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Civilian Radioactive Waste Management System
Management & Operating Contractor

Repository Seals Requirements Study

BC0000000-01717-5705-00018 REV 00/DCN 1

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Prepared for:

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EXECUTIVE SUMMARY

The Yucca Mountain Site Characterization Project, managed by the Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O) is conducting investigations to support the Viability Assessment and the License Application for a high-level nuclear waste repository at Yucca Mountain, Nevada. The sealing subsystem is part of the Yucca Mountain Waste Isolation System. The Yucca Mountain Site Characterization Project is currently evaluating the role of the sealing subsystem (shaft, ramp and exploratory borehole seals) in achieving the overall performance objectives for the Waste Isolation System. This report documents the results of those evaluations.

This report presents the results of a repository sealing requirements study. Sealing is defined as the permanent closure of the shafts, ramps, and exploratory boreholes. Sealing includes those components that would reduce potential inflows above the repository, or that would divert flow near the repository horizon to allow vertical infiltration to below the repository. Sealing of such features as emplacement drifts was not done in this study because the current capability to calculate fracture flow into the drifts is not sufficiently mature.

The objective of the study is to provide water or air flow performance based requirements for shafts, ramps, and exploratory boreholes located near the repository. Recommendations, as appropriate, are provided for developing plans, seals component testing, and other studies relating to sealing.

REQUIREMENTS AND STANDARDS

In the study, a review of the current state and federal regulations that apply to sealing a high-level nuclear waste repository was conducted. The standards included the current Interim Postclosure Standard based on peak dose, the NRC standards in 10 CFR 60 specific to disposal of nuclear waste in geologic repositories, and state regulations as applied to sealing boreholes. The interim standards include isolation requirements for the entire disposal system, of which seals would be a part of this system. The interim standards do not specify requirements for individual subsystems that are a part of the disposal system. Because the current standards apply to peak doses from the overall disposal system to the accessible environment, and the capability to calculate the performance effect of seals on the total system does not currently exist, it was determined to be more appropriate to use seal subsystems standards as defined by the NRC in 10 CFR 60 in developing water flow or air flow performance-based requirements. The standards in 10 CFR 60 include quantitative requirements for radionuclide release in 10 CFR 60.113, qualitative requirements for preferential pathways through shafts, ramps, and boreholes in 10 CFR 134, and other requirements specific to field testing for seals in 10 CFR 60.142. The state regulatory requirements applicable to sealing boreholes are stated in the Nevada Administrative Code for sealing, abandonment of geothermal or injection wells, and casing string removal, capping, and removal of structures and other facilities.

STUDY METHODOLOGY

The study methodology for water flow included a technical approach to determine hydrological performance goals based on the performance of the engineered barrier system for specific radionuclides of concern, to determine water flows into the repository, and then to determine the need for sealing. If the determination of the need for sealing shows components are necessary, then seal design requirements are developed. The study methodology for air flow included developing a maximum release limit for two radionuclides of concern, performing air flow analysis for the heated repository, and selecting a design requirement for backfill.

A detailed stochastic waste package performance simulation model (CRWMS M&O 1995) was used in the study to develop water flow performance goals based on the performance of the engineered barrier system. Various corrosion models are incorporated into this model as discussed in detail in Section 3.3 of the report. The analysis considered the radionuclides ^{99}Tc, ^{79}Se, ^{135}Cs, ^{59}Ni, ^{237}Np, ^{210}Pb, and ^{226}Ra. The water flow performance goals were developed from relationships for radionuclide releases for comparison to the NRC limit as derived from 10 CFR 60.113 for each radionuclide, developing an envelope for the ratio of release rate divided by the NRC limit, and then developing water flow performance goals for the most critical radionuclides in the inventory. The analysis derived water flow rates that complied with the NRC limits for the most critical radionuclides (^{99}Tc and ^{79}Se). The results of this analysis show a water flow performance goal of 500 m^3 per year at 10,000 years compared to a previous goal of 140,000 m^3 per year from 1,000 to 10,000 years (Fernandez et al. 1987). The differences in release rates in the derived hydrologic performance goals are due to modeling differences for radionuclides and a higher repository thermal loading.

The potential for convective air flow and the release of gaseous radionuclides from the repository was evaluated for compliance to the NRC regulation (10 CFR 60.113) for restricting or limiting radionuclide releases from the engineered barrier system to one part in 100,000. This regulation established an allowable air flow goal for the release of gaseous radionuclides as 5 percent of the maximum release rates for ^{14}C and ^{129}I.

AIR FLOW ANALYSIS

To evaluate shaft/ramp/ backfilling requirements, a convective air flow analysis was performed. The model considered that cool air is drawn in through the North and South Ramps, and the Development Intake Shaft. The air enters the repository and rises over the central block of the repository through boreholes, the Emplacement Exhaust Shaft and the overlying welded and nonwelded tuff units. The analyses showed that if a general backfill is selected to restrict flow to one percent of the flow through the rock, the required conductivity expressed as a hydraulic conductivity for the shaft, ramp or exploratory borehole backfill is 10^{-2} cm/s. A backfill with a hydraulic conductivity of 10^{-2} cm/s thus would suffice to restrict the release of gaseous radionuclides to within NRC limits and is specified as a design requirement for air flow.

WATER FLOW ANALYSIS

Various performance scenarios were developed for estimating flows to the underground repository through the shafts, ramps, and exploratory boreholes. The range of potential anticipated flows considered infiltration rates ranging from 5 mm per year to 30 mm per year. The inflow rates to the underground facility reflect these infiltration rates, the capture zone area, unanticipated conditions, and potential climate change conditions.

The results showed that anticipated water flows through shafts were of the order of 1 to 170 m^3 per year, and would not likely exceed the flow capacity of backfilled shafts. The anticipated flow rates for the ramps was from 400 to 2,400 m^3 per year and reflects infiltration through dominantly vertical fractures. Under unanticipated conditions, flows might be higher for short episodic events (27,000 m^3 per year) for flow through discrete faults. However, the flows are relatively small since shafts and ramps are located outside of flood plain areas. The flows reflect potential transient flow from a perched water zone, and flow through intersecting fault zones. Evidence suggests that fast travel paths may exist through fracture or fault zones.

REPOSITORY SEALING AND OPTIONS

An assessment of the need for sealing shafts and ramps was performed by comparing the allowable water flow goals to the anticipated water flows of the underground repository. The comparisons showed that for the range of anticipated water flows from the shafts, ramps, and underground facility, the flows from the underground shafts and ramps at an infiltration rate of 5 mm per year might not exceed the allowable flow as determined from the requirement for release of radionuclides from the engineered barrier system. For these anticipated flows, seals would not be necessary. At an infiltration rate of 30 mm per year, the allowable flow rates would be exceeded and there would be requirements for seals. For unanticipated flows, there is the potential that flows through shafts and ramps might also exceed the allowable water flows over short periods of time.

For deep exploratory boreholes that intersect or go below the repository horizon, the need for repository seals is established on the basis that they could represent preferential pathways from the repository horizon to the groundwater table. The potential exists for perched water zones near the zeolitized zones where a significant permeability contrast would exist. The potential exists for perched water to enter the deep exploratory boreholes below the repository horizon, and transmit water to the groundwater table. Therefore, deep boreholes require sealing.

In order to develop allowable water flow goals for individual sealing components in shafts and ramps, a process of performance allocation was used. For example, because water might enter the underground repository and flow through the seal components, enter waste emplacement drifts and potentially affect overall performance, the seals are subject to performance allocation. An allocation of the allowable flow that would not exceed the water flow performance goal for the engineered barrier system was determined for the shafts, ramps, and underground repository.

In performance allocation, the relative ease or difficulty in sealing is evaluated to establish the sealing criteria for each component. In determining the potential difficulty, the allocation considered the difference in uncertainty in the number of sealing or engineered components required to achieve the performance goal for the underground facility and the performance goal for the shafts and ramps. In the underground facility, the potential exists for water to enter more directly and contact the waste. Contrary to this uncertainty, the numbers and locations of the shafts and ramps are currently defined together with their relationship to the underground facility. The flowpath lengths are longer for water flow to enter the repository and contact the waste. The number and types of sealing components can thus be defined with more certainty for the shafts and ramps than for the underground facility. Also, the site environmental conditions that would impact seal performance were evaluated. In the underground facility, the sealing components would be subject to higher temperatures and stresses than those components in the shafts and ramps.

These considerations were taken into account in determining the performance allocation of the shaft and ramps. Because the allowable flow based on the NRC requirements far exceeds the anticipated flows of the ramps, shafts, and underground in the early years after repository closure while the waste packages are essentially intact, all but 2,400 m^3/year of the total allowable flow is assigned as the performance goal of the shafts and ramps to the point in time (approximately 3,300 years after closure) when the total allowable flow equals the anticipated flow to the underground drifts. After that time 99 percent of the allowable flow is assigned to the repository thus, allowing only 1 percent of the total allowable flow to be assigned to the shafts and ramps whose sealing requirements can be more easily achieved.

The allowable water flow goals are modified to account for drainage at the base (low points) of the repository or the ramps and shafts. Storage capacity is defined as a volume that could be retained, and allowed to drain into the rock over short durations up to one year. The storage capacity is determined in part by the anticipated flows that would flow to the low point of the repository and in part by water flow through the shafts/ramps. It is concluded that capacity from infiltration into underground drifts can be augmented by designing storage capacity at the low point of the repository or by constructing sumps.

Design relations were developed to provide a flexible approach for determining design flow rates through the shaft and ramp seal subsystem, and the total storage capacities at the base of the repository that meet the NRC requirements. The total storage capacity can range from 17,000 to 49,000 m^3 per year. The corresponding seal design flow rates would range from 3,500 m^3 per year to 35,000 m^3 per year. The design flow rates for individual seal components based upon a total of four shafts and ramps equals one quarter of these computed flow rates. If consideration is given to four shafts and ramps, and the design of a seal near the base of the repository that is approximately 9 m long under a hydrostatic head of 370 m, the required hydraulic conductivity is 10^{-6} cm/s to restrict flow to 3,500 m^3 per year. For an order of magnitude increase in flow rate, 35,000 m^3, the required hydraulic conductivity is 10^{-5} cm/s which would be more easily achieved. These sealing requirements are flexible such that flow rates and total storage capacities can be selected, and the relationship is described in further detail in this report.

In developing a repository sealing strategy, various seals are proposed in each of the shafts and ramps and deep exploratory boreholes. The sealing concepts, configurations, and analyses presented stress flexibility and robustness and can be easily adjusted as the results of the site characterization and repository design activities are made available.

The components included an Anchor-to-Bedrock Plug, Upper Seals located in the PTn and TSw, and shaft backfill. These seals provide redundancy in using multiple seals with different materials for sealing in several host rock formations. In general, the seals might be constructed of earthen and cementitious materials since each material has advantages and disadvantages regarding strength, and durability. Also, the sealing concepts provide for primary grouting, and contact grouting of the seal/rock interface. Primary grouting might be performed to reduce the permeability in the modified permeability zone (fractured rock around shafts and ramps due to boring), since this zone has been found through previous sealing studies to be a preferential pathway for water flow. Contact grouting might be performed to reduce the permeability at the interface zone since this zone has also been found to be a preferential pathway for flow.

On the basis of this repository sealing study, the following design requirements are proposed:

Water Flow Sealing Requirements

Seal the deep exploratory boreholes within the extended repository boundary so that water flow through the sum of all exploratory boreholes that intersect the repository is less than 1 percent of the water flow through the rock, (This can be achieved by providing an effective seal conductivity of 10^{-5} to 10^{-6} cm/s.) Seal shafts and ramps such that the mathematical relationships are satisfied for seal flow and storage capacity as presented in Section 5.3 or Figure 5-18 of the report. (Also, this can be achieved with effective seal conductivities of 10^{-5} to 10^{-6} cm/s.)

Air Flow Sealing Requirements

Limit air flow from the repository to the ground surface through the sum of all deep boreholes (within the extended repository boundary that intersect the PTn or are deeper[1]) and shafts and ramps to less than 1 percent of the air flow through the rock. This can be achieved with a backfill in the shafts, ramps, and boreholes that has a hydraulic conductivity of 10^{-2} cm/s.

For shafts, and ramps that provide access for materials handling, and ventilation of the repository, seals would be constructed upon retreat from the repository, and at the completion of underground operations.

The high-temperature environment at the potential repository horizon could result in borehole casing failure or failure of the open borehole prior to sealing that would limit access to the lower sealing locations. Even for the cased boreholes, the higher temperature environment might increase stress in the surrounding rock and result in formation collapse against the casing and accelerated corrosion. These considerations indicate potential advantages to borehole seal placement prior to waste emplacement to ensure the placement of high-quality seals.

In some cases, exploratory boreholes may be used for performance confirmation testing after waste emplacement. For existing boreholes, studies will be conducted, and certain borehole casing may be re-worked to assure casing integrity to the extent practical prior to seal emplacement. If certain deep exploratory boreholes are intended to be used for post waste emplacement monitoring within the waste emplacement areas, an adequate separation distance to assure borehole stability as determined from structural analysis between the borehole and the nearest waste emplacement drift should be maintained.

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[1]The extended repository boundary extends 400m away from the repository boundary as determined from lateral dispersion analysis.

In addition to these primary requirements, secondary requirements are proposed to assure that static loads from overlying seal materials and interactions with the host rock due to thermal loading are accommodated by the seal system.

Recommendations

It is recommended that the Yucca Mountain Site Characterization Project develop plans for seals in individual boreholes, shafts and ramps. These plans should contain design specifications and construction drawings and should consider the general and specific problems encountered at specific sealing locations after completion of site investigations. The plans for sealing exploratory boreholes should provide detailed information from a combination of mechanical caliper, and video logging to search for any obstructions. Injection pressures may be determined by controlled hydrofracturing in zones near seal locations. In areas where primary grouting is necessary, grout designs will be tailored to provide materials performance at specified grout-injection pressures, viscosity, and strength. The plans should address state regulations for cementing the annular space for casing near the ground surface.

The plans for sealing shafts and ramps should provide detailed drawings illustrating seal geometry, the extent of key excavations, and grout holes. The plans should detail any requirements for removal of artificial support, and construction quality control during emplacement of seals. Materials specifications should provide the properties such as hydraulic conductivity or unconfined compressive strength to be developed by the sealing materials such as grouts, concrete and earthen backfill.

This report presented information on repository seal component and performance confirmation testing. Previous sealing studies (Fernandez et al. 1993) identified seal component and performance confirmation tests, and provided a schedule for testing to support the LA. As design concepts are developed, it is recommended that in situ testing of seal components be performed to support design efforts. This testing might utilize different earthen and cementitious sealing materials in both fractured and unfractured tuff to support seal design efforts.

This report addresses repository seals in shafts, ramps, and exploratory boreholes. Other sealing requirements for sealing components in the underground facility may need to be developed to control water flows from the perimeter mains, and to direct this flow to areas where water can be drained into the tuff below the repository. Further, water flows into waste emplacement areas may need to be restricted from flowing to the low end, or low points, of the repository. Previous studies (Fernandez et al. 1987) have shown that there would be higher difficulty in achieving water flow goals in the higher temperature environment. Thus, it is recommended that additional performance assessment and sealing evaluations be conducted to develop sealing requirements within the underground repository. These studies should evaluate the current repository design, and the potential for water to concentrate in the low points of the repository and increase saturation levels with the potential for an increased flux rate to the groundwater table. Should the recommended evaluations indicate the need to seal emplacement drifts or modify drainage flows, it should not impact the amount of emplacement drifts/area required. It may, however, affect the slopes of the drifts and the cost to add such measures as diversion dams or grouting of cracks, if needed, may increase.

A summary of the recommendations for requirements for the seals system that were developed based on the results of this study are the following:

Boreholes

The seals system for boreholes should be designed to meet the following criteria:

- The system shall provide sealing to boreholes that meet the criteria of coming within 100 meters of the repository horizon or deeper and for those boreholes that are within an area bounded by a distance of 400 meters from the repository emplacement area perimeter.

- To insure that boreholes should not become preferential pathways for radionuclides, the system shall limit vertical water flow through the sum of all boreholes that intersect the repository to less than one percent of the vertical water flow through the rock mass that extends 400 meters beyond the repository perimeter drifts. Based on the current expected number of boreholes that meet the above criteria (six existing and one planned), the one percent or less flow can be achieved by sealing the boreholes with an effective seal conductivity of between 10^{-4} to 10^{-3} cm/s. This criterion is flexible in that if additional boreholes are drilled the permeability requirement would become more stringent.

- Borehole seals shall limit airflow consistent with the criteria listed below for shafts and ramps.

Shafts and Ramps

The seals system for shafts and ramps would be designed to meet the following criteria:

- The system shall limit air flow through the sum of all of the subsurface openings (i.e., boreholes, ramps, and shafts) to less than one percent of the air flow through the rock mass over the area that extends to 400 meters beyond the repository perimeter. This can be readily achieved with the sealing permeabilities specified above for the boreholes and below for the shafts and ramps.

- The system shall be designed to provide for a total storage capacity of water at the repository horizon which will accommodate a rate of 17,000 to 49,000 m^3/yr. Storage capacity is defined as a volume that could be retained and allowed to drain into the rock in one year's time without contacting the waste packages.

- To achieve the subsystem requirement of limiting the release rate of any radionuclides to less than 1 part in 100,000 per year, the system shall limit the total flow rate through shaft and ramp seals equal to or less than the value computed from the following equation. The storage capacity is based on the value used in the above criterion.

$$\text{Flow rate} = (0.98 \bullet \text{Total Storage Capacity in } m^3/yr) - 13{,}234\ m^3/yr$$

This flow rate can be achieved by providing seals which have conductivities 10^{-5} to 10^{-6} cm/s with the higher conductivity corresponding to the higher flow.

Operating Conditions

The system shall be designed for the following environmental conditions and lifetime:

- The system shall be designed for the following applicable environmental conditions:

Subsurface Environments	Minimum and Maximum Conditions
In-Situ Rock Temperature	13 to 90 °C
Water Infiltration	5 to 30 mm/year
pH of Infiltration Water	4.5 to 10.5

- To provide reasonable expectation of meeting the Mined Geologic Disposal System radionuclide release requirements, the system shall be designed for permanent installation with a design life goal of 10,000 years.

If in the regulatory process a decision is reached to make the borehole or shaft/ramp seals more robust then the design can be easily changed by scaling the work done in this report. Lower conductivity seal material, backfill, or larger seal plugs could all be considered to increase the robustness of the seal.

Subsurface Sealing and Water Diversion

Some additional evaluations of the performance impact of repository engineered water drainage which may concentrate radionuclides in a localized area and possible flow into emplacement drifts should be done. The capability to perform such evaluations should exist after January 1998.

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FIGURES

FIGURES (Continued)

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1. INTRODUCTION

This document reports the work conducted in the Repository Seals Requirements Study over the period from October 1, 1996 through May 30, 1997.

1.1 OBJECTIVE

The objective of this report is to provide water flow or air flow performance-based requirements to seal the shafts and ramps accessing the repository and exploratory boreholes located near the repository. The effort evaluated sealing shafts, ramps, and boreholes, which is the focus of issues in 10 CFR 60, *Disposal of Radioactive Wastes in Geologic Repositories*. (10 CFR 60.134).

1.2 SCOPE

This report addresses sealing issues in the context of both the Viability Assessment, and the License Application. Also, the report identifies the requirements for the development of additional information needed (if any). Recommendations will be provided, as appropriate, for developing plans, seals component testing, and other studies relating to sealing. Additional seal component testing is recommended to support License Application.

1.3 BACKGROUND

The Yucca Mountain Site Characterization Project (YMP), managed by the U. S. Department of Energy (DOE), is examining the possibility of developing a high-level radioactive waste repository in an unsaturated tuff formation beneath Yucca Mountain. Yucca Mountain is located on and adjacent to the Nevada Test Site, Nye County Nevada. Coincident with completion of the *Site Characterization Plan: Yucca Mountain Site, Nevada Research and Development Area, Nevada* (SCP) (DOE 1988), describing the activities necessary to satisfactorily characterize the Yucca Mountain Site was a *Site Characterization Plan Conceptual Design Report* (SCP-CDR), which described the configurations, design concepts, etc., for the potential repository (MacDougall et al. 1987).

The Yucca Mountain Repository Sealing Program evolved from the U.S. Nuclear Regulatory Commission (NRC) regulatory requirements for preventing radionuclide migration and potential releases to the accessible environment. Fernandez and Freshley (1984) produced a report that presented repository sealing concepts and provided performance calculations.

Fernandez et al. (1987) defined performance goals for three major sealing subsystems for the then Nevada Nuclear Waste Storage Investigation Project. These subsystems included shafts and ramps, exploratory boreholes, and structures in the underground facility. This technical basis report established performance goals for the subsystems to limit radionuclide migration due to inward groundwater flow and outward air flow, established a performance-allocation process between two of the three subsystems, and then established design requirements for individual sealing components. The components included the use of cementitious seals and earthen backfill in the shafts, ramps, and exploratory boreholes. Because of the special characteristics of sealing a repository in the unsaturated zone, the report identified other special components for the underground facility. For example, subsurface water diversion and water impoundment structures were proposed for the underground facility.

The original sealing concepts emphasized the selection of sealing locations in low temperature zones, and at locations of optimum rock mass quality. As repository designs evolved, sealing concepts evolved, and a number of specialized studies were performed. Case and Kelsall (1987) performed a study to evaluate the changes in rock mass permeability in the modified permeability zone (MPZ) around the exploratory shaft. Other specialized studies evaluated seal hydration effects (Case et al. 1992) and the interactions of cementitious and earthen materials with groundwater at Yucca Mountain. Another specialized study evaluated seals when subjected to seismic loading (Fernandez et. al. 1992).

In 1989, the YMP requested that the repository sealing program conduct a series of special studies that examined the potential impact of exploratory facilities on the long-term performance of the repository. These studies (Fernandez et al. 1989) evaluated the potential extent of surface water flooding relative to the shafts, and aided in the design of the exploratory shaft pad. Other studies evaluated the removal of shaft lining to minimize adverse geochemical interaction effects.

The SCP-CDR (DOE 1988) included a combination of analytical, laboratory, and field studies to investigate sealing components. The process used in the sealing program was to assess the need for sealing; to define the design requirements for components by defining performance goals; to measure the material properties; to assess the performance of the sealing design; to perform laboratory analysis and field testing; and then to reassess seal designs. The field studies were categorized as either site characterization studies to determine special properties of the seals, and performance confirmation studies that would validate the process of analysis, design, and construction of repository seals. In the field testing program, site characterization studies included grouting studies, seal hydration studies that evaluated the interaction of the sealing materials with the surrounding rock mass, and performance-confirmation studies involving the construction and testing of large scale components such as shaft seals and backfill.

