced in the repository will be spent fuel from commercial light-water reactors. The spent fuel will be received either as intact fuel assemblies or as consolidated fuel rods. This report assumes that most spent fuel emplaced in the repository will be consolidated, either in the repository surface facilities or before shipment to the repository.

The reference PWR spent fuel assembly is the same as in the PRSA study (MacDougall, 1987). This reference PWR assembly is 8.4 in. square (17-by-17 array) and 160 in. long, and contains 264 fuel rods (each 0.37 in. in diameter and 151 in. long).

The major radionuclide inventories of the PWR spent fuel used in this study are shown in Table 5-1. These inventories are based on the data presented in Roddy (1986), and they contribute 99 percent of the offsite dose. These data assume a 33,000 Mwd/MTU (megawatt-days per MTU) burnup, an initial loading of 0.46 MTU/assembly, and a 10 yr cooling period. More detailed physical characteristics of spent fuel are described in Appendix F of MacDougall (1987).

5.1.2 Defense High-Level Waste

Under the terms of the Nuclear Waste Policy Act of 1982, HLW resulting from the defense activities of the United States government must be disposed of in an NRC-licensed repository. It is assumed that waste containers will be produced at the Savannah River Defense Waste Processing Facility and each will accommodate only 0.5 MTU (equivalent) of vitrified DHLW.

There will also be some vitrified HLW from the West Valley reprocessing plant (WVHLW), but the quantities of this type of waste will be small and therefore are not considered in this report.

5.1.3 Total Annual Waste Receipts

The waste receipt rates for the Yucca Mountain repository are taken from Appendix F of MacDougall (1987).

The Yucca Mountain repository is assumed to accommodate 70,000 MTU of HLW in the form of spent fuel, WVHLW, and DHLW. The Nuclear

Table 5-1

MAJOR RADIONUCLIDE CONTRIBUTORS TO OFFSITE DOSES^(a)

<u>Isotope</u>	<u>Spent Fuel (Ci/Assembly)^(b)</u>		<u>DHLW Glass (Ci/Canister)^(c)</u>	
	<u>PWR</u>	<u>BWR</u>	<u>Sludge</u>	<u>Sludge & Salt</u>
Co-60	9.782(+2)	1.221(+2)	1.865(+2)	1.539(+2)
Ni-63	3.008(+2)	2.695(+1)	2.690(+2)	2.217(+2)
Kr-85	2.238(+3)	7.185(+2)	--	--
Sr-90	2.639(+4)	8.615(+3)	4.792(+4)	3.945(+4)
Cs-134	2.409(+3)	6.800(+2)	1.780(+2)	3.423(+2)
Cs-137	3.788(+4)	1.245(+4)	1.679(+3)	3.293(+4)
Ce-144	6.875(+1)	1.870(+1)	1.073(+4)	8.835(+3)
Pm-147	4.374(+3)	1.476(+3)	2.631(+4)	2.168(+4)
Pu-238	1.075(+3)	3.263(+2)	1.108(+3)	9.161(+2)
Pu-239	1.444(+2)	5.449(+1)	1.046(+1)	8.639(+0)
Pu-240	2.432(+2)	8.762(+1)	6.650(+2)	5.477(+0)
Pu-241	3.580(+4)	1.274(+4)	1.255(+3)	1.037(+3)
Am-241	7.798(+2)	2.859(+2)	1.733(+1)	9.715(+0)
Cm-244	<u>6.090(+2)</u>	<u>1.624(+1)</u>	<u>1.733(-1)</u>	<u>1.460(-1)</u>
Total	1.133(+5)	3.697(+4)	8.967(+4)	1.056(+5)

(a) Represents isotopes that contribute 99 percent of the bone dose

(b) Roddy (1986)

(c) Baxter (1983)

Waste Policy Act permits loading beyond that limit, once a second repository becomes operational. After a 5 yr startup period, DHLW will be received at a constant rate of 400 MTU, or 800 canisters per year, and spent fuel will be received at a constant rate of 3,000 MTU/yr until the repository reaches its 70,000 MTU capacity.

The spent fuel receipt rate of 3,000 MTU/yr corresponds to an annual throughput of about 3,900 PWR assemblies and 6,550 BWR assemblies. The annual number of containers emplaced will be about 910 consolidated spent fuel containers, 240 intact spent fuel containers, and 800 DHLW containers (MacDougall, 1987).

5.1.4 Waste Package Description

The spent fuel and DHLW containers used in this study are the same as those described in Appendix F of MacDougall (1987). The reference NNWSI spent fuel container and the reference DHLW canister (before overpack) are shown in Figures 5-1 and 5-2, respectively.

More details about the emplacement containers used in the underground facilities can be found in MacDougall (1987).

5.2 Release Factors for Gap Radioactivity

5.2.1 Kr-85 Releases

The only radioactive gas of concern in 10-yr-old spent fuel is Kr-85, which has a 10.7 yr half life. Because of radioactive decay, quantities of other radioactive gases in the fuel rods are no longer significant. The Kr-85 in a fuel rod is distributed through the solid UO_2 spent fuel matrix and in the rod plenum. Following an accident, most of the Kr-85 will remain trapped in the fuel. It is assumed that 30 percent of the Kr-85 inventory in a damaged fuel rod will be released (NRC, 1972).

Note: Containers of consolidated fuel will contain more rods than indicated. (The rods are shown for illustrative purposes only.)

Figure 5-1
Reference NNWSI Spent Fuel Container

NOTES:

1. THIS CANISTER WILL BE OVERPACKED WITH A 26-IN.-DIAMETER CONTAINER. A FULLY LOADED CONTAINER HAS A MAXIMUM WEIGHT OF 5,500 LB.
2. DIMENSIONS SHOWN DO NOT INCLUDE OVERPACK. OVERPACKED CONTAINER HAS A DIAMETER OF 26 IN. AND IS 126 IN. LONG.

Figure 5-2

Reference DHLW Canister

5.2.2 Gap Activity (Cs) Release

The two release mechanisms for Cs considered in this analysis are those described by Lorenz (1980a, b), who reported that in a severe thermal environment (between 500°C to 900°C), a spent fuel cladding breach will result in a release of 0.028 percent of the total Cs inventory in a fuel rod (burst release). In addition, if the breached fuel is continuously subjected to high temperature, such as in a fire, diffusion of Cs from the main fuel matrix will result in an additional significant release (diffusion release). Lorenz (1980b) showed that, in a period of 1 hr, an additional 0.041 percent of the total Cs inventory will be released as a result of this diffusion mechanism at a high temperature of about 1,200°C.

5.3 Fuel Pellet and DHLW Pulverization Factors

Spent fuel accidents involving large mechanical impacts may cause fuel pellet pulverization. Any resulting UO_2 fuel particles may be released and become a significant airborne source term. Studies of the pulverization mechanism by Jardine (1982) and Mecham (1981, 1983), as summarized in MacDougall (1987), found that the fraction of an irradiated UO_2 specimen pulverized into respirable particles (i.e., particles with diameter less than 10 microns) is linearly proportional to the impact energy density:

$$\text{PULF} = 2 \times 10^{-4} * E/V$$

where PULF = fraction of irradiated UO_2 specimen pulverized into sizes less than 10 microns (dimensionless)

E = impact energy (Joules)

V = volume of UO_2 specimen (cm^3)

This factor is used for both spent fuel and DHLW during kinetic impact to the waste form. For a drop event, the impact energy density may be expressed as follows:

$$E/V = \rho g h$$

where ρ = waste form density (g/cm³)

g = gravitational acceleration (cm/sec²)

h = height of drop (cm)

5.4 Particle Escape Factors

Although airborne fuel particles may be generated by an impact, some fraction will be retained by the combination of fuel cladding, emplacement container, and transporter cask barriers. Both the PRSA report and this study assume that 10 percent of the airborne fuel particles will escape from the breached cladding (escape factor = 0.1). The escape factors for the breached emplacement container and the transporter cask are also assumed to be 0.1. The bases for these escape factors can be found in Appendix F of MacDougall (1987).

6.0 TRANSPORT ANALYSIS

In this section, the mechanisms for radionuclide transport through the atmospheric pathway are briefly discussed. Depletion of radionuclides inside the underground facilities due to various mechanisms (such as deposition along tunnels and shafts) was neglected in this study. As a result, estimates of releases are conservative. A detailed description of transport mechanisms can be found in Appendix F of MacDougall (1987).

6.1 Filtration of Particles

The design of the underground ventilation system is given in MacDougall (1987). When radioactivity is detected in the air, monitors in the emplacement area activate standby HEPA filtration systems. The mining and development area is not equipped with any filtration system.

The emplacement area filtration system consists of two stages of HEPA filters in series. The filtration efficiency of one HEPA filter for airborne particles is conservatively taken as 99 percent; the combined filtration efficiency for two HEPA filters in series is taken to be 99.99 percent (MacDougall, 1987). This filtration factor (1×10^{-4}) will be applied to all particles and Cs released from the emplacement area when HEPA filtration systems are in operation. For Kr-85 releases, a filtration factor of 1 is used because Kr-85 is a noble gas, which is not removed by HEPA filters.

6.2 Atmospheric Dispersion

Radionuclides that are released into the atmosphere will be diluted by atmospheric dispersion as they are transported to the site boundary. The PRSA report (MacDougall, 1987) calculated an atmospheric dispersion factor (x/Q) of $6.4 \times 10^{-5} \text{ sec/m}^3$ for a ground-level release, a 5 km site boundary distance, a Pasquill

F stability condition, and a wind speed of 1 m/sec, which is based on NRC guidance (NRC, 1972). This study uses the same atmospheric dispersion factor.

6.3 Deposition Factors

The deposition of radioactive particles during transport to the site boundary causes a reduction in the airborne concentration of particles at the site boundary. The PRSA study in Appendix F of MacDougall (1987) determined that 5 percent of the airborne fuel particles will reach the repository site boundary. This value of 5 percent is adopted and used in this study.

7.0 DOSE CONSEQUENCE ANALYSIS

7.1 Dose Analysis Methodology

The method of estimating dose consequences to the public is explained in Appendix F of MacDougall (1987). The same method is used in this study, with one exception: no Sr-90 is considered in gap releases (see Subsection 2.3). A brief summary of the dose analysis methodology is given here.

Following a postulated release of radioactive material from the underground areas of the repository, exposure of individuals would occur primarily by two routes: internal exposures from the inhalation of the radioactive material in the plume as it passes the individual; and external exposures from immersion in the plume. Doses are calculated to the maximally exposed offsite individual for both of these pathways (e.g., assuming the individual is directly downwind and at the nearest site boundary).

The inhalation dose from a given intake of radioactive material is dependent on the age of the exposed individual. For this initial study, only adult dose conversion factors (DCFs) are used (MacDougall, 1987). Although the DCFs for other age groups may be larger, the adult breathing rate is the highest and adults would receive the maximum doses for those radionuclides that are expected to be released in repository underground accidents. In addition, all DCFs used in this report reflect 50 yr dose commitments because inhaled radioactive material may remain in the body for considerable periods following intake.

The external whole-body dose (due to immersion) is almost entirely attributable to gamma radiation produced by the radioactive materials in the plume. Beta particles have a relatively short range in air and are attenuated by clothing and the skin. Therefore, they do not contribute significantly to the whole-body external dose, although their contribution to skin doses may be

considerable. Both whole-body immersion doses (due to gamma radiation) and immersion skin doses (due to betas and gammas) are calculated.

Two conservative assumptions are made in assessing the gamma component of the immersion dose: shielding that might be provided by residential or other structures was assumed to be zero (because there are no structures at the site boundary), and the plume was assumed to be semi-infinite in extent. The term "semi-infinite" is used to describe a cloud of radioactivity that is infinite in extent only on one side of a plane (e.g., above the surface of the ground). Actually, because the cloud of radioactive material will be finite, the semi-infinite assumption conservatively overpredicts the doses.

The general equations used to calculate the immersion and inhalation doses during accidents are the same as those in NRC (1977).

The equations for immersion and inhalation doses are as follows:

$$\text{Whole Body} \quad D_B = S_F * X/Q * \sum_i X_i \text{DFB}_i \quad (7-1)$$

$$\text{Skin} \quad D_S = X/Q * \sum_i (S_F * X_i * \text{DF}_i + X_i * \text{DFS}_i) \quad (7-2)$$

$$\text{Organs} \quad D_{ja} = R_a * X/Q * \sum_i X_i \text{DFA}_{ija} \quad (7-3)$$

D_B = Whole body external dose from immersion (rem)

S_F = Shielding factor due to residential structures, equal to 1.0 for this study (dimensionless)

X/Q = Atmospheric dispersion coefficient (sec/m^3)

- X_i = Number of curies of isotope i released as a result of the accident (Ci)
- DFB_i = Whole body dose conversion factor for a semi-infinite cloud of radionuclide i (rem-m³)/(Ci-sec)
- D_S = Dose to skin from immersion (rem)
- DF_i, DFS_i = Gamma and beta skin dose factors (respectively) for a semi-infinite cloud of radionuclide i (rem-m³)/(Ci-sec)
- D_{ja} = Dose to organ j for an individual in age group a due to inhalation (rem)
- R_a = Breathing rate or inhalation rate for individuals in age group a (m³/sec)
- DFA_{ija} = inhalation dose conversion factor for radionuclide i, organ j, and age group a (rem/Ci inhaled)

Several additional assumptions are used with these equations:

- o χ/Q values were established for the Pasquill F stability class and a 5 km site boundary distance.
- o A breathing rate of 3.47×10^{-4} m³/sec was used in the calculations (NRC, 1974). Based on current NRC guidance, this approach is appropriate when the duration of the release is less than 8 hr.
- o Lung doses due to Kr-85 and bone doses due to Cs and pulverized fuel are summed to provide a conservative estimate of a maximum dose to a critical organ. Details and discussions of these assumptions are found in Appendix F of MacDougall (1987).

7.2 General Treatment

Doses due to the release of an entire fuel assembly and an entire DHLW container are calculated to generate values that could be scaled or adjusted for each individual scenario. The doses obtained for an entire assembly or container do not represent credible or possible consequences of accidents at the repository. However, when combined with the estimated release fractions, pulverization factors, retention factors, gap inventories, deposition factors, and other pertinent factors, these values can be employed to determine the potential dose consequences for various postulated accident scenarios.