In 1993, a study produced information on the field test requirements for seals (Fernandez et al. 1993, and Fernandez and Case 1993). The field testing concepts were developed further by providing analysis of the individual field test concepts, selecting instrumentation, and developing test procedures. Also, the 1993 studies presented a summary of other SCP activities that generated information for analyzing and designing the repository sealing system.

In 1994, the Yucca Mountain Sealing Program produced a report (Fernandez et al. 1994) on the sealing strategy of exploratory boreholes. This topical report presented detailed information on the site characterization exploratory borehole program, borehole logs, and specialized calculations as to the influence of elevated temperatures on seal performance at potential sealing locations. The report addressed when, where, and how to seal exploratory boreholes. Another report (Fernandez and Richardson 1994) presented a summary of the available technologies for sealing and backfilling.

Since the time of completion of the original sealing studies, changes have been made to the design of the repository. These changes included tunnel boring for the majority of the underground workings, flatter drift grades, and direct in-drift emplacement of larger diameter waste packages.

Further, the current repository is smaller and waste is emplaced at a higher thermal load density than in the previous SCP-CDR design. Measurements underground have indicated potentially higher moisture fluxes and show evidence of fast water flow through fractures. No sealing design studies have been performed since the time of the development of SCP-CDR conceptual design. These changes have resulted in a re-evaluation of the sealing requirements.

1.4 OVERVIEW OF THE REPOSITORY SEALING APPROACH

An overview of the repository sealing approach is presented in Figure 1-1. The repository sealing program develops a sealing strategy by evaluating regulatory requirements for sealing, and then identifies sealing requirements for the repository seal system. As discussed in detail in Section 4.0, these goals relate to water flow through the vadose zone toward and away from the repository, and to air flow by advection due to the rise in temperature in the host rock. Based on these goals, the program identifies the significance of penetrations. Major penetrations, such as shafts and ramps accessing the repository, are easily identified and included as part of the repository sealing system. Also, exploratory boreholes that are within an extended repository boundary might affect repository performance, are included. Based on geologic and hydrologic characterization, preliminary sealing locations that would provide the most assurance that the seal performance requirements can be achieved, are identified. The geologic and hydrological characterization also provides information on how to seal and how the immediate surrounding geologic media would perform. The geologic and hydrological characterization provides information on the need for redundant seal structures and on alternative sealing strategies.

The nature of the penetrations provides a basis for locating seals away from the high temperature environment of the repository where possible. Nevertheless, during the postclosure period, the seals near the repository horizon may experience elevated temperatures.

1.5 REPORT ORGANIZATION

The organization of this report follows the outline in the *Technical Documentation Preparation Plan for the Repository Seals Study* (CRWMS M&O 1997b):

- The Executive Summary provides a top-level description of the study and the results.
- Section 1 provides the study objective, scope, background, overview of the Repository Seal Program, and organization of the report.
- Section 2 documents the requirements and standards (both Federal and State) including the quality assurance requirements considered.
- Section 3 provides documentation of the study methodology which includes the performance scenarios and assumptions, the development of the performance goals for the sealing system, the results of the calculation of the potential radionuclides that might be released from the waste packages, the water flow performance goals developed from the radionuclides release and preferential pathways, and the allowable air flow goals.

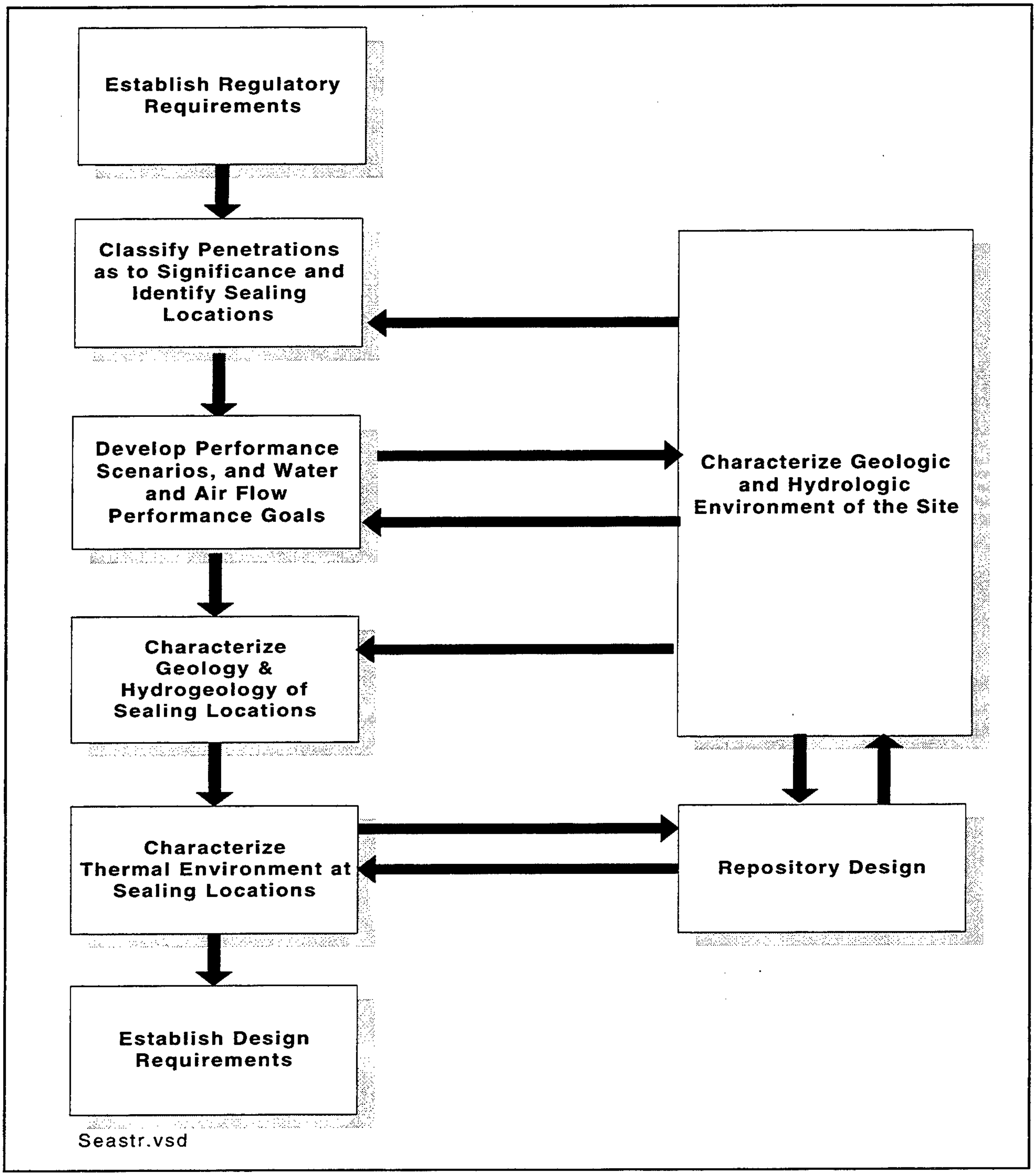

Figure 1-1. Overview of the Repository Sealing Approach

- Section 4 documents the results of the air flow and water flow calculations performed to support the development of the seal requirements.

- Section 5 addresses the need to design sealing components and provides the sealing strategy. A summary of the functions and design requirements for seals is also provided.

- Section 6 documents the results and recommendations of the study.

- Section 7 lists the references used in the study.

- Section 8 contains the acronyms used in the report.

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2. REQUIREMENTS AND STANDARDS

At present, there are no regulations that provide a long-term performance standard for radiological releases from the potential repository since 40 CFR 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, was remanded by the courts. It was found to be inapplicable to disposal sites for high-level waste that are licensed according to the Nuclear Waste Policy Act of 1982. Consequently, 40 CFR 191 no longer applies to Yucca Mountain. In the absence of such a standard, an "Interim Postclosure Standard" has been established by the DOE. This standard requires that the probability of exceeding a dose rate of 15 mrem/yr not exceed 50 percent over 10,000 years when calculated for the average individual in a critical group about 30 km from the Yucca Mountain. In addition, doses are required to be evaluated out to the time of peak dose to gain insight regarding long-term repository performance and to assess whether engineering measures, with the potential for causing significant reductions in peak dose over very long time frames, can be implemented at reasonable cost.

In understanding the applicable regulatory requirements that form the technical basis for repository seals in shafts and ramps, and exploratory boreholes, it is necessary to define sealing. For the Yucca Mountain project, sealing is defined as the permanent closure of the shafts, ramps, and exploratory boreholes. It includes shaft and ramp backfill, seals or plugs in shafts, ramps, and seals in exploratory boreholes.

In arriving at a strategy for developing hydrologic performance goals, the current interim standards were evaluated for applicability. The interim standards include isolation requirements for the entire disposal system. The standards do not specify requirements for individual subsystems that are a part of the disposal system. The previous U.S. Environmental Protection Agency criteria provide release limits for specific radionuclides considering all releases from significant processes and events that may affect the disposal system. Because the current standards apply to the peak doses resulting from radionuclide releases from the overall disposal system to the accessible environment, it was determined that the approach used in evaluating performance goals from previous assessments was more appropriate to use. Therefore, seal subsystems standards as defined by the NRC in 10 CFR 60, were used to develop the performance goals.

2.1 REGULATORY REQUIREMENTS (10 CFR 60 and State)

2.1.1 Federal Regulatory Requirements

These quantitative requirements are stated in 10 CFR 60.113(a) (1)(ii)(B) as:

> "The release rate of any radionuclides from the engineered barrier system following the containment period shall not exceed one part in 100,000 per year of the inventory of that radionuclide calculated to be present at 1,000 years following permanent closure, or such other fraction of the inventory as may be approved by the Commission: provided, that this requirement does not apply to any radionuclide which is released at a rate less than 0.1 percent of the

> calculated total release rate limit. The calculated total release rate limit shall be taken to be one part in 100,000 per year of the inventory of radioactive waste, originally emplaced in the underground facility, that remains after 1,000 years of radioactive decay."

The qualitative design criteria for seals for shafts, ramps and boreholes is given in 10 CFR 60.134 and is divided in two categories:

> "(a) General design criterion. Seals for shafts and boreholes shall be designed so that following permanent closure they do not become pathways that compromise the geologic repository's ability to meet the performance objectives for the period following the permanent closure.
>
> (b) Selection of materials and placement methods. Materials and placement methods for seals shall be selected to reduce, to the extent practicable: (1) the potential for creating a preferential pathway for ground-water; or (2) radioactive waste migration through existing pathways."

In addition to the basic requirements above for establishing air or water flow performance goals, other federal regulations provide for license amendments for closure to include tests results for seals (10 CFR 60.51(a) (4); the inclusion of seals in overall system performance assessments (10 CFR 60.112); evaluation of adverse conditions that would require complex engineering measures, and the development of a specific field testing for seals (10 CFR 60.142).

Regulation 10 CFR 60 Section 122, *Siting Criteria*, identifies potentially adverse conditions if they are characteristic of the controlled area or may affect isolation within the postclosure controlled area as: "Rock or ground-water conditions that would require complex engineering measures in design and construction of underground facility or in the sealing of boreholes or shafts." The sealing of boreholes and shafts are not considered to require complex engineering as they will rely on and use current state of the art technology (Fernandez and Richardson 1994).

The design testing section states (10 CFR 60.142):

- During the early or development stages of construction, a program for in situ testing of such features as borehole and shaft seals, backfill, rock, and the thermal interaction effects of the groundwater shall be conducted.

- The testing shall be initiated as early as practicable.

- A backfill test section shall be constructed to test the effectiveness of backfill placement and compaction procedures against design requirements before permanent backfill placement is begun.

- The test sections shall be established to test the effectiveness of borehole and shaft seals before full-scale operation proceeds to seal boreholes and shafts.

2.1.2 State Regulatory Requirements

The Nevada Revised Statutes 534 for Underground Water and Wells require abandoned wells to be plugged or be granted a waiver for plugging if determined to be useful for monitoring by the state engineer. The Nevada Administrative Code (NAC) provides details for compliance as stated in:

NAC 534A.150, Sealing of Holes

> "All holes must be sealed at the surface with natural soil or concrete regardless of the diameter or depth of the hole."
>
> "Holes drilled into or through artesian aquifers must be sealed to prevent upward leakage after drilling pipe is withdrawn at the conclusion of drilling operations."

NAC 534A.490, Abandonment of Geothermal or Injection Well

> "Cement used to plug the well, except cement used for surface plugging, must be placed in the hole by pumping through drill pipe or tubing. The cement must consist of a mix which resists high temperatures."
>
> "Cement plugs must be placed in the uncased portion of wells to protect all subsurface resources. These plugs must extend a minimum of 100 lineal feet above the producing formations and 100 linear feet below the producing formations or to the total depth drilled, whichever is less. Cement plugs must be placed to isolate formations and to protect the fluids in those formations from interzonal migration."
>
> "Where there is an open hole, a cement plug must be placed in the deepest casing string by:
>
> - Placing a cement plug across the guide shoe extending a minimum of 100 lineal feet above and below the guide shoe, or to the total depth drilled, whichever is less; or
>
> - Setting a cement retainer with effective control of back pressure approximately 100 lineal feet above the guide shoe, with at least 200 lineal feet of cement below, or to the total depth drilled, whichever is less, and 100 lineal feet of cement above the retainer.

If there is a loss of drilling fluids into the formation or such a loss is anticipated or if the well has been drilled with air or another gaseous substance, a permanent bridge plug must be set at the casing shoe and capped with a minimum of 200 lineal feet of cement."

"A cement plug must be placed across perforations, extending 100 lineal feet below, or to the total depth drilled, whichever is less, and 100 lineal feet above the perforation. When a cement retainer is used to squeeze cement into or across the perforations, the retainer must be set a minimum of 100 lineal feet above the perforations. Where the casing contains perforations at or below debris or collapsed casing, which prevents cleaning, a cement retainer must be set at least 100 lineal feet above that point, and cement must be squeezed in the interval below the retainer."

"The approval of the administrator must be obtained before casing is cut and recovered. A cement plug must be placed in such a manner as to isolate all uncased intervals and guide shoes that are not protected by an inner string of casing. The plug must extend a minimum of 50 feet above and below any such interval or guide shoe."

"All annular spaces extending to the surface must be plugged with cement."

"The innermost string of casing which reaches ground level must be cemented to a minimum depth of 50 feet below the top of the casing."

"The hardness and location of cement plugs placed across perforated intervals and at the top of uncased or open holes must be verified by setting down with tubing or drill pipe a minimum weight of 15,000 pounds on the plug or, if less than 15,000 pounds, the maximum weight of the available tubing or drill pipe string. If a cement retainer or bridge plug is used to set the bottom plug, a test is not required for that interval."

"The surface must be restored as near as practicable to its original condition."

"Any interval that is not filled with cement must be filled with good quality heavy drilling fluids. (Added to NAC by Comm'n on Mineral Res., eff. 11-12-85)"

NAC 534A.500 Casing Strings to Be Cut off and Capped; Removal of Structures and Other Facilities

> "All casing strings must be cut off below ground level and capped by welding a steel plate on the casing stub. All structures and other facilities must be removed. (Added to NAC by Comm'n on Mineral Res., eff. 11-12-85)"

When applying to the State of Nevada for borehole permits, the DOE has committed to provide a detailed plan for plugging and sealing boreholes. It is anticipated that this report which provides the requirements for the design of seals for the shafts, ramps, and boreholes will satisfy this requirement of the State.

2.2 QUALITY ASSURANCE

The quality assurance program applies to the development of this technical document. A QAP-2-0 activity evaluation was completed and documented (IOC LV.SEA.RDM.5/97-032, *Perform System Studies*, from R. Memory to Systems Analysis Department, May 1997). No NLP-2-0 determination of importance evaluations were required. This QAP-2-0 evaluation determined that the work performed to develop this study report is subject to the *Quality Assurance Requirements and Description*, DOE/RW-0333P, requirements because it impacts items that are on the *Q-List* (YMP 1997) by direct inclusion. This study report will, as appropriate, provide recommendations for requirements to be included in the project requirements documents. Appropriate procedures, such as QAP-3-5, *Development of Technical Documents*, were used in the preparation, review, and approval of the document and will be used in any revisions to the document. In accordance with QAP-3-5, a *Technical Document Preparation Plan* (CRWMS M&O 1997b) for this document was developed, issued, and utilized to guide the development of this study report. In addition, inputs to this study from external organizations were collected in accordance with QAP-3-12. Finally, scoping analyses were conducted as a part of this study to support determination of sealing requirements. These scoping calculations were conducted in accordance with NLP-3-27, *Support Engineering Calculations.*

2.3 DESIGN INPUT TO THE REPOSITORY SEALING REQUIREMENTS STUDY

The sealing requirements study used design input from several sources since the water and air flow performance goals relate to performance assessment of the engineered barrier system, and other requirements relate to the repository design. The design input to the study was requested and prepared according to QAP-3-12 Revision 7 entitled "Transmittal of Design Input", and is included as part of the CRWMS M&O records package for the study. The performance assessment group provided information on the release of radionuclides of concern from the engineered barrier system, and as reported in *Design Input from PA to Systems Engineering for the Seal System Study* (CRWMS M&O 1997l). The repository design group provided information on the current repository as reported in *Preliminary Repository Model 12 2/20/97 and Emplacement Drift Lengths 2/24/97* (Drawings) (CRWMS M&O 1997m). The site group provided information on the hydrologic properties of welded and non-welded tuff (CRWMS M&O 1997n).

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3. STUDY METHODOLOGY

This section presents information on the study methodology to develop air- and water-flow performance goals for the sealing subsystem. Section 3.1 presents performance scenarios and other assumptions supporting the performance scenarios in addition to the information from design inputs in the previous section. Section 3.2 presents the basic methodology for determining air- and water-flow performance goals for the sealing system. It outlines the basic methodology for assessing the need for sealing and determining seal design requirements. Section 3.3 presents radionuclide releases from the Engineered Barrier System (EBS). Section 3.4 presents analyses of the radionuclide releases to determine the water-flow performance goal from the EBS. Section 3.5 presents allowable water-flow goals based on a preferential pathways criterion for comparison purposes. Section 3.6 presents allowable air flow goals for ^{14}C and ^{129}I.

3.1 PERFORMANCE SCENARIOS AND ASSUMPTIONS

Information regarding the sealing environment has changed since the time of previous studies based on an improved understanding of the hydrological environment. This information also includes rock saturations, the percolation flux, and thermal loadings. The important assumptions are presented below, and other sections of the study are referenced for more information.

The important assumptions for this study include:

- The percolation flux into shafts, ramps, and boreholes equals the infiltration flux that occurs through direct infiltration of fractures exposed in outcrops at Yucca Mountain. Alluvial areas are not considered significant areas of recharge (Section 4.2.2).

- Emplacements are located in the center of the drifts with an area mass loading of 19.8 to 24.7 kgU/m^2 (80 to 100 MTHM/acre).

- Groundwater annual anticipated flux estimates at the proposed repository horizon range from 5 mm per year to 30 mm per year (Section 4.3.2) (Flint et al. 1997).

- Groundwater flow under unanticipated flow conditions is assumed to occur at nearly saturated conditions within isolated areas.

- Other important assumptions regarding airflow include:

  - The radionuclides that could potentially enter the repository in a gaseous state are ^{14}C and ^{129}I. For ^{14}C, 0.3 percent of the radionuclide inventory in a stored canister of spent fuel is released as a gas (Section 3.6) (Van Koynenburg et al. 1984). For ^{129}I, the radionuclide inventory in spent fuel may be concentrated in the pellet-cladding gap and/or on the grain boundaries of the fuel (Oversby and McCright 1985). The percentage of the total inventory is assumed to be 0.5 percent (Oversby and Wilson 1985).

- Air flow occurs along specified paths according to Darcy's Law. The air temperature in the shaft or ramp and the surrounding host rock is the same. Air flow is compressible and the air is dry (Section 4.1.3) (Fernandez et al. 1987)

The performance scenarios are developed based on the current understanding of groundwater hydrology and are discussed in detail in Section 4.2. Scenarios are to be considered for water flow into or through the repository through shafts, ramps, and exploratory boreholes under anticipated and unanticipated conditions.

In the current ESF/repository (CRWMS M&O 1996a) design the flatter grades cause the ramps to be long, which in turn increases the possibility of encountering predominantly vertical fracture systems that could periodically transmit water.

A wide variety of boreholes have been developed and drilled as part of the surface-based testing program. Many existing boreholes are described in terms of spatial location, borehole configuration, and purpose in Fernandez et al. 1994. Since this time, other boreholes have been planned as part of the surface-based borehole instrumentation program. The important aspects for developing a seal strategy include the location within or away from the potential repository perimeter and the depth of penetrations. The extended boundary of the repository to be included for plugging of boreholes that can impact the repository is to be determined as part of the airflow calculations (see Figure 3-1).

Under unanticipated surface flooding conditions, water could enter the shafts and ramps, and become "perched" on the upper side of the seals. The water flow that could occur due to periodic sheet flow over penetrations is to be considered in the study.

For a repository located above the water table, it is possible for airborne radionuclides to be released out of the shafts and ramps. The mechanism of convective air flow through a heated repository is analogous to the flow of air through an underground mine from a draft air pressure. As repository heating occurs due to radioactive decay, less dense air rises above the repository and draws air from peripheral sources. This airflow is to be determined in order to develop the backfill requirements in the shafts, ramps and boreholes and is presented in Section 4.1.

3.2 WATER AND AIR FLOW PERFORMANCE GOALS FOR THE SEALING SYSTEM

Fernandez et al. 1987 performed parametric studies of waste package performance, developed performance goals on the basis of direct contact and dissolutioning of nuclear fuel, and then compared performance goals to the anticipated and unanticipated flows to the underground repository. In the analyses presented below, this technical approach is adopted for purposes of calculating hydrological performance goals based on the performance of the EBS and the natural infiltration capacity of the Topopah Spring Unit, and in assessing the need for seals. Hydrological performance goals as used in this report are the allowable amounts of water that could enter the waste disposal areas from the shafts, ramps, and exploratory boreholes such that the radionuclides that can be released to the environment via the groundwater do not exceed the regulatory limits. A performance goal represents the desired performance from a system or subsystem, and can incorporate a margin of safety. Further, performance goals can change during the design process if additional information is acquired or the design approach changes.