The total dose at the site boundary, $D(\text{Fuel})$, due to fuel assembly breach is expressed as the sum of three major contributions:

$$D(\text{Fuel}) = D(\text{Kr-85}) + D(\text{Gap}) + D(\text{Pulv})$$

where $D(\text{Kr-85})$ = dose due to Kr-85 released from the gap

$$D(\text{Gap}) = \text{dose due to Cs released from the gap}$$

$$D(\text{Pulv}) = \text{dose of airborne particles released from fuel pulverization}$$

Each of the above contributions can be evaluated as follows:

$$D(\text{Kr-85}) = 0.3 * \underline{D}(\text{Kr-85}) * N$$

$\underline{D}(\text{Kr-85})$ is the dose due to all of the Kr-85 in a single PWR fuel assembly, N is the number of breached fuel assemblies, and 0.3 is the fraction of the total inventory of Kr-85 in the gap.

$$D(\text{Gap}) = (\text{GB-Cs} + \text{GD-Cs}) * \text{FIL} * \underline{D}(\text{Cs}) * N$$

GB-Cs and GD-Cs are the gap burst Cs release factor (0.028 percent) and the gap diffusion Cs release factor (0.041 percent), respectively; FIL is the filtration efficiency of the HEPA filter system; $\underline{D}(\text{Cs})$ is the dose due to all of the Cs-137 and Cs-134 in a PWR fuel assembly; and N is the number of breached fuel assemblies. The above factors are included in the evaluations whenever they are applicable.

$$D(\text{Pulv}) = \text{PULF} * \text{EPF} * \text{ESPclad} * \text{ESPcont} * \text{ESPcask} * \\ (\text{FIL or DEP}) * \underline{D}(\text{Part}) * N$$

PULF is the pulverization factor of spent fuel pellets (0.02 percent); EPF is the energy partition factor (20 percent); ESPclad, ESPcask, and ESPcont are the escape factors for fuel cladding, casks, and containers, respectively (each factor is assumed to be 10 percent); FIL is the efficiency of the HEPA filtration system; DEP is the depletion factor due to deposition (5 percent) after a particulate release into the environment. $\underline{D}(\text{Part})$ is the dose due to release of all the particles in a PWR fuel assembly; and N is the number of breached fuel assemblies. The above factors are included in the evaluations whenever they are applicable.

The total dose at the site boundary due to a breach of a high-level waste canister can be similarly expressed as:

$$D(\text{HLW}) = \text{PULF} * \text{ESPcan} * \text{ESPcont} * \text{ESPcask} * \\ (\text{FIL or DEP}) * \underline{D}(\text{HLW}) * N$$

ESPcan is the escape factor for the glass waste canister, $\underline{D}(\text{HLW})$ is the dose due to an entire canister of HLW at the site boundary, and N is the number of canisters breached. All other factors have the same meanings as described above.

The preceding discussion of HLW doses is included for illustrative purposes. In this study, only accidental radiation doses based on releases from spent fuel are determined. These releases result in worst-case consequences.

For failure of an entire fuel assembly, the doses, $\underline{D}$, at the 5 km site boundary are as follows:

$$\underline{D}(\text{Kr-85}) = 1.20 \times 10^{-4} \text{ rem (lung dose)}$$

$$\underline{D}(\text{Pulv}) = 1.77 \times 10^{-5} \text{ rem (bone dose)}$$

$$\underline{D}(\text{Cs}) = 5.28 \times 10^{-1} \text{ rem (bone dose)}$$

These doses for a single fuel assembly already take into account the atmospheric dispersion factor χ/Q . They are slightly different from the doses in the PRSA in MacDougall (1987) because this study uses radionuclide inventories from Roddy (1986), whereas the previous PRSA used data from Alexander (1977).

Maximum organ doses are calculated for each of the three contributions based on the above values. To be conservative, these organ doses are summed to estimate the critical organ dose for an individual at the site boundary.

The calculation of each accidental dose takes into consideration either filtration (FIL) or deposition (DEP). Both factors are not used at the same time because most of the airborne particles with diameters larger than 1 micron will be removed by the HEPA filter. As a result, the airborne particles released into the atmosphere through the HEPA filters will be very small and will have a very low rate of deposition compared to that of unfiltered particles, which generally have higher deposition factors.

7.3 Accident Scenario Dose Consequences

Table 7-1 lists the offsite doses for the underground accident scenarios developed in Subsection 3.3. The method of dose calculation follows that of Appendix F of MacDougall (1987). The explanations of the factors used were briefly discussed in Sections 5.0 and 6.0, and the formulas for calculation were briefly discussed in Subsections 7.1 and 7.2. The factors used to calculate the offsite doses are also listed in the table. These factors reflect the major assumptions for this study, listed in Subsection 2.3.

As an example, the first row in Table 7-1 pertains to the first two scenarios (1 and 2) associated with a transporter collision in the waste ramp. The associated event tree (presented in Section 8.0) describes the scenarios, which involve a container breach, fire, and a radioactivity alarm failure or a ventilation system failure. The 6 PWR assemblies in the container constitute the total number of waste forms affected during the accident scenarios. No spent fuel would be pulverized in these scenarios, so the dose reduction factors and pulverization factors are not applicable. Cladding on the spent fuel would breach, so that Kr-85 in the gap (30 percent of inventory in fuel) and Cs in the gap (a fraction equal to 2.8×10^{-4} of the inventory in the fuel) would be released. Also, because of the high temperatures during a fire, an additional fraction of Cs (4.1×10^{-4}) would diffuse from the spent fuel and be released. The resulting doses would total 220 mrem at the site boundary.

Compartment and Initiating Event	Scenario Number	Number of Waste Forms	Dose Reduction Factor				
			Escape Factor			Energy Partition Factor	Depletion Factor Due To Deposition
			Cask	Container	Cladding		

1. Waste Ramp

Transporter Collision

6 PWR

1,2	--	--	--	--	--
3	--	--	--	--	--
4,5	--	--	--	--	--
6	--	--	--	--	--
7	No Consequence				

Runaway Transporter

6 PWR

1,2	.1	.1	.1	.2	.05
3	.1	.1	.1	.2	--
4,5	.1	.1	.1	.2	.05
6	.1	.1	.1	.2	--
7	No Consequence				

Earthquake

6 PWR

4,5	No Consequence				
1,2	--	--	--	--	--
3	--	--	--	--	--

2. Performance Confirmation

Container Failure

6 PWR

1,2	.1	--	.1	--	.05
3	.1	--	.1	--	--

Grapple/Hoist Failure

6 PWR

1,2	.1	.1	.1	--	.05
3	.1	.1	.1	--	--
4	No Consequence				

Table 7-1

 FSITE DOSES
 IND ACCIDENT SCENARIOS

	Source Term Release Fraction				Dose Consequence (mrem)			
HVAC filtration efficiency	Kr85	Particles			Kr85	Particles		Total
		Cs Burst	Gap Release			Gap	Pulv.	
			Cs Diffusion	Pulv.				

--	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(-2)	--	2.4(-1)
--	0.3	2.8(-4)	--	--	2.2(-1)	8.9(+1)	--	8.9(+1)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	8.9(-3)	--	2.3(-1)

--	0.3	2.8(-4)	4.1(-4)	2(-4)	2.2(-1)	2.2(+2)	2.1(+0)	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	2(-4)	2.2(-1)	2.2(-2)	4.2(-3)	2.5(-1)
--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	2.1(+0)	9.1(+1)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	4.2(-3)	2.3(-1)

--	0.3	2.8(-4)	--	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	2.2(-2)	--	2.4(-1)

--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	1.1(+2)	2.0(+2)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	2.1(-1)	4.4(-1)

--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	1.1(+1)	1.0(+2)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	2.1(-2)	2.5(-1)

Compartment and Initiating Event	Scenario Number	Number of Waste Forms	Dose Reduction Factor				
			Escape Factor			Energy Partition Factor	Depletion Factor Due to Deposition
			Cask	Container	Cladding		
Transporter Collision		6 PWR					
	1,2		--	--	--	--	--
	3		--	--	--	--	--
	4,5		--	--	--	--	--
	6		--	--	--	--	--
	7		No Consequence				
Transporter Slide		6 PWR					
	1,2		--	--	--	--	--
	3		--	--	--	--	--
	4,5		--	--	--	--	--
	6		--	--	--	--	--
	7		No Consequence				
Drift Collapse		6 PWR					
	1,2		--	.1	.1	--	.05
	3		--	.1	.1	--	--
	4,5		No Consequence				
Earthquake		6 PWR					
	4,5,9,10		No Consequence				
	6,7		--	--	--	--	--
	8		--	--	--	--	--
	1,2		--	.1	.1	--	.05
	3		--	.1	.1	--	--
4. Waste Main							
Transporter Collision		6 PWR					
	1,2		--	--	--	--	--
	3		--	--	--	--	--
	4,5		--	--	--	--	--
	6		--	--	--	--	--
	7		No Consequence				
Runaway Transporter		6 PWR					
	1,2		.1	.1	.1	.2	.05
	3		.1	.1	.1	.2	--
	4,5		.1	.1	.1	.2	.05
	6		.1	.1	.1	.2	--
	7		No Consequence				

	Source Term Release Fraction				Dose Consequence (mrem)			
		Particles				Particles		
HVAC filtration efficiency		Cs	Gap Release					
	Kr85	Burst	Diffusion	Pulv.	Kr85	Gap	Pulv.	Total
--	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(-2)	--	2.4(-1)
--	0.3	2.8(-4)	--	--	2.2(-1)	8.9(+1)	--	8.9(+1)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	8.9(-3)	--	2.3(-1)
--	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(-2)	--	2.4(-1)
--	0.3	2.8(-4)	--	--	2.2(-1)	8.9(+1)	--	8.9(+1)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	8.9(-3)	--	2.3(-1)
--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	1.1(+2)	2.0(+2)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	2.1(-1)	4.4(-1)
--	0.3	2.8(-4)	--	--	2.2(-1)	8.9(+1)	--	8.9(+1)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	8.9(-3)	--	2.3(-1)
--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	1.1(+2)	2.0(+2)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	2.1(-1)	4.4(-1)
--	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(-2)	--	2.4(-1)
--	0.3	2.8(-4)	--	--	2.2(-1)	8.9(+1)	--	8.9(+1)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	8.9(-3)	--	2.3(-1)
--	0.3	2.8(-4)	4.1(-4)	2(-4)	2.2(-1)	2.2(+2)	2.1(+0)	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	2(-4)	2.2(-1)	2.2(-2)	4.2(-3)	2.5(-1)
--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	2.1(+0)	9.1(+1)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	4.2(-3)	2.3(-1)

Compartment and Initiating Event	Scenario Number	Number of Waste Forms	Dose Reduction Factor					Depletion Factor Due To Deposition	F	
			Escape Factor			Energy Partition Factor				
			Cask	Container	Cladding					
Earthquake										
		6 PWR								
	4,5		No Consequence							
	1,2		--	--	--	--	--	--		
	3		--	--	--	--	--	--		
5. Panel Access Drift										
Transporter Collision										
		6 PWR								
	1,2		--	--	--	--	--	--		
	3		--	--	--	--	--	--		
	4,5		--	--	--	--	--	--		
	6		--	--	--	--	--	--		
	7		No Consequence							
Runaway Transporter										
		6 PWR								
	1,2		.1	.1	.1	.2	.05			
	3		.1	.1	.1	.2	--			
	4,5		.1	.1	.1	.2	.05			
	6		.1	.1	.1	.2	--			
	7		No Consequence							
Earthquake										
		6 PWR								
	4,5		No Consequence							
	1,2		--	--	--	--	--	--		
	3		--	--	--	--	--	--		
6. Emplacement Drift										
Container Failure										
		6 PWR								
	1,2		.1	--	.1	--	.05			
	3		.1	--	.1	--	--			
Grapple/Hoist Failure										
		6 PWR								
	1,2		.1	.1	.1	--	.05			
	3		.1	.1	.1	--	--			
	4		No Consequence							

	Source Term Release Fraction				Dose Consequence (mrem)			
		Particles				Particles		
HVAC			Gap Release					
filtration		Cs	Cs					
efficiency	Kr85	Burst	Diffusion	Pulv.	Kr85	Gap	Pulv.	Total
--	0.3	2.8(-4)	--	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	2.2(-2)	--	2.4(-1)
--	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(-2)	--	2.4(-1)
--	0.3	2.8(-4)	--	--	2.2(-1)	8.9(+1)	--	8.9(+1)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	8.9(-3)	--	2.3(-1)
--	0.3	2.8(-4)	4.1(-4)	2(-4)	2.2(-1)	2.2(+2)	2.1(+0)	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	2(-4)	2.2(-1)	2.2(-2)	4.2(-3)	2.5(-1)
--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	2.1(+0)	9.1(+1)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	4.2(-3)	2.3(-1)
--	0.3	2.8(-4)	--	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	2.2(-2)	--	2.4(-1)
--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	1.1(+2)	2.0(+2)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	2.1(-1)	4.4(-1)
--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	1.1(+1)	1.0(+2)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	2.1(-2)	2.5(-1)

Compartment and Initiating Event	Scenario Number	Number of Waste Forms	Dose Reduction Factor					Depletion Factor Due To Deposition	F
			Escape Factor			Energy Partition Factor			
			Cask	Container	Cladding				
Transporter Collision		6 PWR							
	1,2		--	--	--	--	--		
	3		--	--	--	--	--	--	
	4,5		--	--	--	--	--	--	
	6		--	--	--	--	--	--	
	7		No Consequence						
Transporter Slide		6 PWR							
	1,2		--	--	--	--	--	--	
	3		--	--	--	--	--	--	
	4,5		--	--	--	--	--	--	
	6		--	--	--	--	--	--	
	7		No Consequence						
Drift Collapse		6 PWR							
	1,2		--	.1	.1	--	--	.05	
	3		--	.1	.1	--	--	--	
	4,5		No Consequence						
Earthquake		6 PWR							
	4,5,9,10		No Consequence						
	6,7		--	--	--	--	--	--	
	8		--	--	--	--	--	--	
	1,2		--	.1	.1	--	--	--	
	3		--	.1	.1	--	--	--	

HVAC filtration efficiency	Source term Release Fraction				Dose Consequence (mrem)			
	Kr85	Particles			Kr85	Particles		
		Cs Burst	Gap Release			Gap	Pulv.	Total
			Cs Diffusion	Pulv.				