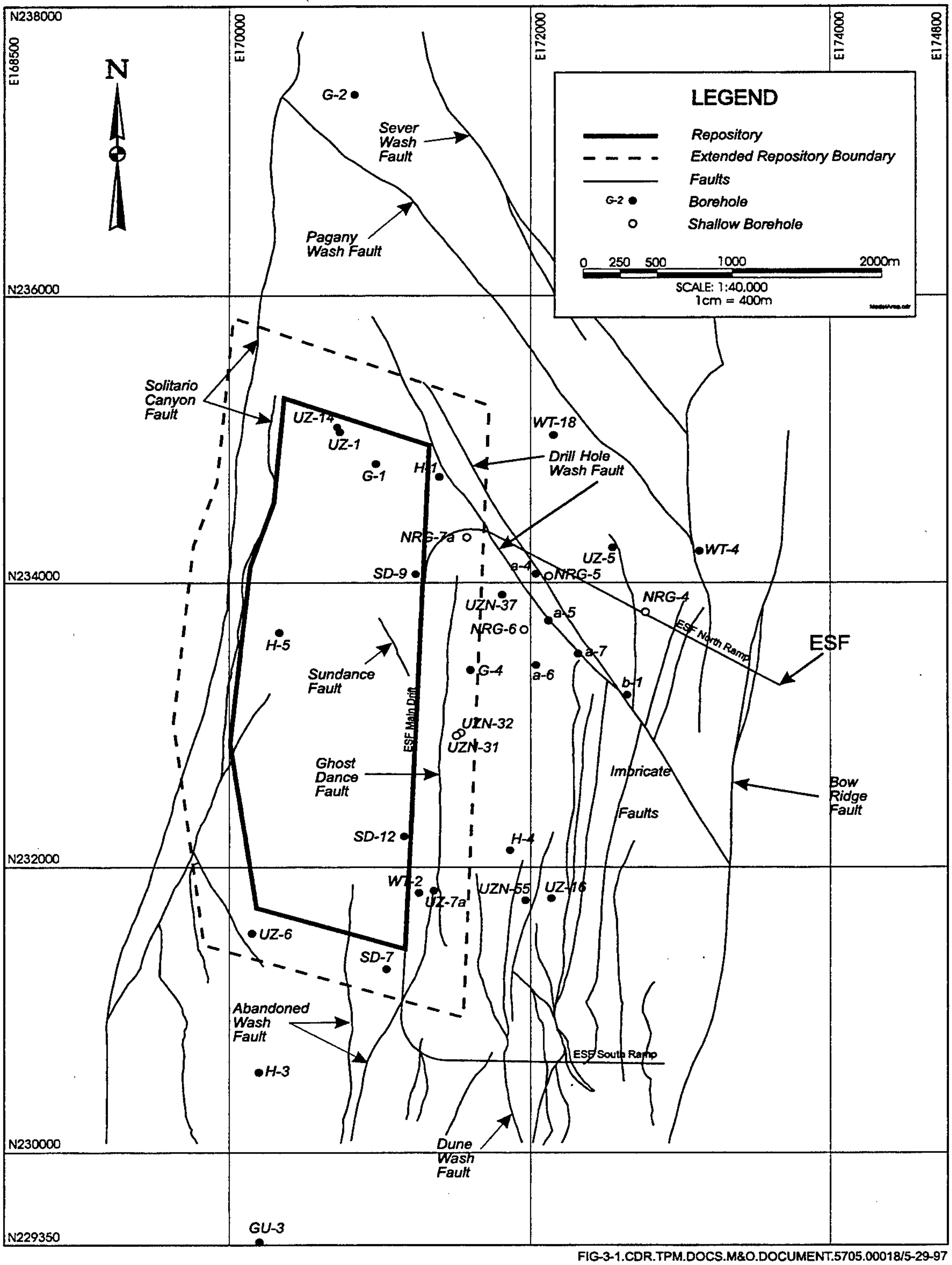

Figure 3-1. Locations of Exploratory Boreholes and Extended Repository Boundary

The approach to developing design requirements for the repository sealing system is illustrated in Figure 3-2 and is based on three steps:

- Determination of the allowable water flow performance goal
- Determinations of water flows into the repository
- Determination of need for sealing.

Hydrological performance goals are developed for the shaft and ramp system based on compliance with the applicable regulations. These allowable water flow goals are based on quantitative criteria in 10 CFR 60.113, and qualitative criteria as presented in 10 CFR 60.134, and are calculated considering the waste package performance and the drainage capacity at the base of the Topopah Spring Formation.

The anticipated water flow into the repository is the water flow that could enter the shafts/ramps and flow through the rock into the emplacement drifts, and potentially contact the waste. Both anticipated conditions and selected, unanticipated scenarioswere evaluated to arrive at volumes of water that could potentially enter the waste disposal areas. Anticipated scenarios are those processes and events that are reasonably likely to occur during the time period in which the repository performance objective must be met. For example, an anticipated condition could include annual infiltration into the penetrations; they also might include episodic flow-down fracture systems. Unanticipated scenarios are those processes and events that are not reasonably likely to occur during the same period but are sufficiently credible to warrant evaluation. An unanticipated scenario could include episodic flow down fault systems intersecting the penetrations.

3.3 RADIONUCLIDE RELEASES FROM THE ENGINEERED BARRIER SYSTEM

A detailed stochastic waste-package performance simulation model (CRWMS M&O 1995) has been developed for the Total Systems Performance Assessment, (TSPA) for the project. The stochastic simulation model incorporates the following corrosion models:

- Humid-air general corrosion model (including uncertainty) for the carbon steel corrosion-allowance (carbon steel) outer barrier

- Stochastic humid-air pitting corrosion model for the carbon steel outer barrier

- Aqueous general corrosion model (including uncertainty

- Aqueous general corrosion model (including pit growth rate distribution) for the corrosion-resistant inner barrier.

The uncertainties in the individual corrosion models were incorporated to capture the variability in the corrosion degradation among waste packages and among pits in the same waste package.

The major assumptions for the waste EBS subsystem incorporated in the performance analyses conducted for TSPA-1995 are discussed below.

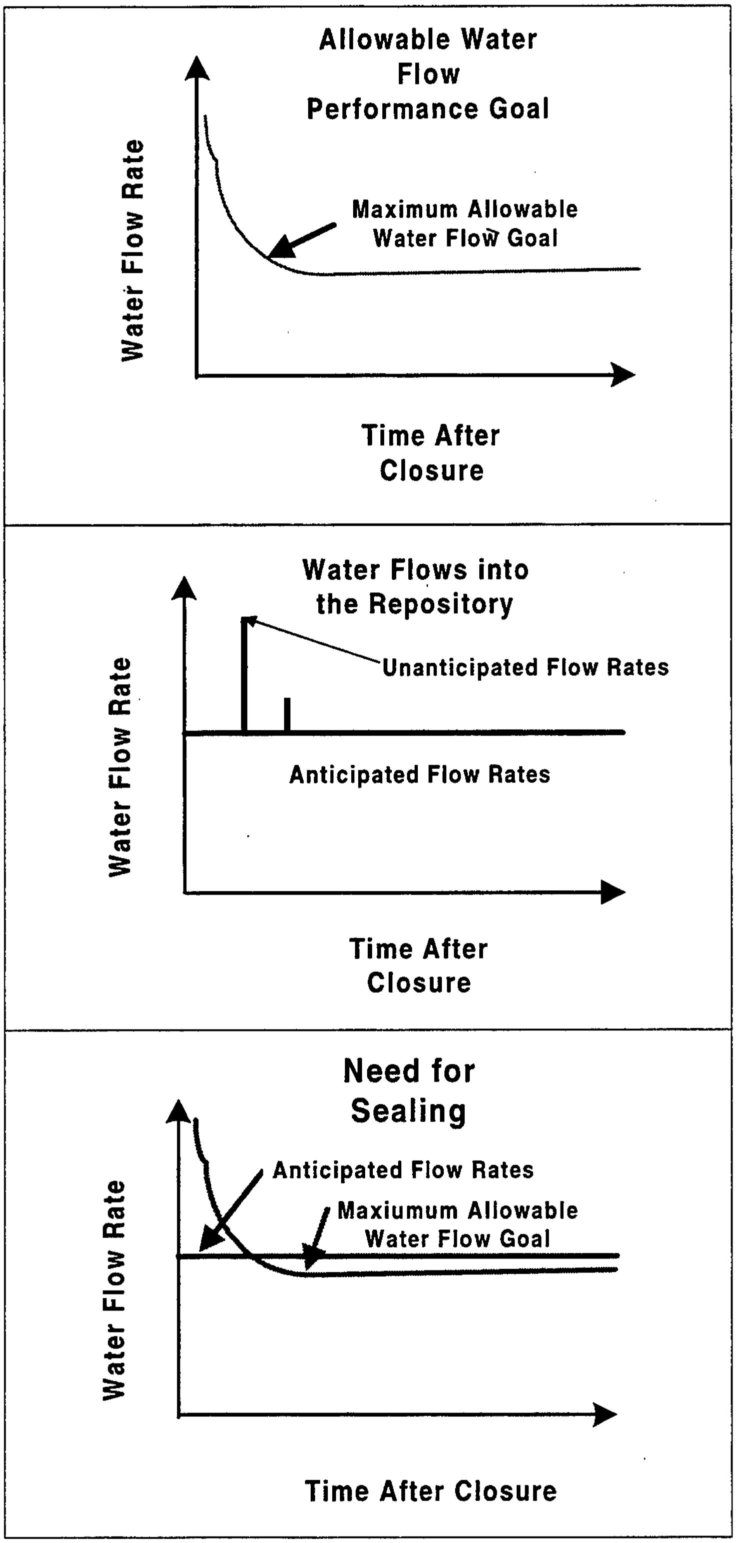

Figure 3-2. Approach Used in Determining Design Requirements

- In this analysis, the waste disposal containers for both spent fuel and vitrified defense high-level waste were assumed to have a two-layer container design with a 100 mm thick carbon steel outer layer.

- The entire waste form surface was conservatively assumed to be covered with a thin water film (i.e., uniform thickness of 1.0 mm) when the waste container had at least one pit penetration and the surface temperature was less than 100°C. Alteration of the waste form is assumed to initiate after the first pit penetration. The water film thickness was used in the calculation of the radionuclide concentration at the waste form surface.

- If a waste container has at least one pit penetration and the waste package surface temperature cools to less than 100°C, the waste packages that are dripped on are assumed to release radionuclides both by diffusion and advection. A complete discussion of the diffusive release from the waste package and the EBS is presented in *Total System Performance Assessment - 1995: An Evaluation of the Potential Yucca Mountain Repository* (CRWMS M&O 1995).

- The releases of ^{14}C and ^{129}I from the EBS were assumed to be gaseous. The gaseous elements are assumed to escape unimpeded from the EBS, and then be dissolved and transported into the geosphere in the aqueous phase. However, there is some uncertainty in the dominant release behavior of ^{129}I from the waste package and the EBS.

- In these analyses, an invert composed of crushed tuff was assumed to underlie the waste packages.

The "drips on waste container" model (CRWMS M&O 1995) assumes the pits in the waste containers to be always filled with corrosion products, so that drips cannot directly contact the waste form, but can only contact the outer surface of the waste container. These corrosion-filled pits act as a mass-transfer barrier, such that mass-transfer occurs only by diffusion through the pits. The radionuclide concentration at the waste container surface is lower than at the waste package. Once the radionuclides diffuse through the pits, they are advected into the dripping water. Also, they diffuse through the invert and backfill, although the diffusive transport is again insignificant compared to advection.

The EBS release model was used to identify radionuclide releases from the EBS at a percolation flux rate of 1.25 mm per year. The calculations used the drips on waste package water contact mode discussed previously with an 83 MTHM/acre thermal load, and the relative humidity-only switch for corrosion initiation. Note that infiltration rates could be higher as discussed in Section 4.2.

The analysis considered several radionuclides. The dominant radionuclides include: ^{99}Tc, ^{79}Se, ^{135}Cs, ^{59}Ni, ^{237}Np, ^{107}Pd, ^{210}Pb, and ^{226}Ra. These radionuclides were calculated to have a maximum release rate greater than 0.1 percent of the total NRC release limit. Radionuclides with a calculated maximum release rate smaller than the NRC limit for the radionuclides were excluded from subsequent analysis (Table 3-1).

Table 3-1. Radionuclides Considered for Compliance with the NRC EBS Release Rate Limit (After CRWMS M&O 1995)

Radionuclide	1000 Year Inventory (Ci/MTHM)	1000 Year Inventory for 63,000 MTHM (Ci)	NRC Limit (Ci/yr)
^{99}Tc	1.43E+01	9.01E+05	9.01E+00
^{59}Ni	2.40E+00	1.51E+05	1.51E+00
^{14}C	1.26E+00	7.94E+04	7.94E-01
^{226}Ra	3.76E-03	2.37E+02	2.37E-03
^{210}Pb	3.75E-03	2.36E+02	2.36E-03
^{135}Cs	5.26E-01	3.31E+04	3.31E-01
^{79}Se	4.88E-01	3.07E+04	3.07E-01
^{237}Np	1.24E+00	7.81E+04	7.81E-01
^{107}Pd	1.29E-01	8.13E+03	8.13E-02
^{129}I	3.52E-02	2.22E+03	2.22E-02
^{239}Pu	3.56E+02	2.24E+07	2.24E+02
^{240}Pu	4.90E+02	3.09E+07	3.09E+02
^{36}Cl	1.13E-02	7.12E+02	7.12E-03
^{94}Nb	8.19E-01	5.16E+04	5.16E-01
^{242}Pu	2.06E+00	1.30E+05	1.30E+00
^{23}Pa	3.88E-04	2.44E+01	2.44E-04
^{126}Sn	8.66E-01	5.46E+04	5.46E-01
^{227}Ac	3.88E-04	2.44E+01	2.44E-04
^{23}U	2.52E+00	1.59E+05	1.59E+00
^{230}Th	2.10E-02	1.32E+03	1.32E-02
^{229}Th	1.60E-04	1.01E+01	1.01E-04
^{228}Ra	1.42E-08	8.95E-04	8.95E-09
^{6}Ni	2.13E-01	1.34E+04	1.34E-01
^{151}Sm	2.06E-01	1.30E+04	1.30E-01
^{233}U	4.05E-03	2.55E+02	2.55E-03
^{236}U	2.94E-01	1.85E+04	1.85E-01
^{238}U	3.16E-01	1.99E+04	1.99E-01
^{93}Zr	2.44E+00	1.54E+05	1.54E+00
^{242}M Am	2.66E-01	1.68E+04	1.68E-01
^{245}Cm	3.19E-01	2.01E+04	2.01E-01
^{235}U	1.76E-02	1.11E+03	1.11E-02
^{238}Pu	1.97E+00	1.24E+05	1.24E+00
^{232}Th	1.42E-08	8.95E-04	8.95E-09
^{244}Cm	6.65E-11	4.19E-06	4.19E-11
^{93}M Nb	2.32E+00	1.46E+05	1.46E+00
^{241}Pu	3.19E-01	2.01E+04	2.01E-01
Total	1.94E+03	1.22E+08	1.22E+03

Figures 3-3 through 3-9 present the release rates for the radionuclides of concern and the NRC limits for a period of 10,000 years (CRWMS M&O 1997c). Figure 3-10 is a composite figure that presents the ratio of the radionuclide release to the NRC limit for all radionuclides of concern. Figure 3-11 presents the release rates of individual radionuclides to the total release rate for the radionuclides of concern.

^{14}C is released from the EBS in gaseous form. The release of ^{14}C is independent of the infiltration or water flow rate. Since restricting the water flow does not reduce the potential release of ^{14}C, it is not used in the selection of the allowable water flow goal.

Note that the application of the NRC criteria to ^{210}Pb and ^{226}Ra for developing hydrologic performance goals for the repository seal system is not applicable because these radionuclides represent the daughter products. They represent a very small portion of the radionuclide inventory at 1000 years, and increase because of the radioactive decay of ^{238}U and ^{234}U, both of which have long half lives relative to ^{226}Ra and ^{210}Pb.

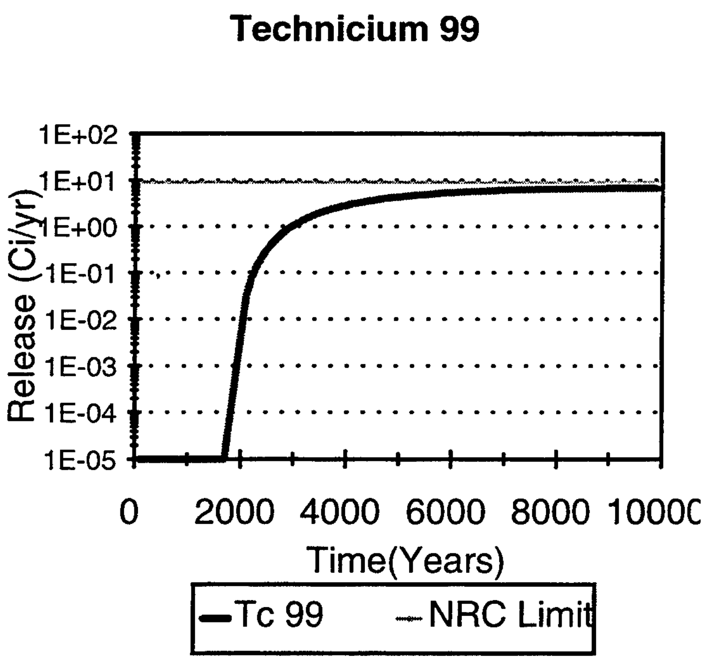

Figure 3-3. Release of ^{99}Tc from the EBS

Selenium 79

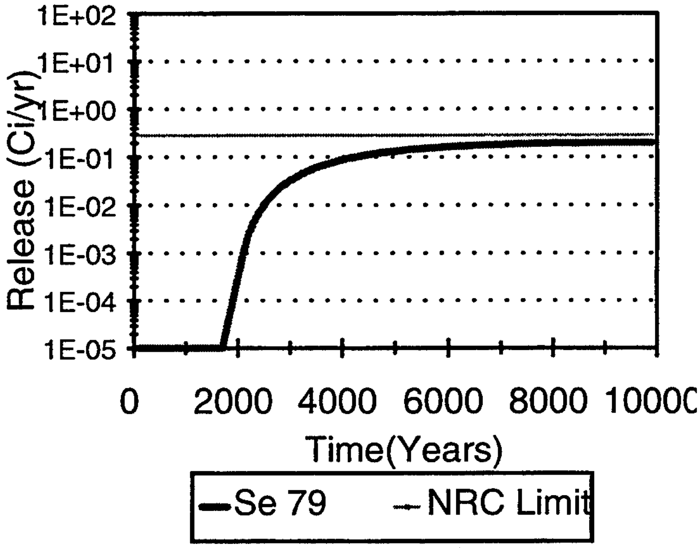

Figure 3-4. Release of Selenium 79 from the EBS

Cesium 135

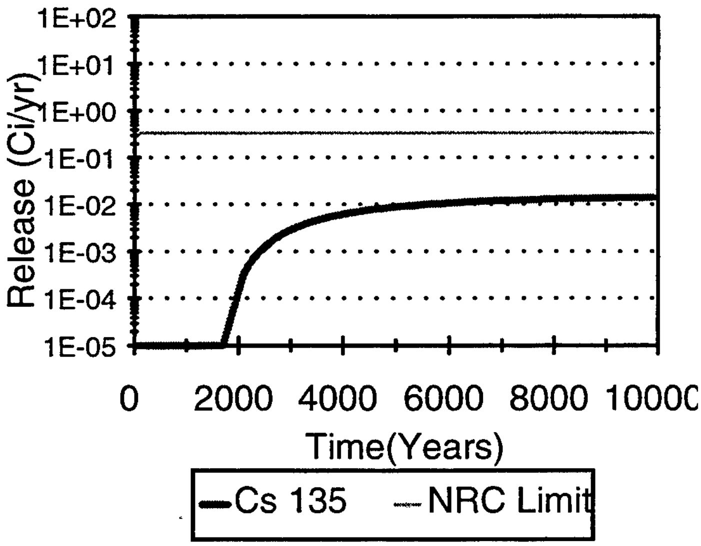

Figure 3-5. Release of Cesium 135 from the EBS

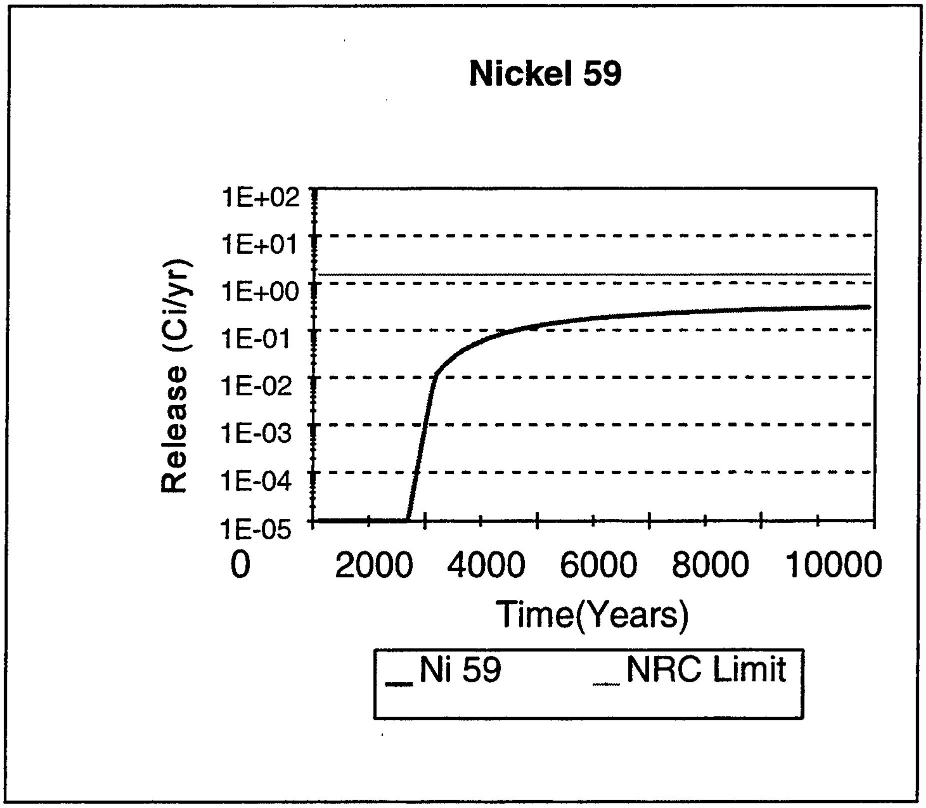

Figure 3-6. Release of Nickel 59 from the EBS

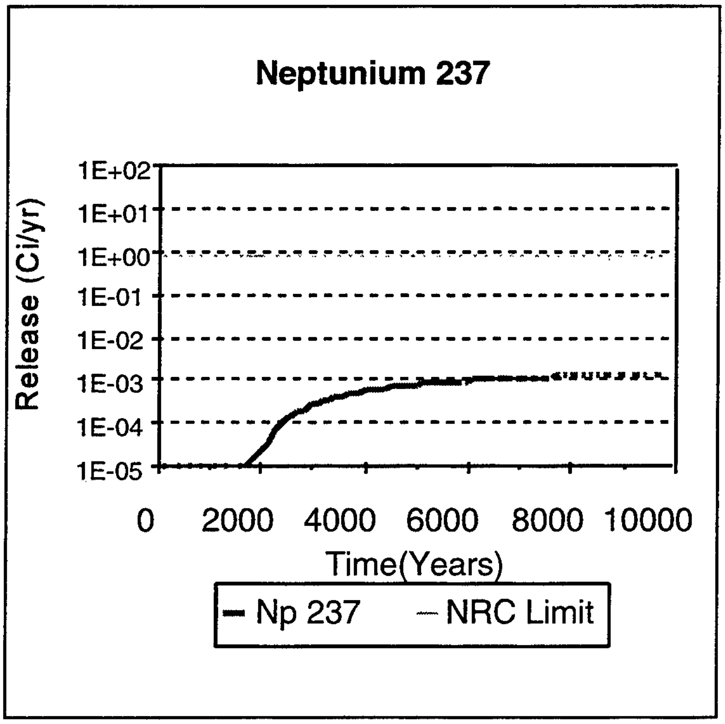

Figure 3-7. Release of Neptunium 237 from the EBS

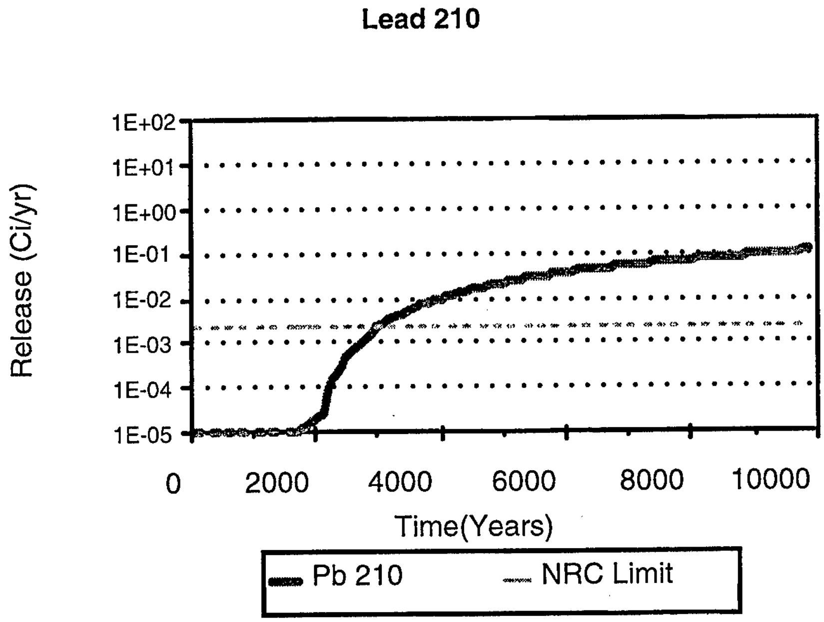

Figure 3-8. Release of Lead 210 from the EBS

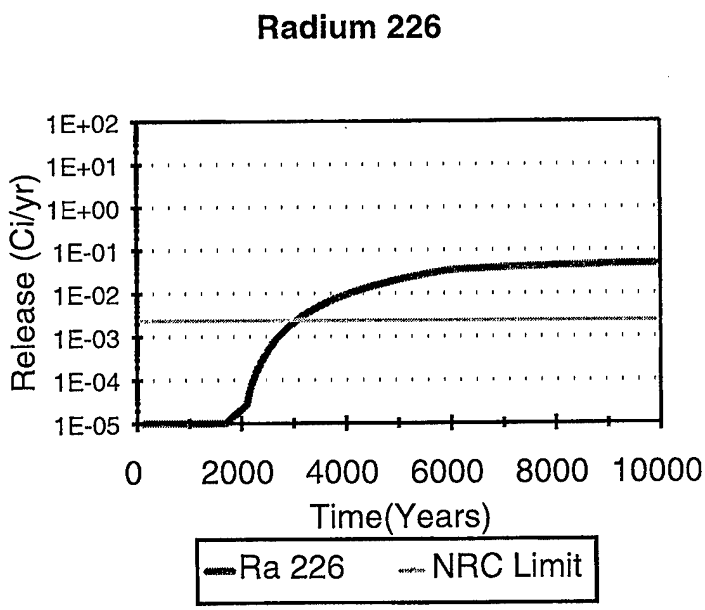

Figure 3-9. Release of Radium 226 from the EBS

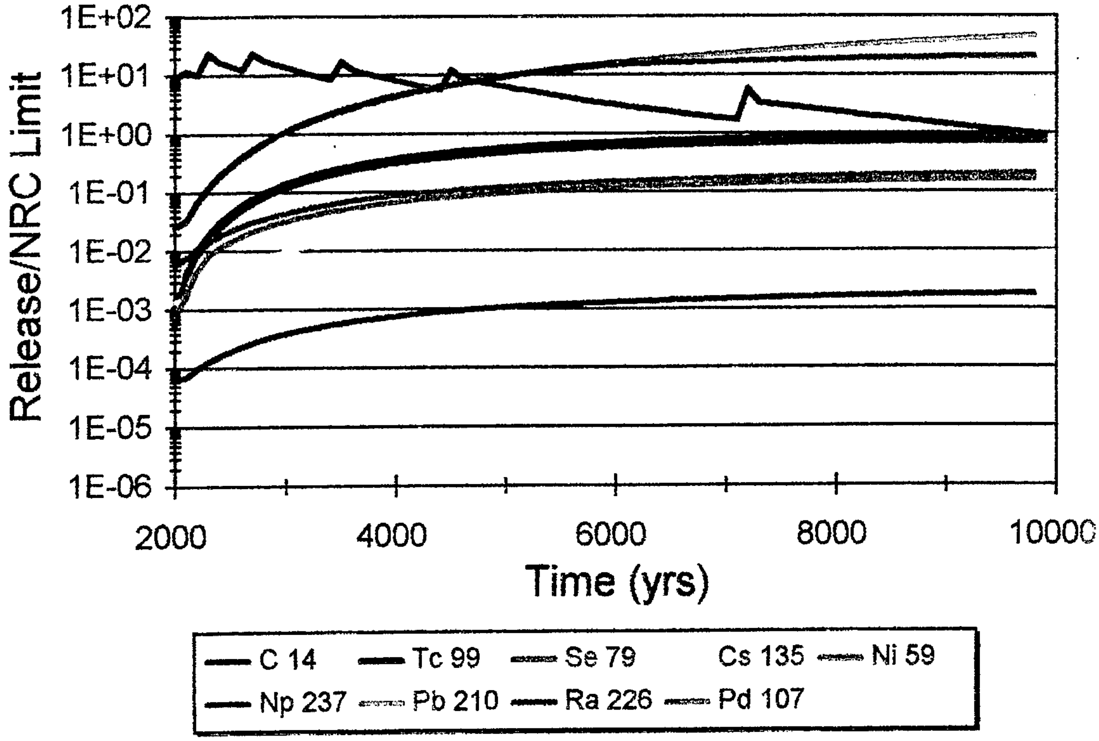

Figure 3-10. Ratio of Radionuclide Release to the NRC for Individual Radionuclides

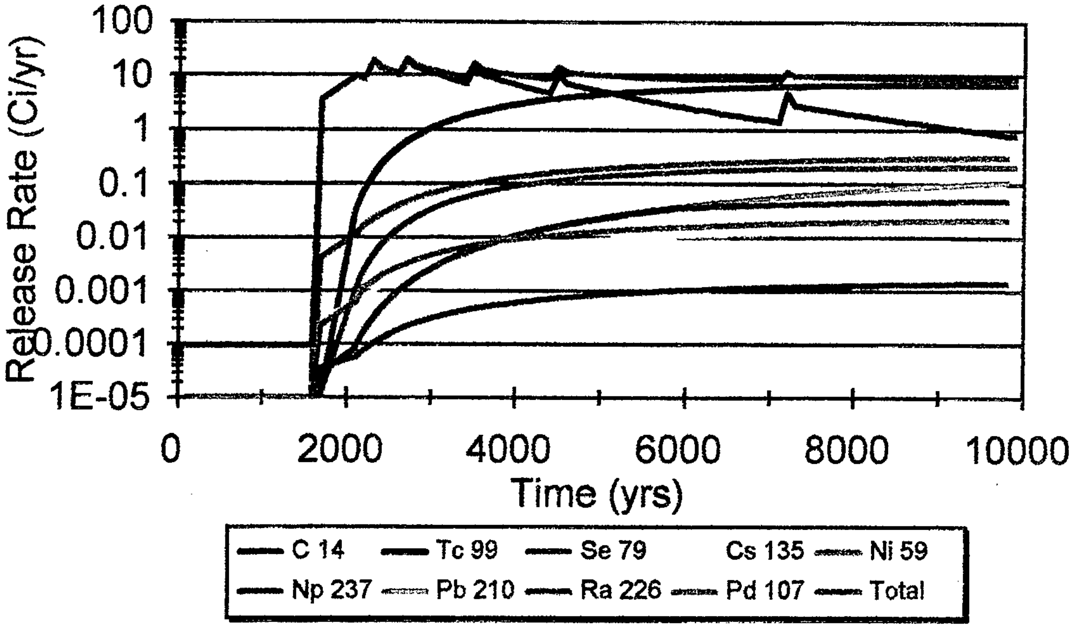

Figure 3-11. Total Release for the Radionuclides of Concern

3.4 WATER FLOW PERFORMANCE GOALS BASED ON ENGINEERED BARRIER RELEASE

A number of analyses were conducted to assess the performance requirements for the repository seals (CRWMS M&O 1997c). The same technical approach was adopted as used to calculate hydrologic performance goals as presented by Fernandez et al. 1987. The technical approach as used in the analyses includes:

- Develop relationships of the radionuclide release rate divided by the NRC limit for the radionuclides of concern using the current repository design thermal loading.
- Develop an envelope for the radionuclides for the ratio of release rate divided by the NRC Limit.
- Develop hydrologic performance goals that satisfy flow rates for the most critical radionuclides in the inventory.

In developing the hydrological performance goals for the repository sealing system, the analysis derived water flow rates that complied with the NRC limits for ^{99}Tc. The analysis assumes that the capture zone equals four times the footprint area of the waste package. The waste inventory consists of 10,938 canisters with dimensions shown in Table 3-2 (CRWMS M&O 1996a).

Table 3-2. Summary of Parameters for Waste Packages

Fuel Type	Diameter (m)	Length (m)	Percentage (%)	Area (m^2)	No. of Waste Packages
44 BWR	1.85	5.85	26.1	43.29	2859
21 PWR	1.85	5.85	37.8	43.29	4137
12 PWR	1.85	5.85	6.2	43.29	682
DHLW	1.97	5.35	29.8	42.16	3260

The allowable water flow goal for the ith radionuclide is calculated as (Fernandez et al. 1987):

$$Q_j(t) = Q_b x \frac{NRC_j}{R_j(t)}$$

where

$Q_j(t)$ = Allowable water flow goal for the jth radionuclide as a function of time,
Q_b = Flow rate corresponding to an infiltration rate of 1.25 mm per year,
NRC_j = NRC release rate limit for the jth radionuclide (Ci/yr), and
$R_j(t)$ = Release of the jth radionuclide from the EBS system.

Note that the analysis considers that the release is linearly proportional to the water flow rate and that some radionuclides may be solubility limited. Thus, the analysis conservatively estimates the allowable water flow rate.

The results of the analysis for the radionuclides of concern are presented in Figure 3-12. Fernandez et al. 1987 presented similar results that were based on a different release model. A comparison between the previous results and the current analysis shows several differences:

- The current most restrictive radionuclide is ^{99}Tc and ^{79}Se. Previous analyses (Fernandez et al. 1987) showed ^{238}Pu, and ^{99}Tc to be the most restrictive radionuclides. The current more restrictive hydrologic performance goal is primarily due to modeling differences for radionuclides, which were found to have radionuclide solubility rates higher than used previously and a higher repository thermal loading.

- The current analysis shows the hydrologic performance goals to be about 500 m^3 at 10,000 years compared to a previous goal of 140,000 m^3 per year from 1,000 to 10,000 years (Fernandez et al. 1987).

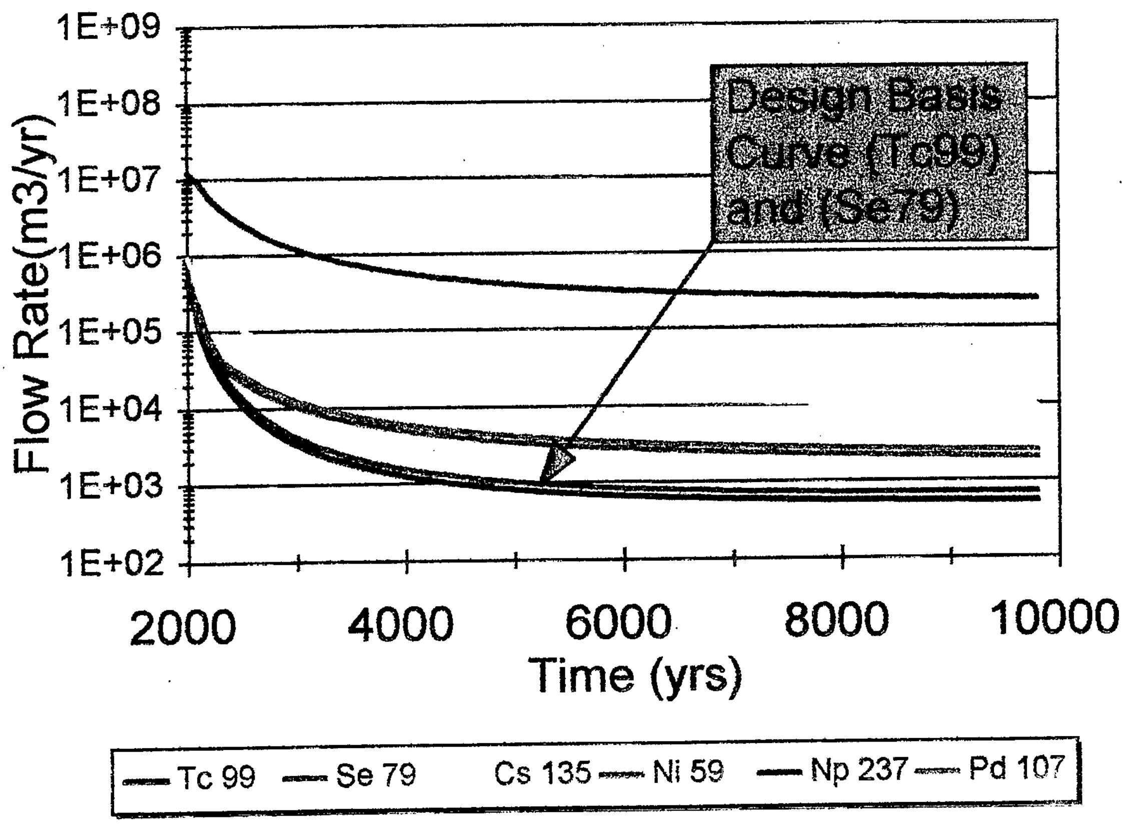

Figure 3-12. Hydrological Flow for the Repository Sealing System

3.5 ALLOWABLE WATER-FLOW GOALS ESTABLISHED ON THE BASIS OF A PREFERENTIAL PATHWAYS CRITERION

Hydrologic performance goals can be established on the basis of a preferential pathways criterion (CRWMS M&O 1997d). This criterion is to limit the flow rate through the seal system to one percent of the flow through the rock at the repository horizon (Fernandez et al. 1994). This hydrologic performance goal is expressed as a function of the infiltration rate as shown in Figure 3-13. The establishment of hydrologic performance goals for the shafts and ramps for the current repository design based on this interpretation of preferential pathways leads to goals that are comparable to the analysis that bases allowable water flow goals on the release from the EBS. Based on the current understanding of infiltration rates, the flow rates based on the preferential pathways criterion would range from 50 to 1200 m^3 per year for shafts, ramps, and exploratory boreholes based on a range of infiltration rates from 1 to 30 mm per year.

3.6 ALLOWABLE AIR FLOW GOALS

The radionuclides that could potentially be released to the repository in a gaseous state are ^{14}C and ^{129}I (Van Koynenburg et al. 1984, CRWMS M&O 1997e, and CRWMS M&O 1997f). As indicated by Van Koynenburg, 0.3 percent of the ^{14}C inventory in a stored canister of spent fuel might be released as a gas. Portions of the ^{129}I inventory in spent fuel may be concentrated in the pellet-cladding gap and/or on the grain boundaries of the fuel (Oversby and McCright 1985). Thus, the percentage of the total inventory of ^{129}I released as a gas is assumed to be 0.5 percent (Oversby and Wilson 1985).

In determining whether the shafts represent a preferred pathway, it is important to consider the total inventory of ^{14}C that can be released as a gas through the shafts. The total allowable ^{14}C and ^{129}I inventories that can be released to the accessible environment up to 10,000 years after closure are 1.26 and 0.0352 Ci/MTHM/yr respectively, for ^{14}C and ^{129}I (CRWMS M&O 1995). Considering 63,000 MTHM as total amount of waste, and the percent released as a gas as presented above, the maximum release limits for each radionuclide as a gas are 0.156 Ci/yr, and 0.005 Ci/yr respectively. Because these values are a small percentage of the total allowable release, the position is adopted that the requirements given in 10 CFR 60.134 are satisfied if the radionuclide releases of ^{14}C and ^{129}I as a gas out of the shaft is restricted to one percent of the allowable release limit for each radionuclide for the repository. The allowable release limit for the radionuclide ^{14}C is obtained as 1.26 Ci/MTHM/yr times 63,000 MTHM divided by 100,000 or 0.794 Ci/yr. Allowing one percent to flow through the shafts and ramps results in an allowable release rate of 0.008 Ci/yr. This represents 5 percent of the maximum release rate as a gas for ^{14}C (or 0.156 Ci/yr). Expressing this limit as a percentage of the flow through the rock that represents the maximum amount of gas released, the allowable flow rate expressed as a percentage of the flow through the rock is determined to be approximately five percent of this flow for ^{14}C, and ^{129}I respectively. This would mean reducing the total gaseous release of ^{14}C to five percent of the maximum release limits presented above.

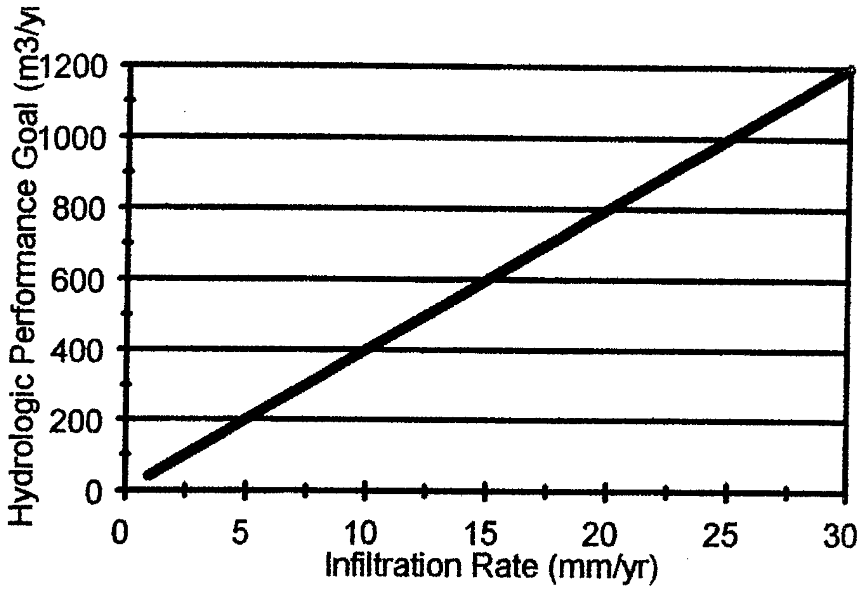

Figure 3-13. Hydrological Performance Goals Based Upon a Preferential Pathways Criterion

4. ANALYSES

4.1 GAS FLOW

This section presents the results of the air flow and water flow calculations performed to support the development of the seal requirements. The flow rate calculations presented in this section were prepared in accordance with NLP-3-27 for supporting engineering calculations.

4.1.1 Air Flow Out of the Repository

For a repository located in the unsaturated zone, there is the possibility of release of radionuclides by convective air flow out of the repository through the shafts, ramps, boreholes, and host rock. Air flow may be enhanced by heating, which provides a mechanism for convective flow and also dries out the rock around the repository, increasing the effective air conductivity. The objectives of this analysis are to evaluate the potential magnitude of the convective air flow from the repository considering the relative influence of the shafts, ramps, boreholes, and host rock in allowing air flow. The calculations include the influence of the MPZ around the shafts, ramps, and boreholes and the degree to which flow can be limited by backfilling or sealing the shafts, ramps, and boreholes.

4.1.2 Flow Mechanisms

In response to the temperature gradients, air will tend to rise through the emplacement exhaust shaft, boreholes through the repository, and host rock. Air will be drawn in through the outlying shafts and ramps (Figure 4-1). This mechanism may occur if the shafts, ramps, and boreholes are open or if their backfill is relatively permeable so that the resistance to airflow through the backfill is less than that through the rock.

Significant flow can occur through the host rock depending on the flow resistances of the shafts, ramps, and boreholes. The waste disposal areas are relatively hot, and the heated air tends to rise vertically through the rock as well as through the emplacement exhaust shaft and boreholes within the repository. Air is drawn in through the peripheral entries (ramps and development intake shaft) maintaining pressure in the repository drifts.

4.1.3 Method of Analysis

For purposes of a simplified analysis, the mechanism of convective air flow through a heated repository is considered to be analogous to the problem of air flow through an underground mine resulting from natural ventilation. Air flow induced by thermal convection is calculated using a network resistance model by a method similar to that used in mine-ventilation studies (Hartman 1982). Flow is calculated using Darcy's law, in which the major input parameters are the resistance to air flow of the underground openings and the host rock, and the pressure gradient calculated from the difference in pressures between the inlet and outlet points (CRWMS M&O 1997g).