--	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(-2)	--	2.4(-1)
--	0.3	2.8(-4)	--	--	2.2(-1)	8.9(+1)	--	8.9(+1)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	8.9(-3)	--	2.3(-1)

--	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(+2)	--	2.2(+2)
1(-4)	0.3	2.8(-4)	4.1(-4)	--	2.2(-1)	2.2(-2)	--	2.4(-1)
--	0.3	2.8(-4)	--	--	2.2(-1)	8.9(+1)	--	8.9(+1)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	8.9(-3)	--	2.3(-1)

--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	1.1(+2)	2.0(+2)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	2.1(-1)	4.4(-1)

--	0.3	2.8(-4)	--	--	2.2(-1)	8.9(+1)	--	8.9(+1)
1(-4)	0.3	2.8(-4)	--	--	2.2(-1)	8.9(-3)	--	2.3(-1)
--	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(+1)	1.1(+2)	2.0(+2)
1(-4)	0.3	2.8(-4)	--	2(-4)	2.2(-1)	8.9(-3)	2.1(-1)	4.4(-1)

8.0 RESULTS AND SUMMARY

This section presents the results of the analysis in terms of event trees, which identify accident scenarios and their associated annual probabilities and dose consequences. Following the methodology of the PRSA for surface facilities in MacDougall (1987), reference accident scenarios are identified here.

The event trees developed from the discussions in Subsection 3.3 are shown in Figures 8-1 through 8-21. The probabilities are taken from Table 4-2 of Subsection 4.2; the doses are taken from Table 7-1 in Subsection 7.3.

Event trees are shown for five underground compartments as follows:

o Waste ramp	Figures 8-1 through 8-3
o Performance confirmation area	Figures 8-4 through 8-9
o Waste main	Figures 8-10 through 8-12
o Panel access	Figures 8-13 through 8-15
o Emplacement drift	Figures 8-16 through 8-21

An event tree is constructed for each of the 21 initiating events that survived the screening process in Subsection 3.2. Of the 129 scenarios depicted in these event trees, only 99 result in a potential radiological release. Of these 99 scenarios, 66 result in a potential dose greater than 50 mrem. None of these evaluated doses exceed 220 mrem at the site boundary. The calculated doses are all less than the 500 mrem value used to define items important to safety in 10 CFR 60 (NRC, 1986).

A panel of engineers estimated the annual probability of each initiating event and the conditional probability of each intermediate event based on engineering judgment and historical data. All the intermediate event probabilities depend on the occurrence of the associated initiating event. The conditional probability of an intermediate event is the probability that it

will occur given that the events preceding it on the event tree also occur. By using conditional probabilities for intermediate events, one can calculate the annual probability of the scenario (or combination of events) as the product of the probabilities of each event in the scenario. The 66 scenarios that result in doses greater than 50 mrem have annual probabilities ranging from $1 \times 10^{-13}/\text{yr}$ to $5 \times 10^{-4}/\text{yr}$.

The annual probabilities and the dose consequences of each of the 129 scenarios are shown graphically on the scatter diagram in Figure 8-22. Thirty-three of the 66 scenarios that could result in doses greater than 50 mrem have annual probabilities greater than $10^{-9}/\text{yr}$. These 33 scenarios are identified as reference scenarios and are listed in Table 8-1.

Figure 8-22 and Table 8-1 show four reference scenarios with doses and annual probabilities that are relatively high compared with those of other scenarios. These four scenarios occur in the emplacement drift and performance confirmation area compartments. All have dose consequences of about 200 mrem; two of them have annual probabilities of $1 \times 10^{-5}/\text{yr}$, while the other two have annual probabilities of $5 \times 10^{-4}/\text{yr}$. All four scenarios involve container failure during emplacement or removal, resulting in a drop of the container into the borehole, with coincident failure of the airborne radioactivity monitoring system or ventilation exhaust filter system.

In conclusion, this preliminary study indicates that the potential offsite doses resulting from postulated underground accidents are less than the 500 mrem value used to define items important to safety. However, 33 reference scenarios are identified that could result in doses greater than 50 mrem and that have probabilities greater than $10^{-9}/\text{yr}$. These reference scenarios require further detailed study before a preliminary Q-list for the underground facility can be established. The study does not address an estimate of the uncertainties therefore conclusions or decisions made as a result of this report should be made with caution.

8-3

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-2
Event Tree for Runaway Transporter in the Waste Ramp

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-3
Event Tree for Earthquake in the Waste Ramp

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-4
Event Tree for Container Failure in the Performance Confirmation Area

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-5
Event Tree for Grapple/Hoist Failure in the Performance Confirmation Area

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-6
Event Tree for Transporter Collision in the Performance Confirmation Area

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-7
Event Tree for Transporter Slide in the Performance Confirmation Area

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-8
Event Tree for Drift Collapse in the Performance Confirmation Area

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-9
Event Tree for Earthquake in the Performance Confirmation Area

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-10
Event Tree for Transporter Collision in the Waste Main

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-11
Event Tree for Runaway Transporter in the Waste Main

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-12
Event Tree for Earthquake in the Waste Main

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-13

Event Tree for Transporter Collision in the Panel Access Drift

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-14
Event Tree for Runaway Transporter in the Panel Access Drift

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-15
Event Tree for Earthquake in the Panel Access Drift

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-16
Event Tree for Container Failure in the Emplacement Drift

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-17
Event Tree for Grapple/Hoist Failure in the Emplacement Drift

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-18
Event Tree for Transporter Collision in the Emplacement Drift

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-19
Event Tree for Transporter Slide in the Emplacement Drift

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-20
Event Tree for Drift Collapse in the Emplacement Drift

Note : All intermediate event probabilities are rounded to one significant figure; therefore, they may not sum to unity.

Figure 8-21
Event Tree for Earthquake in the Emplacement Drift

Table 8-1

REFERENCE SCENARIOS FOR UNDERGROUND FACILITIES

<u>Compartment</u>	<u>Scenario</u>	<u>Annual Probability (1/Yr)</u>	<u>Dose (mrem)</u>
Waste Ramp	Transporter Collision		
	with fire & radiation alarm failure	5×10^{-9}	2.2×10^2
	with radiation alarm failure	5×10^{-7}	8.9×10^1
	with ventilation system failure	1×10^{-8}	8.9×10^1
	Runaway Transporter		
	with radiation alarm failure	5×10^{-8}	9.1×10^1
	with ventilation system failure	1×10^{-9}	9.1×10^1
Performance Confirmation Area	Container Failure		
	with radiation alarm failure	5×10^{-4}	2.0×10^2
	with ventilation system failure	1×10^{-5}	2.0×10^2
	Grapple/Hoist Failure		
	with radiation alarm failure	5×10^{-7}	1.0×10^2
	with ventilation system failure	1×10^{-8}	1.0×10^2
	Transporter Collision		
	with radiation alarm failure	5×10^{-9}	8.9×10^1
	Transporter Slide		
	with radiation alarm failure	5×10^{-8}	8.9×10^1
	with ventilation system failure	1×10^{-9}	8.9×10^1
Waste Main	Transporter Collision		
	with fire & radiation alarm failure	5×10^{-9}	2.2×10^2
	with radiation alarm failure	5×10^{-7}	8.9×10^1
	with ventilation system failure	1×10^{-8}	8.9×10^1
	Runaway Transporter		
	with radiation alarm failure	5×10^{-8}	9.1×10^1
	with ventilation system failure	1×10^{-9}	9.1×10^1
Panel Access Draft	Transporter Collision		
	with fire & radiation alarm failure	5×10^{-9}	2.2×10^2
	with radiation alarm failure	5×10^{-7}	8.9×10^1
	with ventilation system failure	1×10^{-8}	8.9×10^2
	Runaway Transporter		
	with radiation alarm failure	5×10^{-8}	9.1×10^1
	with ventilation system failure	1×10^{-9}	9.1×10^1

Table 8-1 (Cont'd)

<u>Compartment</u>	<u>Scenario</u>	<u>Annual Probability (1/Yr)</u>	<u>Dose (mrem)</u>
Emplacement Drift	Container Failure		
	with radiation alarm failure	5×10^{-4}	2.0×10^2
	with ventilation system failure	1×10^{-5}	2.0×10^2
	Grapple/Hoist Failure		
	with radiation alarm failure	3×10^{-5}	1.0×10^2
	with ventilation system failure	5×10^{-7}	1.0×10^2
	Transporter Collision		
	with fire & radiation alarm failure	5×10^{-9}	2.2×10^2
	with radiation alarm failure	5×10^{-7}	8.9×10^1
	with ventilation system failure	1×10^{-8}	8.9×10^1
	Transporter Slide		
	with radiation alarm failure	5×10^{-6}	8.9×10^1
	with ventilation system failure	1×10^{-7}	8.9×10^1
	Earthquake		
	with transporter slide & radiation alarm failure	5×10^{-8}	8.9×10^1
	with transporter slide & ventilation system failure	5×10^{-8}	8.9×10^1

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Appendix A
REVIEW OF COMPUTER PROGRAMS FOR TRANSPORT ANALYSIS

Introduction

This appendix consists of a brief discussion of the aerosol transport mechanisms that are expected to be encountered in a mined repository and a brief review of some of the computer programs that may be useful in describing radionuclide transport in a mined repository.

For radionuclides to be released from a mined repository to the environment (atmosphere), it is necessary for the material to become airborne. In Section 3.0, accident scenarios that resulted in a fraction of the waste becoming airborne were developed. Because the mine is continuously ventilated, the airborne radionuclides will be transported by forced convection and may be released to the atmosphere. A fraction of the airborne waste will be deposited in the mined repository as a result of the various deposition mechanisms, and the rest will be released to the environment.

The dominant expected mechanisms for removal of airborne particles from the airstream are gravitational settling, diffusional plateout, and inertial deposition. Gravitational settlement results from the downward gravitational force on airborne particles. Diffusional plateout occurs when particles diffuse through the air and eventually contact surfaces where they are deposited. Inertial deposition arises as a result of the inertia of airborne particles traveling in a bulk air (gas). When this air goes around bends and corners, it changes direction, but the particles maintain their initial trajectory, strike and stick to the walls, and are thus removed from the airstream.

In general, an aerosol transport equation may include additional removal mechanisms and other physicochemical interactions between airborne particles and surfaces. The aerosol transport equation has a point-function solution. In a point-function solution, the properties of the system are evaluated at each point in time and space. The

point-function solution for a simple (transport) governing equation might be obtained readily. On the other hand, for a complicated governing equation, the solution may be difficult to obtain analytically, or may require the application of appropriate numerical techniques.

To obtain a solution using numerical techniques, one of two approaches is usually taken: the finite-difference (or finite-element) technique or the control volume method. The control volume method is briefly described below.

To facilitate a numerical technique, the domain of interest is divided into n subdomains (control volumes). The space-dependent particulate concentration is represented by the average particulate concentration in each subdomain. This technique results in a conversion of the governing equation into n coupled ordinary differential equations. The solution yields the average concentration for each subdomain as a function of time. If the number of subdomains increases indefinitely, then the problem is reduced to the point-function solution. In the control volume (subdomain) technique, higher efficiency of the numerical analysis can be gained at the expense of accuracy (or vice versa).

Review of Computer Programs That Predict Aerosol Formation and Transport

Most of the reviewed computer programs were developed for the purpose of predicting aerosol formation and transport during a severe reactor meltdown. These programs investigate the formation of particles and gases due to the extreme temperatures of a meltdown.

The general picture of aerosol transport during a meltdown is as follows. Fission products are released to a steam-hydrogen environment in the primary loop. As the gas encounters cooler structures, such as the upper plenum or piping, it loses heat and cools down. Some of the gaseous phase is deposited on the walls, and some undergoes condensation and possible chemical reaction with other nuclides. As condensation occurs, droplets are formed. The droplets collide with each other and result in the formation of larger particles. The particles and droplets are deposited on the walls as a result of gravitational setting, inertial

deposition, chemical reactions, thermophoresis (driven by temperature gradient), etc. Also, in an operational reactor, radioactive decay of short-lived nuclides results in decay heating, which affects heat source distribution, heat transfer rate, and convection patterns.

In a detailed modeling, the governing equation includes all the above interactions. The solution is obtained with the aid of extensive computer programs and powerful computing machines.

RAFT Computer Program. The RAFT computer program evaluates transport of fission products (radionuclides) through the steam/hydrogen environment of an LWR primary loop (Im, 1987). The RAFT computer program requires thermal hydraulic conditions and aerosol release rates as inputs. The program determines the release rate from the primary loop to the containment vessel. It considers heterogeneous nucleation, homogeneous nucleation, aerosol agglomeration, aerosol convection, aerosol deposition due to diffusion, thermophoresis, eddy impaction, inertial deposition, gravitational deposition, vapor deposition, and chemisorption on surfaces within the primary system. The solution is obtained by discretization of spatial and temporal domain, i.e., finite difference. This program may be applicable for underground transport; however, many of the subroutines, such as the one for thermophoresis, are not applicable to the mined repository.

CONTAIN Computer Program. CONTAIN was developed to predict physical, chemical, and radiological conditions inside a containment building following the release of radioactive material from the primary system in a severe reactor accident (Bergeron, 1985). The program divides the system into cells (subdomains). Each cell can be divided into two zones: an upper gaseous zone and a lower molten fuel/liquid zone. The lower zone may be absent. Transport is from one cell to the other with the rate specified by the user. The program considers decay and subsequent decay heating and compositional change, condensation, agglomeration, and deposition. CONTAIN is a very extensive program and covers other topics such as hydrogen burning, sodium/spray fires, and aerosol removal by spray and other engineering safety features. This

program may be applicable to the transport of radionuclides in a mined repository, but some of the subroutines would not be useful.

TRAP-MELT2 Computer Program. TRAP-MELT2 was developed for aerosol transport through the primary loop during a severe accident (Jordan, 1985). The program does not address leakage from the primary loop to the containment. The primary loop is divided into a maximum of 10 cells (subdomains). In each cell, particle concentration is uniform. Interconnection between different cells is possible. The radionuclides will be transported in gaseous or particulate/droplet phases. Particle deposition, vapor deposition, and reevaporation are also included. Chemisorption, which results in retention of gaseous material by the structure, is also modeled. The program requires thermal hydraulic data, mass flow rate, and initial composition as an input. The deposition mechanisms considered are vapor sorption, particle deposition due to turbulent flow, particle deposition from laminar flow, thermophoretic deposition, gravitational settling, coagulation due to Brownian motion, and turbulent deposition. Owing to the closed loop nature of the program, it cannot be applied directly to a mined repository. However, modifications may result in a program that is capable of radionuclide transport in a mined repository.

FIRAC Computer Program. The FIRAC computer program was developed to determine radionuclide transport in a fuel cycle facility (Nichols, 1985). FIRAC uses the subdomain technique. The radionuclides are released as a result of fire. The program can use either steady-state flow or transient flow as an input.