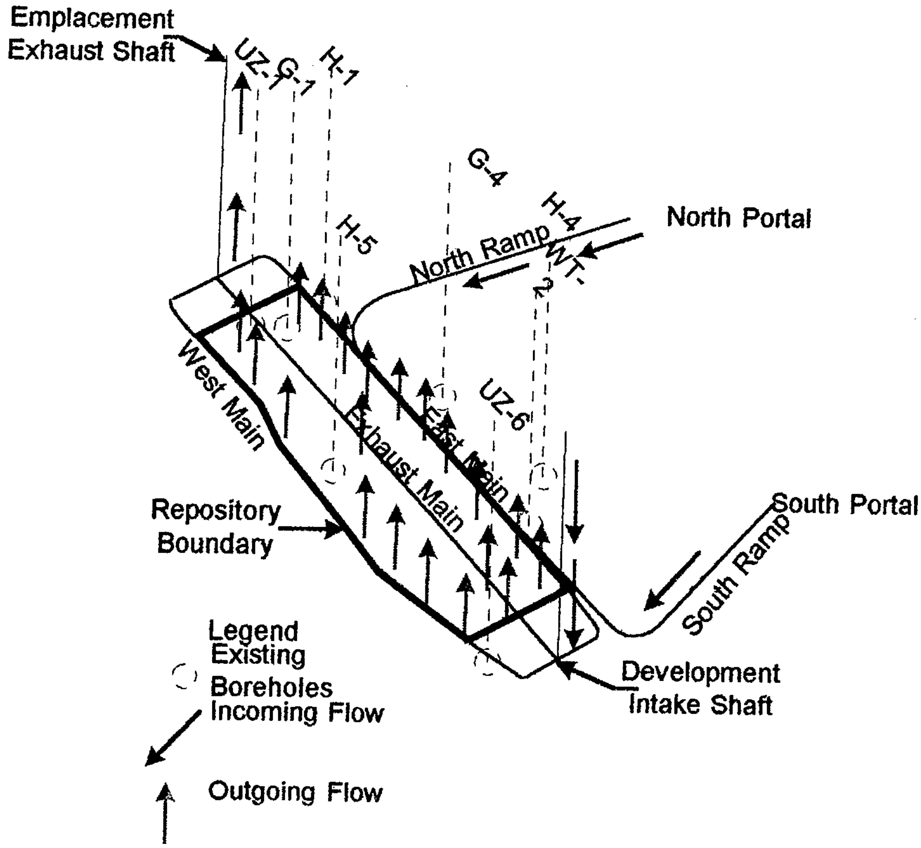

Figure 4-1. Repository Air Flows

The method for calculating flow through a heated repository based on methods normally used for mine ventilation studies, and is an approximation of a complex problem in thermodynamics. The following assumptions were used in the analyses.

Darcy's Law is valid

The resistance to air flow through open or a backfilled drift may be characterized as either laminar or turbulent. In turbulent flow, resistance is nonlinearly related to potential. In laminar flow, resistance is linearly related to potential, and flow may be calculated using Darcy's law for a fractured or porous media.

The results of the analyses were used to check the validity of Darcy's law by calculating the Reynolds number from the air velocity or specific discharge, air kinematic viscosity, and the characteristic dimension. In the case of laminar flow through a straight, open drift, the characteristic dimension is the tunnel diameter, and the calculated Reynolds number should be less than 2,000 (Daugherty and Franzini 1965). In the case of laminar flow through backfill, the characteristic dimension is the mean grain size diameter, and Darcy's law is valid as long as the Reynolds number does not exceed 10 (Freeze and Cherry 1979). In both cases, the calculated Reynolds numbers were within the specified limits and the assumption of head loss varying linearly with flow rate was found to be justified.

Air temperatures in the shaft are the same as in the adjacent rock

Convective air flow through a heated repository will involve a complex coupling of heat transfer from the rock to the air, which will tend to drive air flow, and heating or cooling of the rock by passage of the air, which will tend to reduce the driving mechanism. In the modeling studies which follow, the effects of cooling of the rock are ignored. The air is assumed to be at the same temperature as the adjacent rock at all points in the repository, including the shafts, ramps, and boreholes.

Intuitively, this simplified approach is most valid for the case of a backfilled repository in which air flows relatively slowly and temperatures are able to equilibrate. The faster the air flows, the greater the volume of air moving through the repository, and the more likely it is that the rock will be heated or cooled to the extent that convection slows down. A converse effect of rapid air flow which could occur is that the air flow is not sufficient to cool the rock in the repository significantly. Flow through the repository would be greater than that calculated using this simplified approach if air in the exit shafts (or rock) is not cooled by heat transfer to the rock. The driving pressure would then be about three times higher than that calculated with the assumption of equilibrated temperatures. This higher driving pressure would occur because air would be expelled at the ground surface at the same temperature as the temperature of the emplacement drifts, a condition which is intuitively overconservative.

On balance, the approach adopted in these calculations is considered to be valid for scoping studies, particularly when input parameters for temperatures and air resistances are approximated.

Air flow is incompressible and the air is dry

Since convective transport evolves from air buoyancy effects dependent on temperatures, thermal properties such as air density and air viscosity will change through the circuit. In reality, flow is compressible with the actual resistance to the mass flow rate dependent on density and viscosity. In the analyses presented in this report, air compressibility effects on fluid flow are ignored for reasons of simplification. This assumption is considered to be reasonable given that the pressures involved are small (i.e., <0.1 psi). According to Hartman (1982), compressibility effects may be ignored for mine static head pressure drops of less than 5 kPa (0.72 psi) or where differences in elevation are less than 430 m.

Convective transport can, in general, involve both the transport of air and water vapor. The development of high temperatures at the repository horizon will result in drying and lowering of moisture content of the rock. It is thus assumed that the air may be dry at the time at which peak temperatures are reached. This assumption is conservative because the effect of adding moisture to the convective flow will be to increase the work required to lift the air to the surface and this will in turn reduce the flow rates.

Air circulation occurs along specified paths

The model assumes that a particular path for air circulation is established and that flow is one-dimensional through the shafts, ramps, boreholes, and through damaged or undamaged tuff. The model ignores the development of secondary circulation currents that might develop in the host rock above or below the repository away from the waste containers.

4.1.4 Model Description

The analytical method used to solve for air flow involves assembling a "network stiffness matrix" (Zienkiewicz 1977) of various resistances representing the network for underground openings and (as appropriate) the rock mass. The driving pressure head (buoyancy effect of the hot gas) is calculated using a temperature distribution determined from the repository performance model assessments with the results applied to a system of linear equations that model the flow resistances, which in turn are used to calculate air flows through the network. The following sections describe the temperature and pressure boundary conditions, air conductivities (material properties), and model geometry (networks) used in the analyses.

4.1.5 Temperature and Pressure Distributions

A conservative upper bound to the calculation of draft pressure based on thermodynamic considerations was determined. The temperature profile for the rock above the repository was taken from the results of the Performance Assessment Model analysis from thermal loading systems studies (CRWMS M&O 1993). The temperature profiles for the exhaust shafts and ramps were developed from this study, geothermal gradient, assuming a temperature of 13°C at the ground surface and a geothermal gradient of 0.031°C per meter (CRWMS M&O 1997g). The draft pressure was calculated for each exhaust shaft, the ramps, an equivalent borehole shaft, and the repository rock. These draft pressures were calculated by integrating air density over depth for the temperature profiles to determine two pressures at the repository horizon and then taking the difference in these two pressures.

From examination of these draft pressures it was apparent that air flow would occur into the repository via the development intake shaft and the ramps. Air flows out of the repository via the emplacement exhaust shaft, the boreholes through the repository, and the rock. For simplification of the analysis and to conservatively calculate the maximum air flow from the repository, the maximum draft pressure head for the repository was determined and applied to the network of flow resistances added together for the inlet and outlet flow paths. The calculated maximum draft pressure (i.e., pressure difference) was 13.1 lb/ft^2 (0.09 psi), which corresponds to 2.5 inches of water gage. By comparison, according to Hartman (1982), the natural ventilation pressure generated by natural geothermal energy in mines is usually less than 0.5 inches water gage and seldom exceeds 3 inches except in extreme cases. The calculated draft pressure falls within this range and would be expected to be higher than 0.5 inches, since the generation of heat in an underground nuclear-waste repository results in higher temperature contrasts than those experienced in a typical underground mine.

4.1.6 Air Conductivities

The resistance to air flow for incompressible fluid flow through shafts, ramps, and boreholes depends on the lengths and cross-sectional areas of the flow regime and the air conductivities of the backfill and the surrounding MPZs. The repository drifts were conservatively assumed to be open and connected such that no flow resistance for them was modeled. The MPZs were modeled around the shafts, ramps, and boreholes with the cross-sectional area of the MPZ around them assumed to extend out one shaft radius from the wall (Case and Kelsall 1987).

Backfill air conductivities were varied over a range of equivalent hydraulic conductivity from 10^{-4} to 100 cm/sec. The upper bound for air conductivity corresponds to a gravel, while the lower bound corresponds to a silty sand (Freeze and Cherry 1979). The lower bound might also correspond to a compacted backfill engineered for low permeability by adding silt or clay fines.

The equivalent air conductivity of the MPZ was taken to be 20 and 60 times higher than the conductivity of the undisturbed tuff averaged over an annulus one radius wide. The equivalent conductivity factor of 20 corresponds to expected conditions at depth. The equivalent conductivity factor under worst case assumptions ranged from 40 to 80 times the undisturbed conductivity. The average value of 60 was selected for analysis. The equivalent conductivity of the overlying rock above the repository was determined, as subsequently explained, to take into account strata with varying conductivities, and the MPZ was assumed to be either 20 or 60 (Case and Kelsall 1987) times more permeable than the undamaged rock in each stratigraphic unit. The permeability of the MPZ was developed from laboratory and field testing measurements that coupled elastic or elastoplastic stress relief from excavation to changes in conductivity. For flow through the roof above the waste emplacement drift, it is necessary to know the cross-sectional areas of the emplacement drifts as well as the air conductivity. This area was taken as the footprint of the total emplacement drifts area and was estimated to be 4,029,000 m^2 (CRWMS M&O 1997g).

The equivalent conductivity for flow through the rock to the ground surface was calculated according to the relation (Freeze and Cherry 1979):

$$\frac{L}{Ke} = \sum_{i=1}^{n} \frac{L_i}{K_i} \tag{4-1}$$

where

- Ke = equivalent conductivity of the tuff for vertical flow (m/sec)
- L = distance from the repository roof to the ground surface (m)
- L_i = thickness of each unit (m)
- K_i = air conductivity of each unit (m/min)

The average thickness of the units above the repository was determined to be (Fernandez et al. 1994):

- Tiva Canyon (welded) = 107 m
- Paintbrush (non-welded) = 40 m
- Topopah Spring (welded) = 192 m

The air conductivity[1] of the nonwelded Paintbrush was converted from a hydraulic conductivity of 3.0×10^{-6} to 3.0×10^{-4} cm/sec. The air conductivity of the welded units (Tiva Canyon and Topopah Springs) was converted from a hydraulic conductivity ranging from 3.0×10^{-6} to 2.0×10^{-5} cm/sec (Bodvarsson and Bandurraga 1996).

Equation 4-1 indicates that the equivalent conductivity of strata in series tends to be dominated by the unit with the lowest conductivity. Table 4-1 shows the equivalent hydraulic conductivities (Ke) calculated for the low, intermediate, and high combinations of hydraulic conductivities of the welded (Kw) and nonwelded (Knw) units.

Table 4-1. Equivalent Hydraulic Conductivity of Tuff

Sensitivity Case no.	KW (cm/sec)	Knw (cm/sec)	Ke (cm/sec)
1	3.0×10^{-6}	3.0×10^{-6}	3.0×10^{-6}
2	2.0×10^{-5}	3.0×10^{-6}	1.2×10^{-5}
3	2.0×10^{-5}	3.0×10^{-4}	2.25×10^{-5}

In order to calculate the total flow in and out of the repository, the following general flow conductance equation is used:

$$Q_{total} = C_{total} \times \Delta P \qquad (4\text{-}2)$$

where

Q_{total} = total flow in or out of the repository
C_{total} = total conductance $(1/(1/C_{in}+1/C_{out})$
ΔP = draft pressure

Based on Darcy's Law the flow conductance equation for the rock above the repository was derived to be:

$$C = \frac{K_a \times A}{L\, \rho_a\, g} \qquad (4\text{-}3)$$

[1]Air conductivity may be derived by calculating an intrinsic permeability from the hydraulic conductivity relationship presented by Freeze and Cherry (1979, P. 27) and then by calculating the air conductivity using the fluid properties of air.

Or expressing the conductance in terms of hydraulic conductivity:

$$C = \frac{K_w}{\rho_w} \cdot \frac{\mu_w}{\mu_a} \cdot \frac{1}{(g \cdot L)} \cdot A$$

(4-4)

where

K_w = Hydraulic conductivity of the tuff
K_a = Air conductivity of the tuff
μ_w = Viscosity of water at the average tuff temperature
ρ_a = Density of air at the average rock temperature
ρ_w = Density of water at the average tuff temperature
μ_a = Viscosity of air at the average tuff temperature
L = Length from repository to surface
A = Cross-sectional area of the repository (footprint)
g = Acceleration due to gravity

For the shafts, ramps, and boreholes the conductance equation was derived to include the modified permeability zone (MPZ) as follows:

$$C_{Ramp} = \frac{\mu_w \; A(3Factor.Kw + Kbf_w)}{\rho_a \; \mu_a g L}$$

(4-5)

where in addition to the above definitions the following are defined as

Factor = the MPZ conductivity increase over the undamaged rock (20 or 60 times the conductivity of the rock)
Kbf_w = hydraulic conductivity of the backfill

The conductances for each flow path were calculated using the above appropriate equation and then added appropriately for those flow paths in series and in parallel to obtain the total conductance of the network.

4.1.7 Model Geometry

In the network used to calculate the flow, the drifts were assumed to be open and to offer no resistance to flow. The total air-flow rate was calculated for series flow into the repository drifts downward through the development intake shaft and the ramps (including associated damaged zones) and out of the repository upward through the emplacement exhaust shaft and boreholes (including associated damaged zones) and through the repository tuff strata above the repository. (No attempt was made to calculate the distribution of flow among drifts, mains and access drifts).

By definition in this case, all flow through the rock occurs in the emplacement drifts. This is a conservative definition because in reality some flow up the emplacement exhaust shaft could be short-circuited through the mains without passing through the emplacement drifts.

4.1.8 Results

The total air flow out of the repository was calculated for a range of backfill hydraulic conductivities and the expected MPZ factor of 20. The rock hydraulic conductivity was varied from a low equivalent tuff conductivity to a high value as discussed in Section 4.1.6, Table 4-1. The results are shown in Figure 4-2.

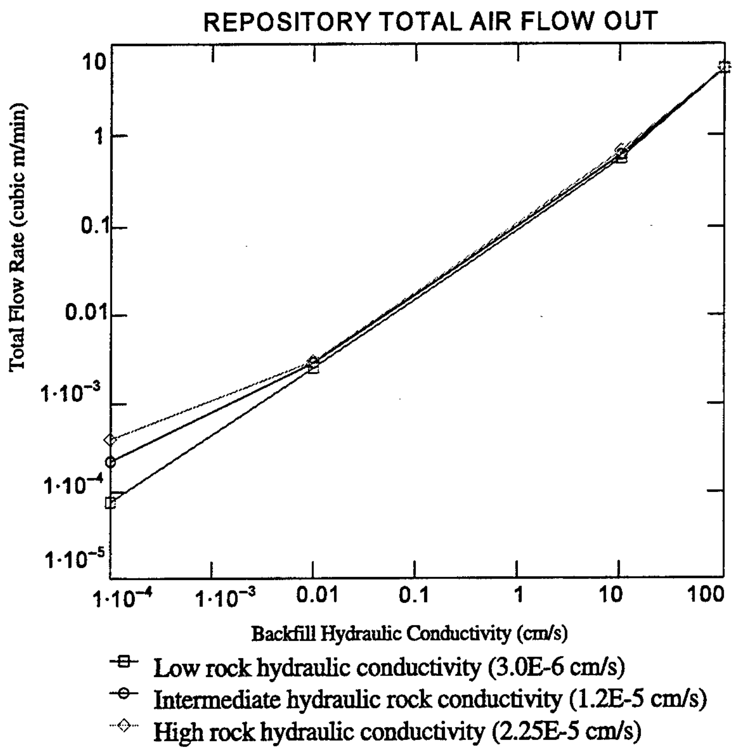

Figure 4-2. Repository Total Air Flow Out for an MPZ Factor of 20

The distribution of the flow out of the repository through the emplacement exhaust shaft and through the boreholes (equivalent borehole) was determined by proportioning the total flow to the conductance of each. The percentage of the total flow is shown for each in the following Figures 4-3 and 4-4.

Note that the percentage of the total flow through the boreholes is small compared to the flow through the emplacement exhaust shaft at high rock conductivities.

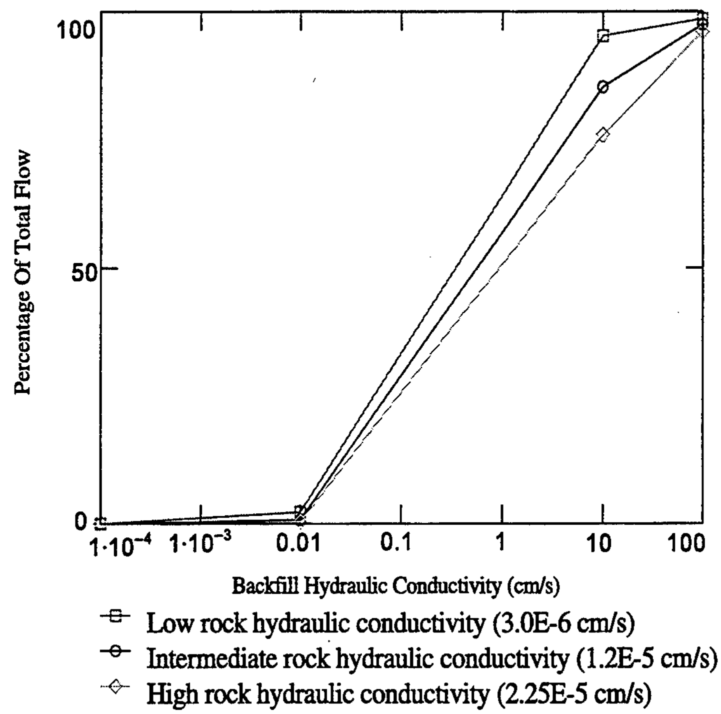

Figure 4-3. Emplacement Exhaust Shaft Flow with an MPZ Factor of 20

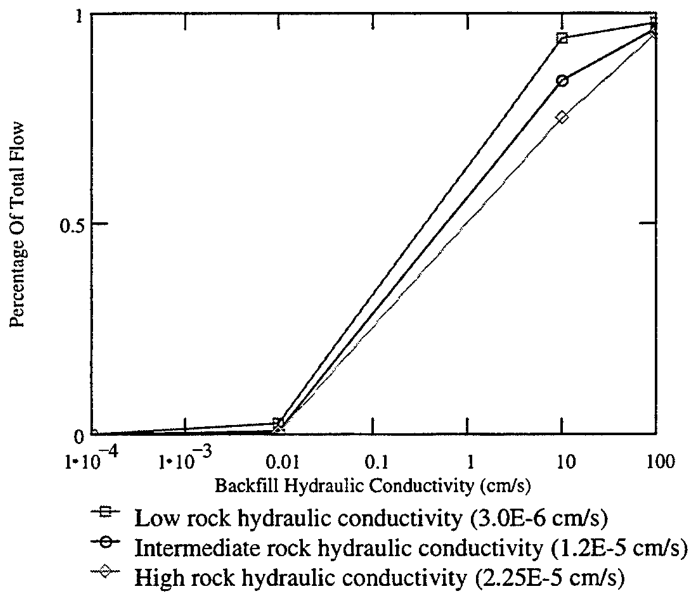

Figure 4-4. Boreholes Total Flow with an MPZ Factor of 20

These same calculations were performed with an MPZ Factor of 60. The results for these sensitivity calculations are shown in the following Figures 4-5 through 4-7.

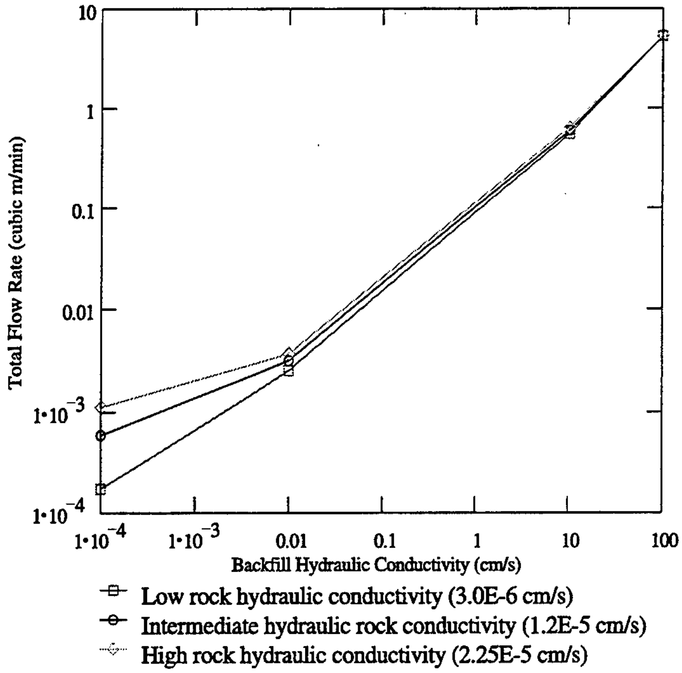

Figure 4-5. Repository Total Air Flow Out with an MPZ Factor of 60

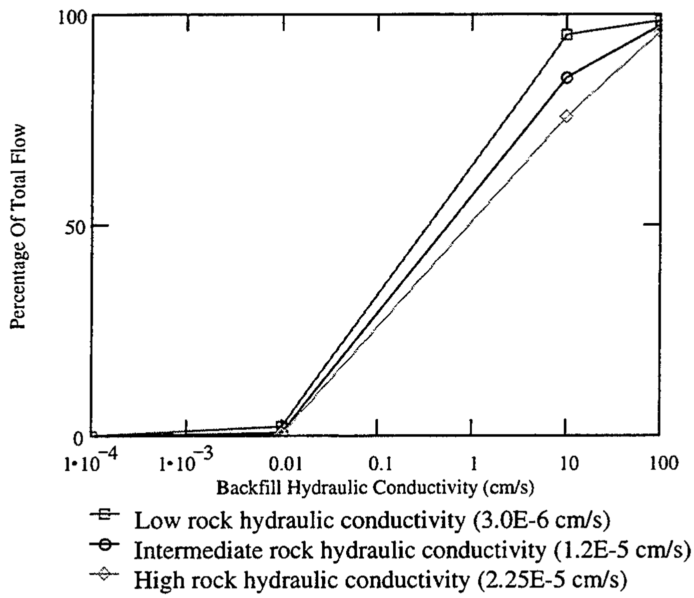

Figure 4-6. Emplacement Exhaust Shaft Flow with an MPZ Factor of 60

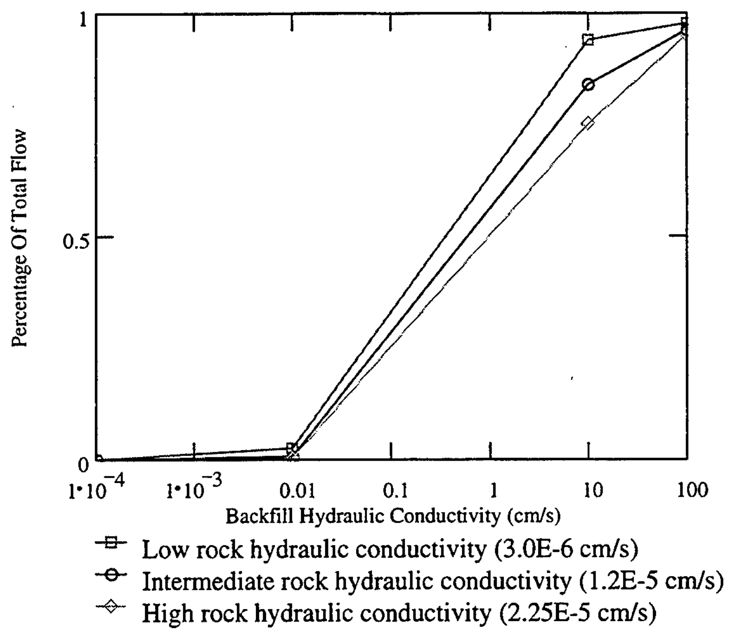

Figure 4-7. Boreholes Total Flow with an MPZ Factor of 60

The figures for total air flow out of the repository (Figures 4-2 and 4-5) with a MPZ Factors of 20 or 60 show little difference in the total air flow for backfill hydraulic conductivity greater than 0.01 cm/sec and with equivalent tuff conductivities for the rock units above the repository that varies from a low of 3.0E-6 cm/sec to a high of 2.25 E-5 cm/sec. This is because the air flow in and out of the repository becomes predominantly that through the shafts, ramps , and boreholes and not through the rock when the backfill conductivity was increased to values greater than 0.01 cm/sec. For backfill conductivities less than 0.01, the total air flow out of the repository is predominately through the rock matrix above the repository. This is clearly shown in Figures 4-3, 4-4, 4-6, and 4-7 where the flow out through the Emplacement Exhaust Shaft and the boreholes (equivalent borehole) starts dominating the total flow for backfill hydraulic conductivity greater than 0.01 cm/sec.

The total flow was found to be dependent on the backfill conductivity and increase from about 1.0E-4 m^3/min to 8.0 m^3/min as the conductivity of the backfill in the shafts, ramps, and boreholes was increased from 1.0E-4 cm/sec to 100 cm/sec. The analysis showed the percentage flow out through the Emplacement Exhaust Shaft varied from about 0 to 97 percent and the boreholes from about 0 to 1 percent as the backfill conductivity increased from 0.01 cm/sec to 100 cm/sec. The balance of the air flows through the rock.

The analysis indicates that to reduce the air flow out of the repository, it is effective to backfill the shafts, ramps, and boreholes. Backfill with a hydraulic conductivity less than 0.01 cm/sec will cause nearly all air to flow out of the repository through the rock. As discussed in Section 5.4.3.2 this value is achievable for earthen materials.

4.1.9 Lateral Dispersion of Airflow

The objective of the following analyses is to determine the extent of lateral dispersion from the edge of the potential repository, which would then determine the extended boundary of the potential repository boundary (CRWMS M&O 1997h). As air flows upward from the potential repository by either barometric or convective mechanisms, lateral spreading of radionuclides through the processes of molecular diffusion and hydrodynamic dispersion is likely to occur. Research (Burkhard et al. 1989; Peterson et al. 1987) associated with barometric or atmospheric pumping suggests that this is a reasonable scenario to consider and that the fractures may play a role in contaminant transport. Some pertinent conclusions follow:

- Contaminant transport in the vertical direction through a nonhomogeneous porous medium is enhanced by atmospheric pumping (Peterson et al. 1987).

- It appears that fractures control the pneumatic diffusivity and contaminant transport of the volcanic rocks (Burkhard et al. 1989).

- Fluid travels much faster along the fractures than through the blocks, and the speed differs along fractures having different apertures (Endo et al. 1984).

Therefore, an analysis was performed to determine the nature and extent of such lateral spreading due to the fractured nature of the tuff.

The advection-dispersion analysis was performed with a two-dimensional plane dispersion model (Javandel et al. 1984). Using a Cartesian coordinate system with the axis oriented along the direction of the flow, the two-dimensional advection-dispersion equation can be written as follows:

$$D_L \cdot \frac{\delta^2}{\delta x^2} \cdot C + D_T \cdot \frac{\delta^2}{\delta y^2} \cdot C - v \cdot \frac{\delta C}{\delta x} - \lambda RC = R \cdot \frac{\delta C}{\delta t} \qquad (4\text{-}6)$$

where

C = Concentration
D_L = Dispersion coefficient along the flow direction
D_T = Dispersion coefficient perpendicular to the flow direction
v = Average linear flow velocity
R = Retardation factor
t = Time
λ = Decay constant

The potential repository can be modeled as a single-line source that is perpendicular to the flow direction. The single-line source is approximately the width of the repository. If the concentration of the solute diminishes exponentially with time, the initial and boundary conditions for the model can be written as follows:

$$C(0,y,t) = C_0 e^{-\alpha t} \qquad -\alpha \leq y \leq \alpha \tag{4-7}$$

and for other values of y:

$$C(0,y,t) = 0$$

$$\mathrm{Lim}_{y \to \pm\infty}\, \delta C/\delta y = 0 \tag{4-8}$$

$$\mathrm{Lim}_{x \to \infty}\, \delta C/\delta x = 0$$

Note that x is defined as the nominal direction of flow and y is defined as the lateral direction of flow. Hence, the analytical solution by Javandel et al. (1984) to this problem is:

$$C(x,y,t) := \frac{x \cdot C_0}{4 \cdot (\pi \cdot D_L)^{\frac{1}{2}}} \cdot \exp\left(V \cdot \frac{x}{2 \cdot D_L} - \alpha \cdot t\right) \cdot \int_{0 \cdot yr}^{\frac{t}{R}} \exp\left[-\left(\lambda \cdot R \cdot \tau - \alpha \cdot R \cdot \tau + \frac{V^2 \cdot \tau}{4 \cdot D_L}\right) - \frac{x^2}{4 \cdot D_L \cdot \tau}\right] \cdot \tau^{-\frac{3}{2}} \cdot \left[\mathrm{erf}\left[\frac{a-y}{2 \cdot (D_T \cdot \tau)^{\frac{1}{2}}}\right] \ldots + \mathrm{erf}\left[\frac{a+y}{2 \cdot (D_T \cdot \tau)^{\frac{1}{2}}}\right]\right] d\tau \tag{4-9}$$

where

C_0	=	Initial concentration
α	=	Decay constant for concentration
x,y	=	Spatial coordinates
R	=	Retardation
t	=	Time
τ	=	Variable for integration
a	=	Repository half width (equivalent radius of the repository)
D_L	=	Longitudinal dispersion
D_T	=	Transverse dispersion
V	=	Average linear velocity of water

and the linear velocity is calculated from the equation $V = L_t/T$

L_t = Total flow path length

T = Total time through the stratigraphic column and is calculated from the following formula:

$$T := \frac{\sum_{i=0}^{2} n_i \cdot L_i \cdot \sum_{i=0}^{2} \frac{L_i}{K_i}}{G \cdot Lt} \quad (4\text{-}10)$$

and where

n_i = Porosities of the ith unit of the strata

Lt = Total flow path length

G = Gradient for airflow (pressure head of air/Lt)

L_i = Flow path length of the ith component of the strata

K_i = Air conductivity of the ith component of the strata

Because most of the air flow is vertical and the rock fractures are mostly vertical, the small fracture porosities were neglected as compared to the rock strata porosities. The average values of the various strata units (CRWMS M&O 1997g) used in the calculation were:

TCw: $n_0 = 0.11$ PTn: $n_1 = 0.45$ TSw: $n_2 = 0.13$

Using the air pressure of the repository of 627 Pa (from Section 4.1.5), the average strata unit thicknesses of 107 m, 40 m, and 245 m for the TCw, PTn, and TSw, respectively with the conservatively largest values of strata hydraulic conductivities used in the previous calculations (Section 4.1), the average linear velocity was calculated to be V = 6.1 m/yr.

The hydraulic conductivities used for the strata units were:

TCw: $K_0 = 2.0\text{x}10^{-5}$cm/sec PTn: $K_1 = 3.0\text{x}10^{-4}$cm/sec TSw: $K_2 = 2.0\text{x}10^{-5}$cm/sec

The values of the other variables defined for the concentration calculation were:

a = 1132 m $C_0 = 1.0$ $D_T = 20$ m x V $D_L = 100$ m x V R = 1.0

$\alpha = 0$ $\lambda = 0$

Then for various values of time (t) the ratio of the concentration at the surface over the repository (339 m) to the initial concentration (C_0) at the repository was determined and plotted as a function of distance from the center as shown in the Figure 4-8. The equivalent edge radius of the repository is shown as 1132 m.

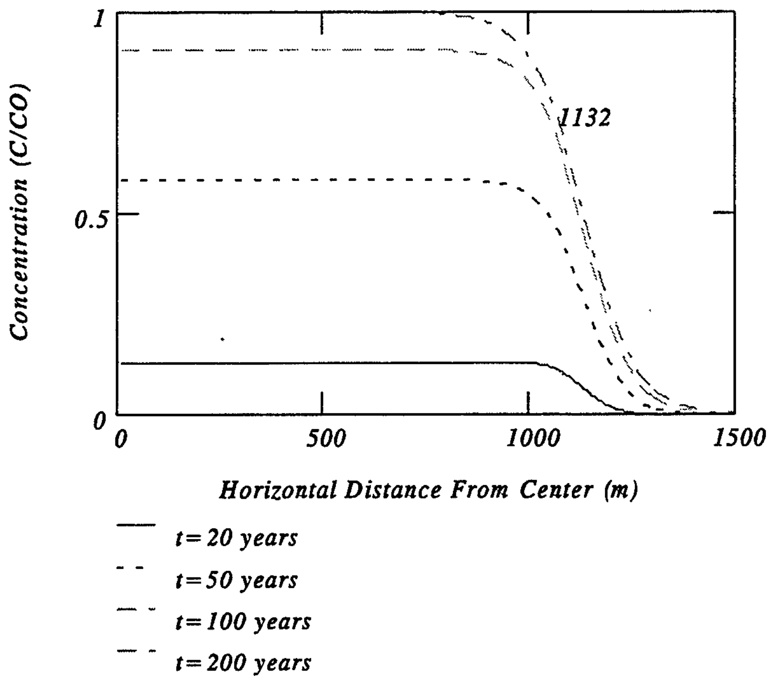

Figure 4-8. Concentration versus Distance at Surface

The figure shows the lateral dispersion (concentration C/Co) to reach a distance outside the repository boundary of about 300 to 350 m. Consequently, boreholes that are within this region should be considered as needing to be sealed. As a conservative boundary, it is recommended to seal deep boreholes within 400 m of the repository footprint.

4.2 WATER FLOW

This section presents estimates of inflows to the underground repository from the shafts, ramps, and exploratory boreholes. The inflows to these penetrations occur from infiltration from fracture systems, fault zones, and perched water zones.

Volcanic rocks are the predominant rock type at Yucca Mountain. They are typically ash flow in origin, but ash fall, bedded, and reworked tuffs are also present. Most tuffs are high-silica rhyolites, but the large-volume ash-flow cooling units are compositionally zoned, grading upward from rhyolite to quartz in the upper part of the sequence (Broxton et al. 1987). Also, the units are quite variable in degree of welding, alteration, and zeolitization. Tuff units above the water table are commonly devitrified or vitric.

The sequence of tuff units at Yucca Mountain include the Paintbrush Group, the tuffaceous beds of the Calico Hills Formation, and other sequence of ash-flow tuffs, and the intercalated lavas (Figure 4-9). These tuffs are quite variable in the degree of welding and their alteration. The fractured welded tuffs exhibit higher permeability than the less fractured nonwelded tuffs. Permeability contrasts (high permeability in welded tuffs to low permeability in nonwelded tuffs) exist at contact zones. The tuffs of primary interest from a sealing perspective are the tuffs of the

Paintbrush Group and tuffaceous beds of the Calico Hills Formation. The Paintbrush Group is comprised of the Tiva Canyon Tuff, the Yucca Mountain and Pah Canyon Tuffs, and the Topopah Spring Tuff. Most of the bedrock outcropping at the surface consists of welded ash flow tuffs of the Tiva Canyon Tuff. Along the western slope of Yucca Crest, the nonwelded and bedded tuffs of the Paintbrush Group are exposed in Solitario Canyon.

4.2.1 Conceptual Model for Flow Through the Unsaturated Zone

The current conceptual model for flow through the unsaturated zone (UZ) is a variation of the model developed by Montazer and Wilson (1984). Data collected from field studies has been in general agreement with their concepts. One significant variation to the conceptual model by Montazer and Wilson, but that was considered in concept by Fernandez et al. 1987 is the evidence of fast pathways. Recent measurements of ^{36}Cl (Fabryka-Martin et al. 1996) have confirmed the existence of fast pathways. Figure 4-10 presents the important aspects of the conceptual model for flow through the unsaturated zone at Yucca Mountain. Variable infiltration, environmental isotopes showing bomb pulse signatures deep within the UZ, lateral diversion of flow, side-slope infiltration, and perching zones above the zeolites are also shown in Figure 4-10.

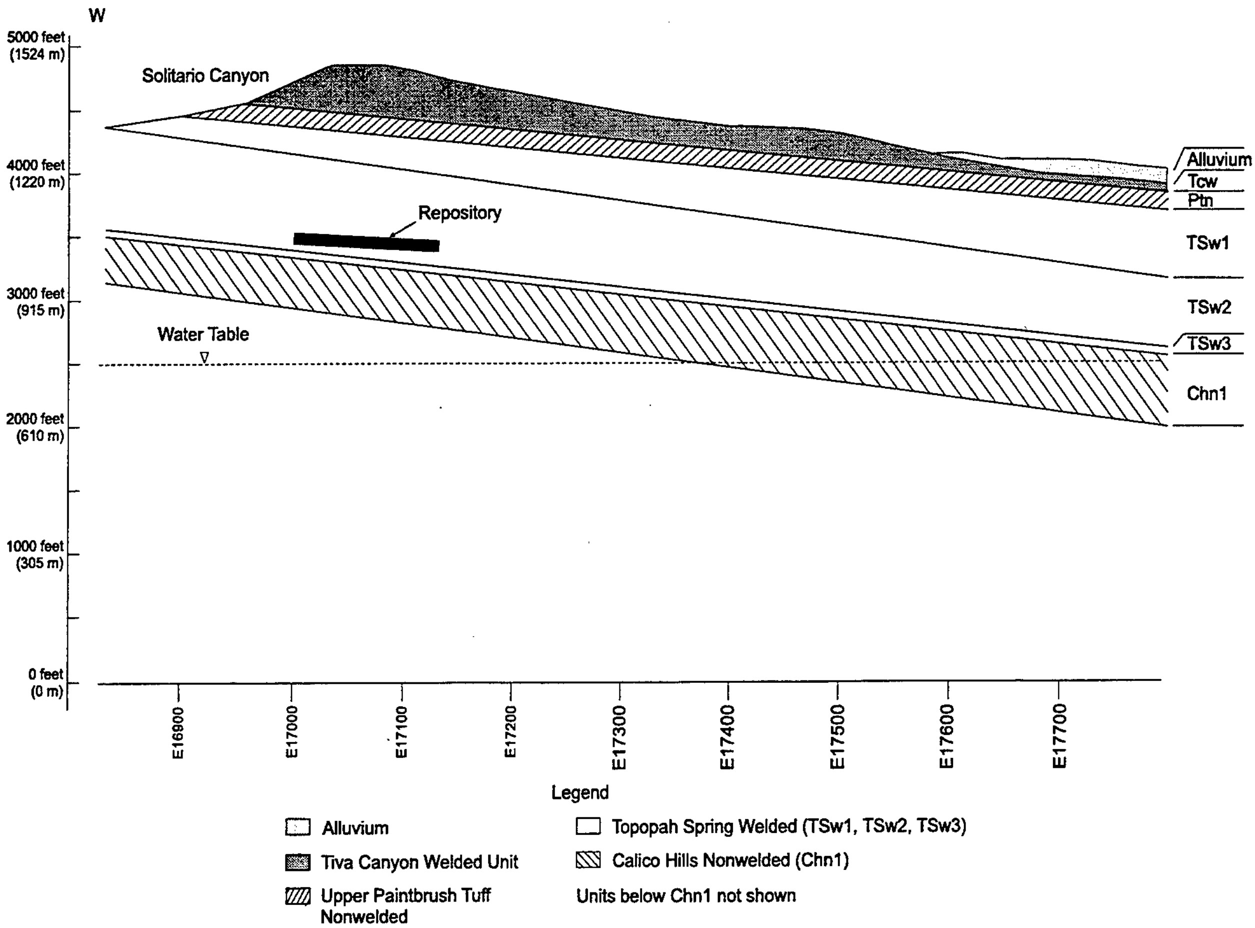

Figure 4-9. Geologic Cross-Section of Yucca Mountain

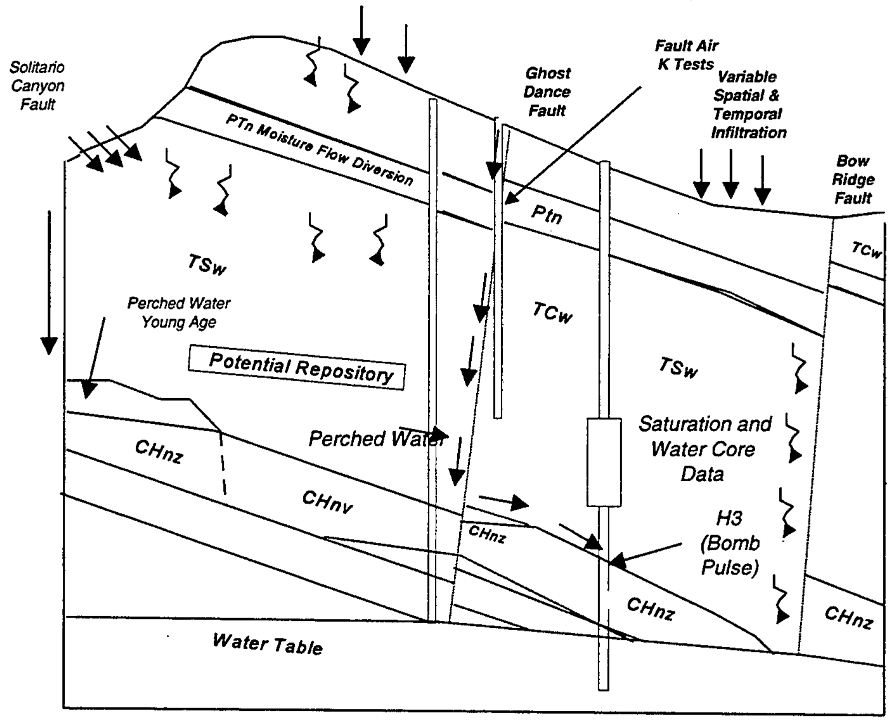

Figure 4-10. A Schematic Cross Section through Yucca Mountain showing Various Conceptual Model Data and Processes (Modified from Bodvarsson, and Bandurraga 1996)

Subsurface hydrologic processes at Yucca Mountain occur in an arid environment with heterogeneous layers of anisotropic, fractured volcanic rocks (Scott and Bonk 1984). The volcanic rocks consist of alternating layers of welded and nonwelded ash flow and air fall tuffs. The primary geologic formations found at Yucca Mountain include the Tiva Canyon Tuff that occurs extensively at the surface, and the older Pah Canyon and Topopah Spring Tuff that form outcrops near the surface, mostly on the western slope of Yucca Mountain.

The welded units typically have low matrix porosities and high fracture densities, whereas the nonwelded and bedded tuffs have relatively higher matrix porosities and lower fracture densities. At smaller scales the fracture density is correlated with increases in the degree of welding of the volcanic rocks.

The most significant structural features at Yucca Mountain are the numerous faults mapped at the surface (Figure 4-11). Several faults are continuous, major features that could penetrate deeply to the repository horizon and define a number of distinct structural blocks. The types of faults occurring in the vicinity of the proposed repository location are north-south-trending, normal faults and northwest-southeast trending, strike-slip faults. The major faults include the Solitario Canyon Fault (or series of faults), which forms the western boundary of the repository block, and the Ghost Dance fault and Drill Hole Wash fault which the forms the eastern boundary. The relationship of these structures to the repository boundary and the location of boreholes is shown.