The gas transport is decoupled from material transport, i.e., it is assumed that the particles have the same velocity as the gas (air). There are no material (chemical) interactions and no phase change between gaseous and solid (particulate) phases. Deposition is due to gravitational settling. Filtration and inertial deposition are also used in the program. Thermophoretic, turbulent deposition, and deposition due to Brownian diffusion are neglected.

Material entrainment based on semiempirical wind tunnel data or tabular data are adopted. The program is capable of determining transport of arbitrary particulate or gaseous species.

TORAC Computer Program. TORAC is developed to determine aerosol transport through a facility due to a tornado (Andrae, 1985). The program is very similar to FIRAC and has the capability of assessing aerosol transport by applying a subdomain method. Ducts and rooms are idealized as nodes. Deposition is due to gravitational settling only. Inertial deposition due to bends is modeled as an equivalent duct length.

Other Computer Programs. Other programs that have not been reviewed, but that may be useful, are PULSE (which is developed for radionuclide transport in a mined repository), MATADOR, and CANAL-2. No documentation was available for these programs.

Conclusions and Recommendations

Transport of airborne radionuclide in a continuously ventilated mine is governed by forced convection, gravitational settling, inertial deposition, and diffusional plateout.

The reviewed computer programs are categorized as (1) programs developed for airborne radionuclide transport during a reactor core meltdown, and (2) programs developed for airborne radionuclide transport in a nuclear fuel cycle facility.

The first category (programs developed for reactor core meltdown) considers many physicochemical interactions and is very complex. These programs have a modular structure, i.e., many subroutines (modules) where each subroutine performs a given task. Many of the physicochemical interactions, such as fuel vaporization, are not applicable to the transport of airborne radionuclides in a mined repository. However, these programs may be applied to the aerosol transport in a mined repository simply by not using many of the subroutines. Furthermore, all the reviewed programs except RAFT use the control volume technique.

Although this technique may be well suited to short transport paths encountered in a primary coolant cycle of a nuclear reactor, it may not be suited for the long drifts of a mined repository unless a drift is subdivided into many control volumes.

The second category (programs developed for a fuel cycle facility) is not directly applicable to the aerosol transport in a mined repository and requires some modifications. Examples of these modifications are convergence of airflow from many drifts into one drift or vice versa, and aerosol transport in the exhaust (vertical) shaft. Furthermore, these programs also use the control volume method.

To apply programs in either category to a long drift in a mined repository, it is necessary to divide the drift into many subsections, which adds to the time and cost of running the program. Adoption and modification of these programs are not recommended because of (1) the increase in cost due to modifications and added execution time and (2) the uncertainty in the amount of airborne releases to the atmosphere due to accumulation of error from each control volume.

In conclusion, the reviewed programs should not be used to estimate airborne radionuclide transport in a mined repository. It is recommended that a simple, yet realistic, model of transport be developed. If the results of this model cannot be used to obtain a satisfactory estimate of radionuclide releases, then one of the reviewed (or other) computer programs could be adopted or modified, or some other means could be employed to assess airborne radionuclide transport.

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Appendix B
INTERACTION MATRICES BY COMPARTMENT

The interaction matrices were constructed in the following manner:

- o Identify structures, systems, components, and potential problems that exist in the compartment
- o Depict each item as the heading of a column and a row
- o Analyze each row on a column-by-column basis to identify a possible interaction between items
- o Mark interactions with an "X" (self-interactions are not marked)
- o Analyze marked interactions for possible accident scenarios, from which a list of internal initiating events is developed

	TRANSP- ORTER	S.F.CONT.	DHLW CONT.	RAMP FLOOR	RAMP WALL	UTILITY TRUCKS
TRANSP- ORTER		X	X	X	X	
S.F.CONT-	X					
DHLW CONT.	X					
RAMP FLOOR	X					X
RAMP WALL	X					
UTILITY TRUCKS				X		

Figure B-1
Interaction Matrix for Compartment #1: Waste Ramp

	TRANSP- ORTER	S.F.CONT.	DHLW CONT.	EMPLAC. DRIFT FLOOR	EMPLAC. DRIFT WALL	BULK- HEADS	SHIELD PLUGS	PLUG INSTALLER	SHIELDING CLOSURE FORKLIFT	ELECT. LINES	AIR DOORS	ELECT. MONIT. INSTRUM.
TRANSP- ORTER		X	X	X								
S.F.CONT.	X											X
DHLW CON- TAINER	X											X
EMPLAC. DRIFT FLOOR	X					X		X	X	X	X	X
EMPLAC. DRIFT WALL						X				X	X	
BULK- HEADS				X	X							
SHIELD PLUGS								X				
PLUG INSTALLER				X			X					
SHIELDING CLOSURE FORKLIFT				X								
ELECT. LINES				X	X							
AIR DOORS				X	X							
ELECT. MONIT. INSTRUM.		X	X	X								

Figure B-2

Interaction Matrix for Compartment #2: Performance Confirmation Area

	REFUELING TANKS	WELDING EQUIP.	HYDRAULIC FLUIDS/ LUBRIC.	FIRE SUPPRESS. SYSTEM	AUTO PARTS	BULK- HEADS	MACHINE SHOP EQUIP.	ELECTRIC. INSTR.	FIRE TRUCK	AMBULANCE	PIPING	AIR COMPRESS.	EMPTY TRANSP.
REFUELING TANKS									X	X			X
WELDING EQUIP.							X				X		
HYDRAULIC FLUIDS/ LUBRIC.							X		X	X			X
FIRE SUPPRESS. SYSTEM													
AUTO PARTS									X	X			X
BULK- HEADS													
MACHINE SHOP EQUIP.		X	X									X	
ELECTRIC. INSTR.													
FIRE TRUCK	X		X		X								
AMBULANCE	X		X		X								
PIPING		X											
AIR COMPRESS.							X						
EMPTY TRANSP.	X		X		X								

Figure B-3
Interaction Matrix for Compartment #3: Waste Emplacement Area Shops

	TRANSP- ORTER	S.F.CONT.	DHLW CONT.	MAIN FLOOR	MAIN WALL	BULK- HEADS	FORK- LIFTS	UTILITY VEHICLES	PERSONNEL TRANSP.
TRANSP- ORTER		X	X	X					
S.F.CONT.	X								
DHLW CONT.	X								
MAIN FLOOR	X					X	X	X	X
MAIN WALL						X			
BULK- HEADS				X	X				
FORK- LIFTS				X					
UTILITY VEHICLES				X					
PERSONNEL TRANSP.				X					

Figure B-4
Interaction Matrix for Compartment #4: Waste Main

	TRANSP- ORTER	S.F.CONT.	DHLW CONT.	PANEL FLOOR	PANEL WALL	BULK- HEADS	AIR DOORS	FORK- LIFTS	UTILITY VEHICLES	UTILITY LINES
TRANSP- ORTER		X	X	X						
S.F.CONT.	X									
DHLW CONT.	X									
PANEL FLOOR	X					X	X	X	X	X
PANEL WALL						X	X			X
BULK- HEADS				X	X					
AIR DOORS				X	X					
FORK- LIFTS				X						
UTILITY VEHICLES				X						
UTILITY LINES				X	X					

Figure B-5
Interaction Matrix for Compartment #5: Panel Access Drift

	TRANSP- ORTER	S.F.CONT.	DHLW CONT.	EMPLACE. DRIFT FLOOR	EMPLACE. DRIFT WALL	BULK- HEADS	SHIELD PLUGS	PLUG INSTALLER	SHIELDING CLOSURE FORKLIFT	ELECT. LYNES	AIR DOORS
TRANSP- ORTER		X	X	X							
S.F.CONT.	X										
DHLW CON- TAINER	X										
EMPLACE. DRIFT FLOOR	X					X		X	X	X	X
EMPLACE. DRIFT WALL						X				X	X
BULK- HEADS				X	X						
SHIELD PLUGS								X			
PLUG INSTALLER				X			X				
SHIELDING CLOSURE FORKLIFT				X							
ELECT. LYNES				X	X						
AIR DOORS				X	X						

Figure B-6
Interaction Matrix for Compartment #6: Emplacement Drift

	INSPECT. HOIST	PUMPS IN SUMPS	RAD MONITOR. SYSTEM	SHAFT STRUCTURE
INSPECT. HOIST				X
PUMPS IN SUMPS				
RAD MONITOR. SYSTEM				X
SHAFT STRUCTURE	X		X	

Figure B-7
Interaction Matrix for Compartment #7: Emplacement Exhaust Shaft

	TUNNEL BORING MACHINE	BULKHEADS	COMMERC. EXPLOS.	EXPLOS. LOADER	ROOF BOLTER	DRIFT WALLS	DRIFT FLOOR	LWD MACHINE	BELTS	JUMBO DRILL	UTILITY VEHICLE	PERSONNEL TRANSP.
TUNNEL BORING MACHINE						X	X					
BULKHEADS						X	X					
COMMERC. EXPLOS.				X		X						
EXPLOS. LOADER			X				X					
ROOF BOLTER							X					
DRIFT WALLS	X	X	X					X				
DRIFT FLOOR	X	X		X	X			X		X	X	X
LWD MACHINE						X	X		X			
BELTS								X				
JUMBO DRILLS							X					
UTILITY VEHICLES							X					
PERSONNEL TRANSP.							X					

Figure B-8
Interaction Matrix for Compartment #8: Mains Under Development

	TUNNEL BORING MACHINE	PILOT HOLE DRILL	REAMER DRILL	BULKHEADS	COMMERC. EXPLOS.	EXPLOS. LOADER	ROOF BOLTER	DRIFT WALLS	LHD MACHINE	BELTS	JUMBO DRILLS	DRIFT FLOOR
TUNNEL BORING MACHINE								X				X
PILOT HOLE DRILL												X
REAMER DRILL												X
BULKHEADS								X				X
COMMERC. EXPLOS.						X		X				
EXPLOS. LOADER					X							X
ROOF BOLTER												
DRIFT WALLS	X			X	X							
LHD MACHINE										X		X
BELTS									X			
JUMBO DRILLS												X
DRIFT FLOOR	X	X	X	X		X			X		X	

Figure B-9

Interaction Matrix for Compartment #9: Panel Drifts Under Development

	ELECTRIC. SUB- STATION	FUEL TANK	HYDRAUL. FLUIDS	USED OIL BARRELS	TIRES	BATTERIES	WELDING GASES	BULKHEADS	GENERAL WAREHOUSE	FIRE SUPPRES.	SHOP FLOOR	SHOP WALL	UTILITY VEHICLE
ELECTRIC. SUB- STATION									X		X	X	
FUEL TANK													X
HYDRAUL. FLUIDS									X		X		X
USED OIL BARRELS									X		X		
TIRES									X		X		X
BATTERIES									X		X		X
WELDING GASES									X				
BULKHEADS											X	X	
GENERAL WAREHOUSE	X		X	X	X	X	X						
FIRE SUPPRES.												X	
SHOP FLOOR	X		X	X	X	X		X					X
SHOP WALL	X							X		X			
UTILITY VEHICLE		X	X		X	X					X		

Figure B-10
Interaction Matrix for Compartment #10: Development Area Shops

	FUEL LYNE	ELEVATOR	HOISTING CAGES	ELECTRIC. LYNES	WATER PIPE LYNES	COMMUN. LYNES	SHAFT STRUCT.
FUEL LYNE							X
ELEVATOR							X
HOISTING CAGES							X
ELECTRIC. LYNES							X
WATER PIPE LYNES							X
COMMUN. LYNES							X
SHAFT STRUCT.	X	X	X	X	X	X	

Figure B-11

Interaction Matrix for Compartment #11: Men and Materials Shaft

	INSPECT. /ESCAPE HOIST	SHAFT STRUCTURE
INSPECT. /ESCAPE HOIST		X
SHAFT STRUCTURE	X	

Figure B-12
Interaction Matrix for Compartment #12: Exploratory Shafts

	CONTAM. MACHINERY	LIQUID CONTAM. WASTES	CONTAM. SOLID WASTES	DAMAGED CONTAINER	TRANSP.	UTILITY VEHICLE	RADIATION DETECTOR	FIRE SUPPRESS. EQUIPMENT	PORTABLE ELECTRIC GENERATOR	FORKLIFTS	FRONT END LOADER	DECON FACILITY FLOOR	DECON FACILITY WALL
CONTAM. MACHINERY		X	X									X	
LIQUID CONTAM. WASTES	X			X	X					X			
CONTAM. SOLID WASTES	X			X	X					X			
DAMAGED CONTAINER		X	X		X								
TRANSP.		X	X	X								X	
UTILITY VEHICLE								X	X			X	
RADIATION DETECTOR													X
FIRE SUPPRESS. EQUIPMENT						X							X
PORTABLE ELECTRIC GENERATOR						X						X	
FORKLIFTS		X	X										
FRONT END LOADER												X	
DECON FACILITY FLOOR	X				X	X			X	X	X		X
DECON FACILITY WALL							X	X				X	

Figure B-13

Interaction Matrix for Compartment #13: Decontamination Facility

	BELTS	UTILITY VEHICLES	LHD MACHINE	ELECT. LINES	COMMUN. LINES	JUMBO DRILL	RAMP FLOOR	RAMP WALL
BELTS			X					
UTILITY VEHICLES							X	
LHD MACHINE	X							
ELECT. LINES							X	X
COMMUN. LINES							X	X
JUMBO DRILL							X	X
RAMP FLOOR		X		X	X	X		
RAMP WALL				X	X	X		

Figure B-14
Interaction Matrix for Compartment #14: Tuff Ramp

Appendix C
FAULT DIAGRAMS FOR INTERMEDIATE EVENTS

This appendix contains 10 fault diagrams for intermediate events.

Figure C-1
Fault Diagram for Container Breach

Figure C-2
Fault Diagram for Ventilation System Failure

Figure C-3
Fault Diagram for Transporter Collision

Figure C-4
Fault Diagram for Container Failure

Figure C-5
Fault Diagram for Grapple/Hoist Failure

Figure C-6
Fault Diagram for Transporter Slide

Figure C-7
Fault Diagram for Fire

Figure C-8
Fault Diagram for Runaway Transporter

Figure C-9
Fault Diagram for Drift Collapse

Figure C-10
Fault Diagram for Radiation Alarm Failure

Appendix D

Information from the Reference Information Base Used in this Report

This report contains no information from the Reference Information Base.

Candidate Information for the Reference Information Base

This report contains no candidate information for the Reference Information Base.

Candidate Information for the Site & Engineering Properties Data Base

This report contains no candidate information for the Site and Engineering Properties Data Base.

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