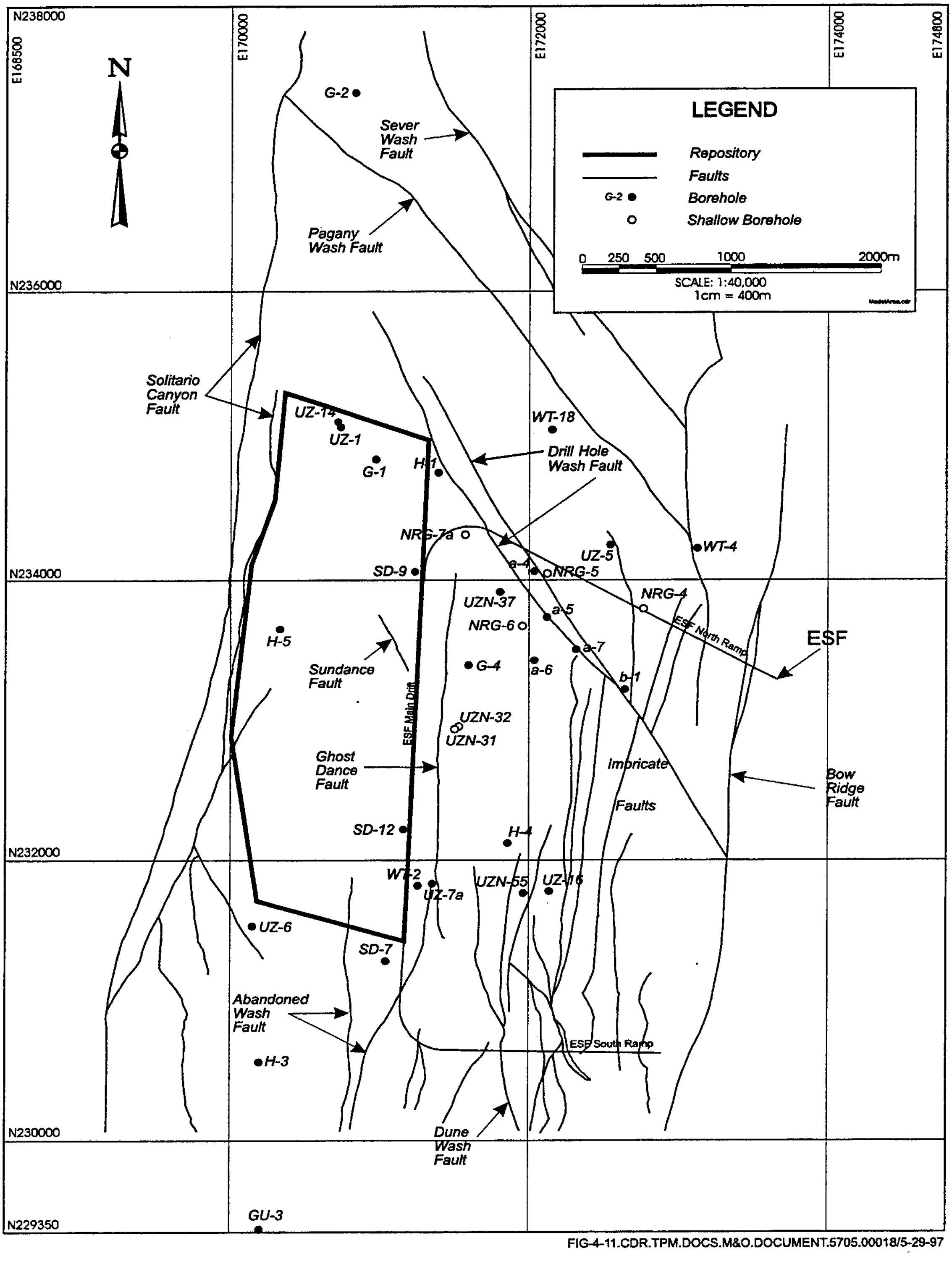

Figure 4-11. Yucca Mountain Faults

4.2.2 Infiltration and Percolation

Infiltration at Yucca Mountain is spatially variable due to variations in soil cover and topography. Also, it is temporally variable due to the nature of thunderstorms that supply precipitation (Hevesi et al. 1994). The current conceptual model for infiltration is based on numerous measurements of water content profiles in shallow boreholes at Yucca Mountain. If there is a significant thickness of alluvium overlying the fractured volcanic rock, an infiltration pulse will not penetrate the underlying rock formations because of attenuation of the pulse by storage in the porous soil layers. Therefore, the high infiltration rates occur on the sideslopes and ridgetops where outcrops are exposed and fracture flow into the volcanics can be initiated.

The proposed repository horizon is near the middle of the non-lithophysal portion of the TSw units. Relatively low matrix saturations measured in the upper portion of the TSw suggests that much of the moisture that infiltrates into the TCw does not reach the TSw. Furthermore, the low saturations suggest that fracture flow is not being maintained through this region. The data suggest that the flux reaching the repository level through the matrix is low relative to the saturated hydraulic conductivity of this unit.

Furthermore, no moisture was observed infiltrating into the radial boreholes of Alcove 1 of the ESF after storm events. These boreholes are located close to the ground surface in the highly fractured TCw formation. Thus, the relatively high porosities of the units in the PTn attenuate infiltration pulses through storage, possibly allowing vapor transport through the relatively permeable TCw to remove a significant portion of the moisture before it percolates to the repository horizon.

While the above observations provide some evidence of a lower percolation rate, the relationship between the net infiltration rate and the percolation rate at the repository horizon has not been completely determined. The PTn may provide a capillary barrier to flow, but this has not been shown conclusively. The net infiltration rate into the TCw unit of water precipitating onto the ground surface at Yucca Mountain provides an upper bound to the percolation flux.

Current evidence suggests this infiltration rate averages 5 mm per year. Current evidence suggests that the infiltration in localized areas could be an order of magnitude higher than this value. Also, various climatic changes may result in an increase in the infiltration rate. Modeling studies suggest that the net infiltration may exceed 30 mm per year (Flint et al. 1997).

Other data suggest that the percolation flux may reach the repository level mainly through episodic fracture flow. These data include observation and testing of perched water located below the repository horizon. Measurements of bomb-pulse isotope levels in samples from the tuff matrix (Yang et al. 1996) and the ESF show that the water is young. These data show shorter travel times than would be possible solely through matrix flow.

4.2.3 Perched Water Zones

The presence of perched water has implications for the travel times and flow paths of water through the unsaturated zone, and may affect the performance of the repository sealing system. Perched water may occur where large-permeability contrasts exist such as at the contact between zeolitic and nonzeolitic units. Perched water zones at Yucca Mountain were reported by Burger and Scofield (1994) in the following boreholes: USW UZ-1, USW UZ-14, USW NRG-7/7a, and USW-9. Additionally, wet zones were reported to be found in the borehole USW SD-12 (Bodvarsson, and Bandurraga 1996). These data suggest that there is an extensive perched-water body around this area. In contrast, pressure transient tests of the perched water zone near SD-7 show small volumes of water.

The perched water occurrences in these boreholes were detected in zones in, or overlying, geologic units that are extensively altered to zeolites. This condition is often encountered in the material underlying the densely welded and fractured TSw.

4.2.4 Groundwater Through Discrete Faults

Figure 4-11 shows faults mapped at the surface in the vicinity of the proposed repository location. While a relatively large number of faults are shown, it is possible that many are minor features that may not penetrate to the repository horizon.

More recent information suggests that the faults might provide flow paths towards the groundwater table resulting in a peak discharge that might occur over a short time period. However, the flows would not likely be sustained. For example, the permeability from studies in Alcove 2 of the ESF show that the permeability of the Bow Ridge fault is about 0.02 cm/s (Bodvarsson, and Bandurraga 1996) and is equivalent to the intrinsic permeability from air permeability testing of the highly permeable bedded tuff formations or highly fractured welded units. Other evidence as obtained from geothermal measurements in boreholes suggests high permeability in the vertical direction.

Intuitively, the conductivity might be expected to be relatively low perpendicular to the fault (because of the presence of clay gouge), but higher within the plane of the fault. This is suggested by the fact that the fault zones serve as permeability barriers to lateral flow. For instance, the water body observed at boreholes SD-7 is thought to be perched over a zeolitic layer and prevented from lateral movement by the presence of the Ghost Dance Fault. Rousseau et al. (1996) presented a similar hypothesis that the perched water body intercepted by borehole UZ-14 is caused by a Solitario Canyon fault splay that has offset the zeolitic Calico Hills Formation and blocks lateral movement of the water.

Fernandez et al. (1987) used the Green and Ampt transient, one-dimensional, analytical solution to assess peak infiltration rates and cumulative infiltration into a fault zone. They assumed that the fault plane surfaces are impermeable, and that water flowing down the fault system is not absorbed into the matrix. In the calculations, the hydraulic conductivity of the fault zone was varied from 10^{-5} to 10^{-2} cm/sec (as used above) and the porosity from 0.004 to 0.4.

The lower porosity value was intended to correspond to the effective fracture porosity of a densely fractured zone, whereas the higher value corresponds to a vuggy breccia zone. Initial saturation was varied from 0 to 85 percent. The times required to achieve saturation down to the water table were evaluated relative to the length of time over which the fault could be recharged at the surface.

To illustrate the variability in the time to saturation of the rock down to the water table, several scenarios that conceivably bound the potential hydraulic properties of a fault system were postulated. The results showed that for a relatively conductive fracture system (10^{-2} cm/sec) with a low porosity (0.004), the saturation times to the repository horizon and the water table are a matter of hours. When the conductivity is the same but the porosity is high (0.4), saturation time extends to almost a month. When the hydraulic conductivity was decreased to 10^{-5} cm/sec, the saturation times were longer for the range of porosities investigated. As would be expected, when the initial degree of saturation of the fault zone increases, the time required to saturate decreases. Using the Green and Ampt solution (Fernandez et. al. 1997)approach, the time to saturate an initially dry system was about twice as long as one starting at a 50 percent saturation level.

The porosity of the fault zone also influenced the volume of water required to saturate to the repository level or to the water table. For a high-porosity (0.4) system, the volume required to saturate to the water table is 200 m^3 per unit area (1 m^2) of the fault exposed at the surface. For a low-porosity (0.004) system, the equivalent volume is only 2.0 m^3. These calculations confirm that saturation of a fault system and infiltration are very sensitive to both the hydraulic conductivity and porosity for the fault system.

4.2.5 Groundwater Inflow Measurements

Ground-water inflow from faults in nonwelded tuff above the water table has been observed in tunnels in Rainier Mesa at the Nevada Test Site (Thordarson 1965). The intent in presenting this information is to illustrate the magnitude of water inflows into tunnels under perched water conditions and potential climatic changes that might increase groundwater inflow rates. It is important to note that no flow rates comparable to those measured at Rainier Mesa have been observed in the ESF.

Typically, the maximum inflow occurred immediately after the water-bearing fracture was penetrated by the tunnel. The inflow then declined rapidly to become a small seep or drip after a few days. Most of the fractures drained completely within a few weeks or months, but water dripped from some fractures for greater than 2 years. In one tunnel system (Ul2e), the estimated total discharge over a 5-year period was 30 to 50 million gallons (Thordarson 1965). The total length of drifts in the system was about 5.8 km and about 110 faults were mapped. Most of the water was produced by 50 to 60 percent of the faults.

Most of the faults described by Thordarson from the U12e tunnel system were minor anticipated faults with stratigraphic displacements measured in inches. Few faults were traced between parallel drifts, indicating lateral extents of less than 30 m to 90 m. Water occurred irregularly and some highly fractured zones were dry even though open fractures were noted. Thordarson noted that water was perched, probably as a result of the faults pinching out at depths or along a strike.

Thordarson reports the occurrence of fracture water into several flow rate categories. These include <1, 1-5, 5-20, and >20 gal/min. The number of occurrences per category were: 117 for <1 gal/min, 41 for 1-5 gal/min, 14 for 5-20 gal/min, and 5 for >20 gal/min, (Thordarson 1965). At one location in G-tunnel at the Nevada Test Site, fracture water drained at a rate of about 0.01 gal/min (Fernandez and Freshley 1984). In making the above comparisons, it is important to note differences in conditions at Rainier Mesa and Yucca Mountain. The tunnels at Rainier Mesa are in an area of greater surface recharge and greater moisture flux in the unsaturated zone than in the proposed repository location at Yucca Mountain (DOE 1986). Tunnels that yield the most perched water were driven into zeolitic-bedded tuff that are similar to the zeolites below the repository horizon. The fractures that contained water were generally drained within days and were poorly interconnected (Thordarson 1965). By contrast, the repository at Yucca Mountain is proposed to be located in densely welded, highly fractured, Topopah Spring Tuff. Because of the pervasive and abundant fractures within the Topopah Spring welded unit, it can be inferred that the fractures are interconnected; thus, this unit is free draining (DOE 1986), and buildup of water in fractures, similar to that encountered at Rainier Mesa, is not likely in the near future.

4.2.6 Flow Into Shafts, Ramps and Exploratory Boreholes

The following analyses are presented to show the potential range of conditions that may be encountered near shafts, ramps, and exploratory boreholes in assessing the need for seals in Section 5.1 (CRWMS M&O 1997i). The actual conditions that may exist near the sealing locations in the shafts and ramps, and especially in the exploratory boreholes would depend on site-specific conditions at sealing locations. For example, it is likely that perched water would vary from location to location, and the potential inflow that might occur from perched water would vary widely. Further it is possible that perched water might develop due to episodic infiltration events, and then reduce by lateral flow at the contact zone, and potential inflows down the shafts, ramps, or exploratory boreholes would be reduced by lateral flow at the contact zone.

In the following discussion, a distinction is made between anticipated and unanticipated flow rates as was made by Fernandez et al. 1987. An anticipated event includes flow processes that are reasonably likely to occur during the time period that the repository performance objective needs to be met. Unanticipated processes are those processes and events that are less likely to occur, but which warrant evaluation as episodic events.

In the following discussion, the percolation flux that would affect flow into shafts, ramps and exploratory boreholes equals the infiltration flux. The infiltration flux rate is expected to range from 5 mm to 30 mm per year (Flint et al. 1997).

4.2.6.1 Flow into Ramps

The flow into the ramps under anticipated conditions might occur from infiltration through dominantly vertical fractures that would intersect the ramp. Under unsaturated flow conditions, with flow dominantly vertically downward, the amount of flow equals the infiltration rate times the cross sectional area intercepted by the flow. The flow is given by:

$$Q = I * A \qquad (4\text{-}11)$$

where

Q = Flow rate to the ramp
I = Infiltration rate (5 - 30 mm/yr)
A = Capture Zone for the ramp

Note that if the effective width of the flow zone is assumed to be twice the diameter of the excavation (Fernandez et. al. 1987), the estimated capture zone for partial convergence that might flow through fractures that are inclined to the tunnel can be evaluated (Figure 4-12). Considering the estimated range of infiltration rates, and the lengths of the ramps, the estimated inflow under anticipated conditions would be from 400 to 2,400 m^3 per year.[2]

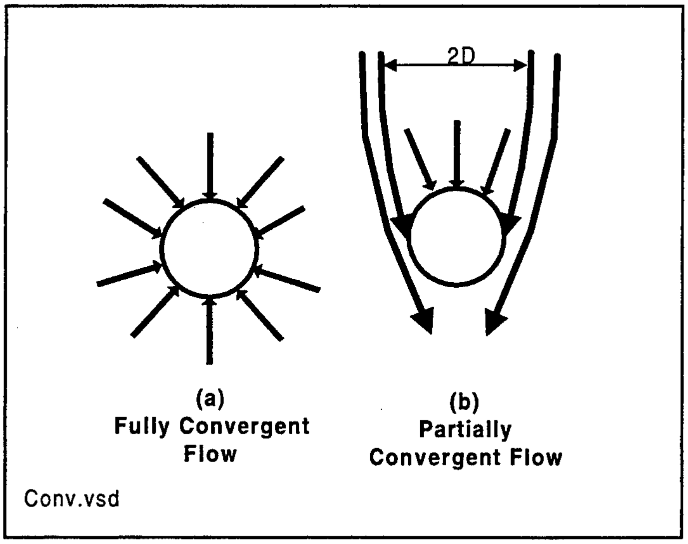

Figure 4-12. Fully Convergent or Partially Convergent Flow Toward a Tunnel

Fernandez et al. 1987 evaluated flow through faults to underground drifts or ramps under unanticipated conditions. Two cases could potentially occur, one in which the fault zone becomes saturated down to the water table producing fully convergent flow to the drifts intersected by the fault and one in which full saturation does not develop, leading to partially convergent flow under near atmospheric pressure (Figure 4-12). The scenario postulated for fault inflow presupposes there will be rainfall and subsequent infiltration in the fault of sufficient intensity and duration to saturate the fault/fracture system intersecting the ground surface.

It is unlikely that flow could be sustained over an extended period of time, and that partially convergent flow is more representative of episodic inflows through fault zones to the ramps. For partially convergent flow with flow essentially vertically downward, Fernandez et al. 1987 allowed for some convergence as in the case for anticipated flow. In the present analysis the area of influence of the tunnel is assumed to be twice the tunnel diameter. Inflow is estimated by:

$$Q = K_f \cdot A$$

[2] The analysis considers two ramps that are 2600 m long, and 7.6 meters in diameter.

where

Q	=	Flow rate through the fault (m^3/s)
K_f	=	Saturated Hydraulic Conductivity of the Fault Zone
A	=	(2D x W) area of influence (m^2)
D	=	diameter (m) of the ramp
W	=	width of fault zone (0.3 m along the ramp)

Note that the effective width of flow is assumed to be twice the diameter of the excavation (7.6 m), and accounts for partial convergence of flow through fractures as was the case for anticipated flow. Using the above relation and the Bow Ridge Fault conductivity of 0.019 cm/sec, the calculated unanticipated inflow is 27,000 m^3 per year.

4.2.6.2 Flow into Shafts

As discussed above, a major finding from investigations of the unsaturated zone is that in the alluvial areas, the infiltration into underlying formations is not significant. The current designs locate the portals to shafts away from flood prone areas or alluvial areas. Therefore, the principal mechanism for flow to reach the shafts is by direct infiltration from fractures intersecting the shaft (Figure 4-13) or from the occurrence of perched water that might result in radial flow to the shaft (Figure 4-14).

If consideration is given to a dominantly vertical fracture zone, and a capture zone radius extending out to twice the shaft diameter, the inflow rate to the shaft can be estimated as the capture zone area times the infiltration rate. The estimated flow rates for a range of infiltration rates of from 5 to 30 mm per year results in anticipated inflows of from 1 to 7 m^3 per year.

For perched water conditions, it is noted that the rate that flow could be conducted down the shaft would equal the shaft backfill conductivity times the shaft cross-sectional area. However, this flow rate greatly exceeds the potential infiltration rate.[3] This suggests for the case of shaft backfill that the perched water zone might be drained rapidly. For anticipated conditions, the radial flow rate towards the shaft would come to a flow equilibrium over the radius of influence as suggested in Figure 4-14. The radius of influence would depend on many site specific factors at the particular location; these include the contrast in permeability, the local vertical infiltration, and the lateral flow on the contact that would tend to reduce flow towards the shaft. If the capture zone is conservatively taken to be 10 times the shaft diameter, the estimated anticipated flow rate over a range of infiltration from 5 mm to 30 mm per year is from 28 to 170 m^3 per year.

Under unanticipated conditions, the flow to a shaft would be similar to that for a ramp (27,000 m^3/yr) for a vertically inclined fault or fracture zone. However, it is less likely that such flows would occur since it not as likely that the vertical shafts would intersect major fault zones.

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[3]The rate equals 90,000 m^3 per year under fully saturated conditions.

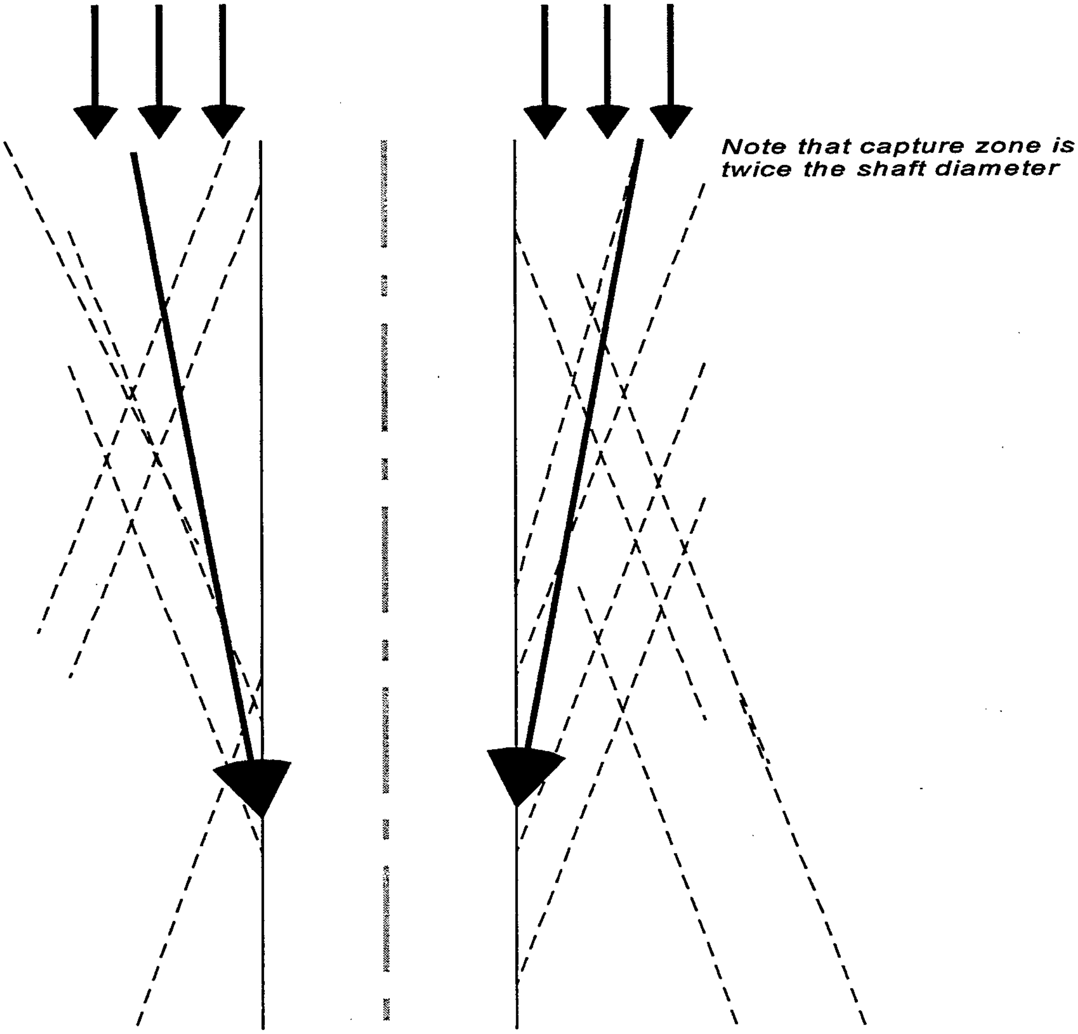

Figure 4-13. Water Flow into Shaft from Fractures

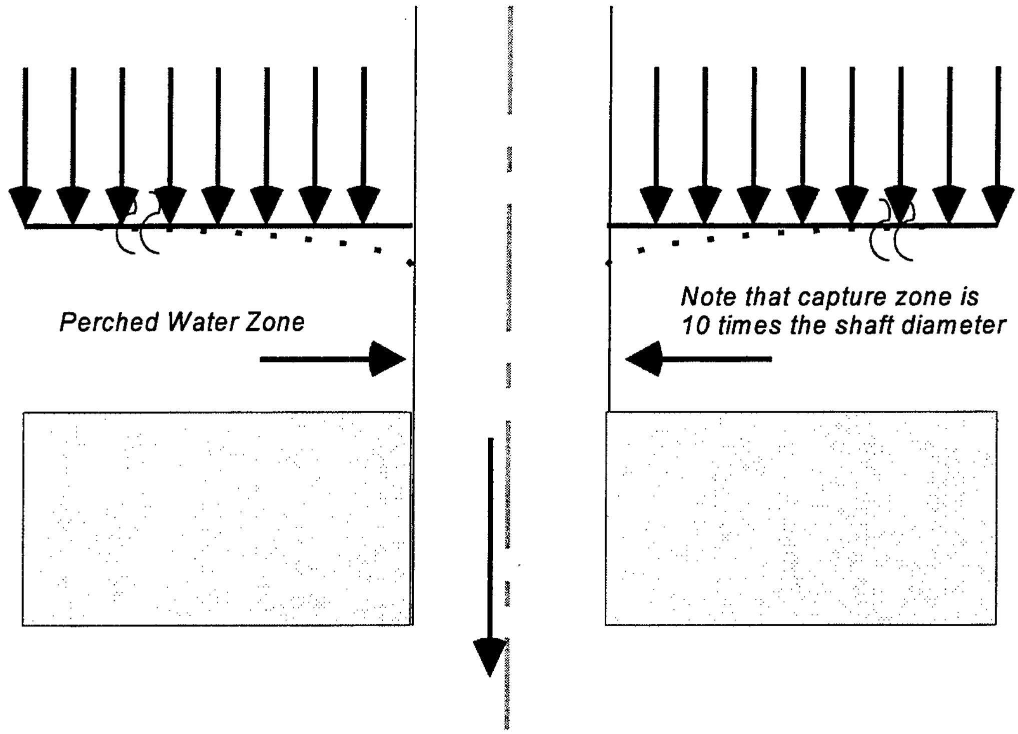

Figure 4-14. Water Flow into Shaft from Perched Water

Under unanticipated conditions, the potential exists for a rapid rise in the level of perched water at the contact zone. Bodvarsson and Bandurraga (1996) estimated the height of perched water at borehole WT-6[4] to be approximately 20 m. For convergent flow under unconfined flow conditions, the flow rate can be estimated from the relation for radial flow to a shaft under unconfined conditions:

$$Q = \pi K \frac{H^2 - H_0^2}{\ln\left(\frac{R}{r_0}\right)} \qquad (4-12)$$

where

- R = Radius of influence
- Q_s = Flow rate into the shaft
- K = Hydraulic conductivity (10^{-5} cm/sec)
- H = Piezometric level at radius R
- H_0 = Piezometric level at the shaft radius
- r_0 = Shaft radius

[4]Note that the occurrence of perched water is at a zeolitic zone or a zone below the repository. No perched water has been observed above the repository although this possibility cannot be discounted.

The maximum discharge for unanticipated flow under unconfined conditions is estimated to be 1,700 m^3 per year. This flow rate would only be sustained for short periods of time for reasons cited previously. The rapid rise in the perched water zone would be quickly dissipated by radial flow towards the shaft.

Flow to the Underground Facility

The flow to the underground repository can be conservatively evaluated assuming that water that enters that underground facility could potentially contact the waste (Fernandez et al. 1987). In the current repository design, the high temperature environment results in a zone of low moisture content, and the capillary barrier would direct water around the waste filled emplacement drifts. The amount of influx would be small under anticipated conditions while the temperature remains high.

In more recent analyses (CRWMS M&O 1995), the amount of water that potentially contacts the waste under anticipated conditions is related to the size of the waste package, and a capture zone. If the performance assessment model assumption is made that the capture zone in the underground facility equals four times the area in plan of the waste package (CRWMS M&O 1995), the total volume of water for a range of infiltrations can be calculated. The range of anticipated inflows equals 2,300 m^3 per year to 14,000 m^3 per year for the respective range of infiltration rates of from 5 to 30 mm per year.

4.2.7 Summary of Water Inflows

The ranges of potential flows to the repository are summarized in Table 4-2 for shafts and ramps, and the underground facility. The range of inflows can be compared to previous analyses that were used to evaluate the need for sealing (Fernandez et al. 1987) as shown below. The current analysis considered infiltration rates ranging from 5 mm per year to 30 mm per year compared to 1 mm per year in the previous analysis. These comparisons show:

- The previous range of anticipated inflows through fractures and perched water conditions was from 10 to 100 m^3 per year and comparable to the current range of from 28 to 170 m^3 per year. These flows are small relative to the flow capacity of the shaft backfill to conduct flow down the shaft.

- The current flows of 27,000 m^3/yr under unanticipated conditions for the shafts are somewhat smaller than previous calculations of 81,000 m^3/yr reflecting the requirement that shafts now be located out of the flood plain areas and not subject to flooding. The flows reflect potential transient flow from a perched water zone, and flow through an intersecting fault zone. The potential flow through the fault zone under unanticipated conditions reflects a high measured conductivity (10^{-2} cm/sec). Other evidence suggests that fast travel paths may exist through fracture or fault zones.

- The current flows for the ramps reflect a capture zone, and the higher infiltration rate than in previous analyses which did not include ramps.

- The current anticipated and unanticipated inflow rates to the underground facility reflect the higher infiltration rates resulting in a larger range than in previous calculations.

Table 4-2. Summary of Anticipated and Unanticipated Flow Rates[1]

Flowpath	Nature of Flow	Anticipated Flow (m^3/yr)	Unanticipated Flow (m^3/yr)
Shaft	Flow down shaft and vertical fractures	1.1 - 6.8	
	Perched water capture zone	28 - 170	1700
	Flow through intersecting fault zone		27,000
Ramp	Flow down vertical fracture system	400 - 2,400	
	Flow through intersecting fault zone		27,000
Total for shafts and ramps		400 - 2,600	
Underground		2,300 - 14,000	
	Anticipated Total Flows	2,700 - 17,600	

[1]The anticipated flows are for multiple shafts while the unanticipated flows are for a single shaft or ramp

5. REPOSITORY SEALING AND OPTIONS

This section presents a discussion of the assessment of the need for repository seals, performance allocation, and modified hydrological performance goals for the repository sealing system. Also, it provides a repository sealing strategy, and guidance for site characterization and repository design. The strategy provides guidance on where to seal, how to seal to achieve hydrologic and air flow goals, and when to seal during repository development. This section has been written with general design information based on the current repository/ESF configurations and waste emplacement concepts. The sealing concepts, configurations, and analyses presented stress flexibility and robustness and can be modified as the results of the site characterization and maturing repository design are made available.

5.1 ASSESSMENT OF THE NEED FOR SEALING

This section assesses the need to provide sealing components for air and water flow. Both shaft and ramp seals, and exploratory boreholes are evaluated. Section 3.6 evaluated the waste package performance for restricting or limiting release from the EBS to one part in 100,000 and established an allowable air flow goal for the release of gaseous radionuclides. The allowable air flow goal was established to limit flow to 5 percent or less of the flow through the rock. In Section 4.1, relationships were developed for backfill, air flow rates and the percentage of flow through a shaft to the flow through the rock. If a general backfill is selected to restrict flow to 1 percent of the flow through the rock, the required hydraulic conductivity for the backfill is 10^{-2} cm/s (Section 4.1). A backfill with a conductivity of 10^{-2} cm/s thus would suffice to restrict the release of gaseous radionuclides to within NRC limits and is recommended as a design requirement.

Under saturated conditions and flow under a unit gradient, the shaft might transmit water through such a backfill at about 90,000 m^3 per year. The analyses presented in Section 3.4 are used to develop the maximum-allowable-hydrological-performance goals of sealing components other than backfill for the sealing system. These goals can be compared with the results of the water flow analyses in Sections 4.2 and 4.3. Performance goals for backfill for the sealing system are developed separately.

Repository sealing is defined as those components that would reduce potential inflows of water above the repository, or that would divert flow near the repository horizon to allow drainage into the Topopah Spring member. The repository sealing strategy thus includes the underground design of facilities at the low end of the repository or near the base for the ramps or the shafts that would impound water, and allow drainage to occur into the underlying formation.

In this assessment, any flows that might enter the underground repository are considered to result in potential inundation, and encroachment of waste containers. Figure 5-1 presents an assessment of the need for sealing shaft and ramp components. The figure shows the range of anticipated flow from the shafts, the ramps and the underground facility for comparison to the allowable water flow goals from the EBS. The comparison shows that for the estimated range of possible flows as shown in Table 4-2, the total flow from all sources would exceed the total flow goals established from the NRC release requirements (allowable limit), and that on the basis of this comparison, the seals would be necessary.

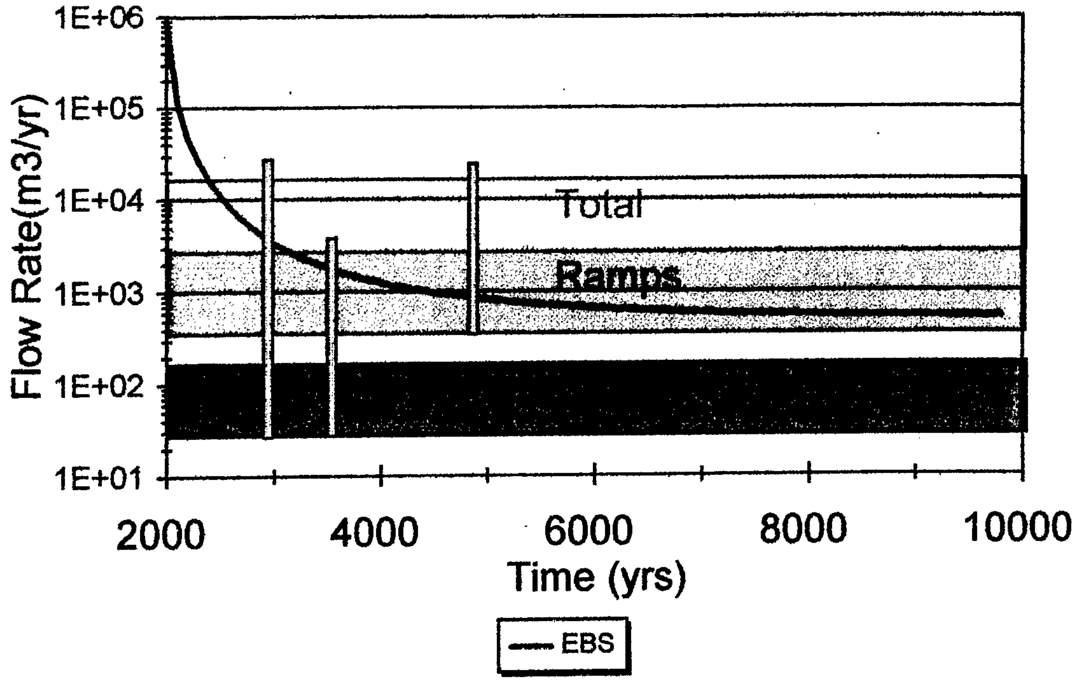

Figure 5-1. Need for Repository Sealing

The study shows that for anticipated conditions, the flows from the underground shafts and ramps at an infiltration rate of 5 mm per year would not exceed the allowable flow as determined from the requirement for release of radionuclides from the EBS. For these anticipated flows, seals would not be necessary. For the ramps, the flow rates at an infiltration rate of 5 mm per year would also not exceed the allowable water flow goal. At an infiltration rate of 30 mm per year, the allowable flow rates would be exceeded and there would be requirements for sealing components. For unanticipated flows, there is also the potential that flows through shafts and ramps could exceed the allowable water flows over short periods of time.

For deep exploratory boreholes that intersect or go below the repository horizon, the need for repository seals is established on the basis that they could represent preferential pathways from the repository horizon to the groundwater table (Figure 5-2). The potential exists for perched water zones near the zeolitized zones to conduct water and nuclides laterally to the deep exploratory boreholes below the repository horizon, and transmit water to the groundwater table.

Fernandez et al. 1994 evaluated flows through boreholes of various depths to assess the relative significance of borehole depth (Figure 5-2). It was found that for existing and proposed boreholes at that time, that flow rates through surficial boreholes were several orders of magnitude lower than for deep boreholes penetrating to the repository. It was concluded that surficial boreholes could be simply backfilled.

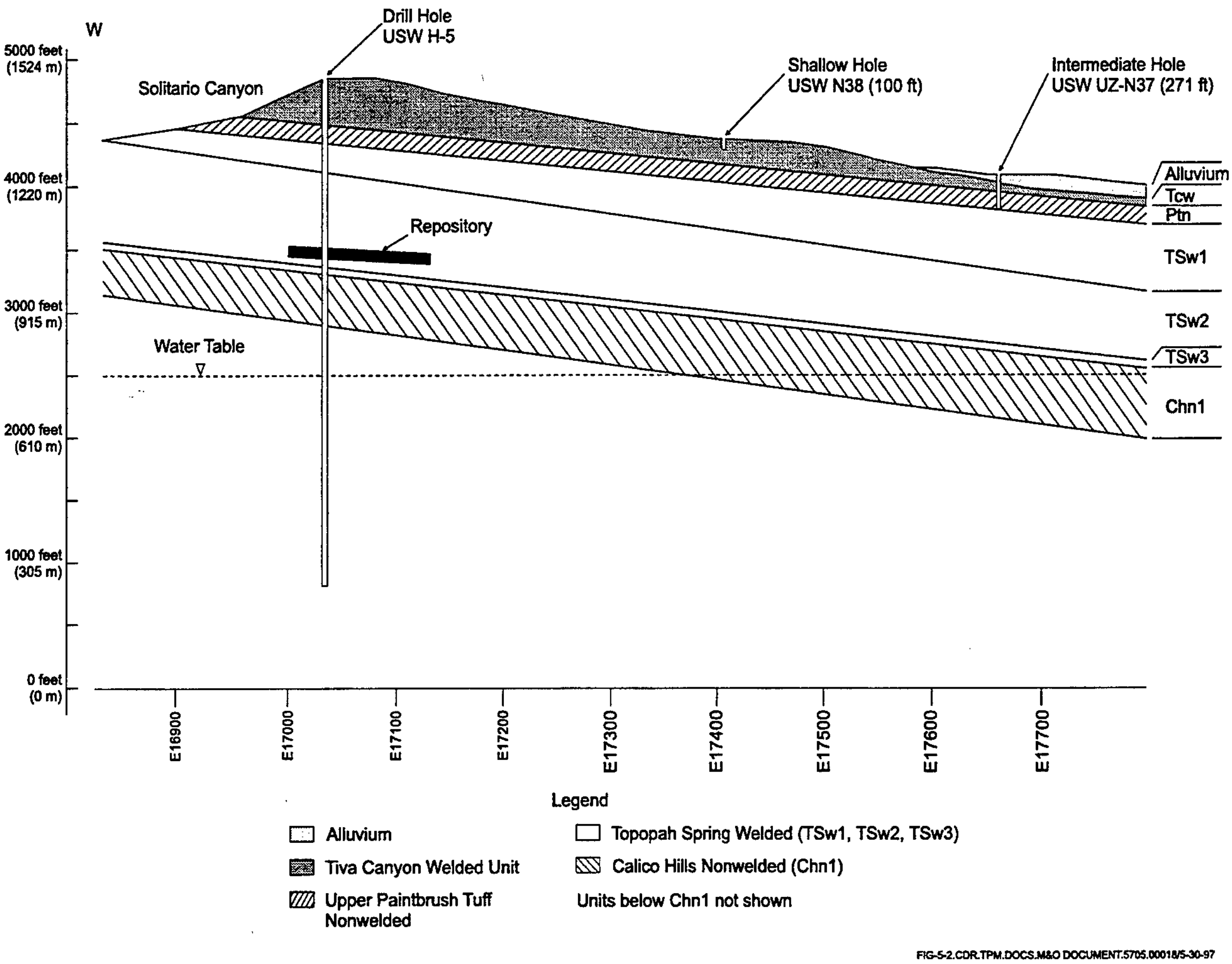

Figure 5-2. Exploratory Boreholes at Yucca Mountain

As for the previous studies (Fernandez et at. 1987, and Fernandez et al. 1994) and this study, the regulations for borehole-seal performance require that "boreholes shall be designed so that following closure they do not become pathways that compromise the geologic potential repository's ability to meet the performance objectives." The position adopted then and now is to restrict the vertical flow through the boreholes within the extended repository boundary to only one percent of the potential for water flow through the rock mass below the repository. For both boreholes and the rock mass, the effective hydraulic gradient was assumed to be one for the condition of vertical infiltration under atmospheric pressure. Considering the area within the potential repository perimeter, the potential vertical flux through the rock mass equals the effective hydraulic conductivity of rock units between the potential repository and the water table times the floor area of the potential repository drifts or more conservatively, the total area within the potential repository. The potential flow through boreholes is taken as the sum of the cross sectional areas of the boreholes within the potential repository area times the effective hydraulic conductivity of the seal material (including the effect of the seal/host rock interface).

The DOE has committed to the State of Nevada to provide plans for sealing all exploratory boreholes prior to sealing that is expected to meet or exceed the State Statues. In addition to the subsurface backfill and seals requirements within the boreholes discussed herein, the DOE will comply with State Statues for capping boreholes.

In summary, the evaluations presented above show there exists a need to provide sealing components for shafts and ramps and exploratory boreholes to either restrict flow above the repository horizon, or to divert flow near the repository horizon.

The sealing and backfilling basic objectives for compliance with the shaft and ramp and exploratory borehole sealing system design requirements and with the applicable regulations include:

- Reducing the amount of water entering the underground facility through shafts, ramps, and exploratory boreholes from the surface and fault systems.

- Placing shaft and ramp seals so that the penetrations do not become preferential pathways for radionuclide release.

- Controlling and diverting the flow of water near the base of the repository to allow drainage into the underlying formation, and to reduce the potential for water from entering waste emplacement areas.

- Restricting the gaseous flow of radionuclides out of the repository to comply with the quantitative and qualitative requirements.

- Reducing the flow through deep exploratory boreholes that might represent a preferential pathway for radionuclides from the repository horizon to the water table.

The following sections describe a performance allocation (an allocation of the allowable flow) between the underground facility and the shafts/ramps subsystems and an overall strategy to seal penetrations to the repository. Performance allocation addresses the issue of how designs for sealing components would consider the potential variability in seal performance due to variations in rock mass properties, and the repository environment.

5.2 PERFORMANCE ALLOCATION

The logic used to arrive at design options (or sealing components), goals and design requirements is presented in Figure 5-3. Performance goals are first allocated between the shafts and ramps and the underground facility subsystems. Design options are identified and the design goals are then established. These design goals can be related to the overall performance goal for the sealing system. For example, because water might (1) enter the underground repository, and (2) flow through the seal components, (3) enter waste emplacement drifts, and potentially affect overall performance, the sealing component design must be subject to performance allocation. After the design goals are selected, design requirements for individual sealing components are calculated.

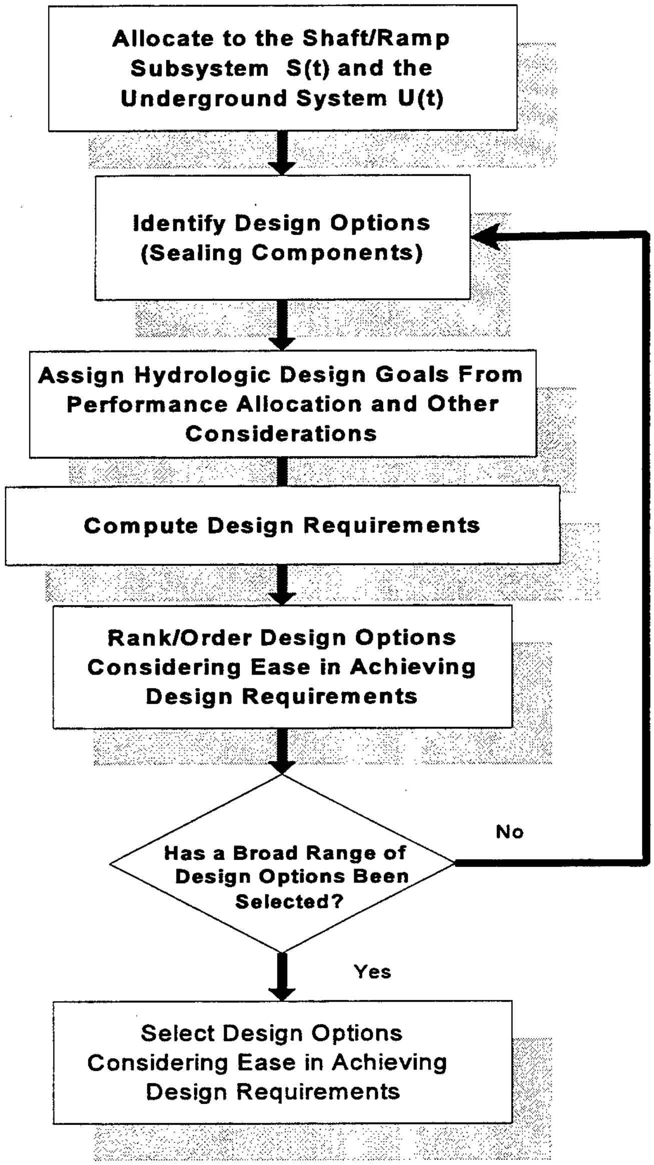

Figure 5-3. Performance Allocation for the Repository Seal System

In Section 3.4, the allowable water flow goals for the isolation system were developed. In this section, these performance goals (for specific times following closure) are allocated between the two major subsystems: the sealing components within the shafts and ramps, and sealing components within the underground facility. Note that the design of sealing or engineered barrier components within the underground facility is outside the scope of this report. However, the performance allocation includes this subsystem in order to define design requirements for the shaft and ramp sealing subsystem.

The allocation between the two major subsystems can be made using the following relationship:

$$T(t) = S(t) + U(t) \tag{5-1}$$

where

S(t) = Allowable water flow goals allocated to seals in the shaft and ramp subsystem
U(t) = Allowable water flow goal allocated to the underground facility
T(t) = Allowable water flow goals for the entire isolation subsystem

When allocating the allowable water flow goals, consider that there is potential difficulty in achieving the performance of the underground subsystem (in other words, the underground facility) in relation to the other subsystems. In determining the potential difficulty, the following were considered:

- **Uncertainty**—The uncertainty of sealing the underground is believed to be greater than the uncertainty in sealing the shafts and ramps due to the greater number of seals or engineered components expected to be required to achieve the performance goal for the underground facility. In the underground facility, the potential also exists for water to enter more directly and contact the waste. The flowpath lengths of the shafts and ramps are longer for water flow to enter the repository and contact the waste. The number and types of sealing components can thus be defined with more certainty for the shafts and ramps than for the underground facility.

- **Site Conditions**—In the underground facility, the sealing components will be subject to higher temperatures and stresses than those components in the shafts and ramps, causing higher levels of engineering design.

These considerations suggest a comparatively greater difficulty in achieving a desired performance for sealing or engineered components in the underground facility, as compared to sealing components in the shafts and ramps. Because of the greater uncertainty in the number and locations of engineered systems required in the underground facility, and the higher temperature environment, the performance goal for the underground facility was taken as the anticipated flow that could enter the underground facility (2,300 m^3/year) until the time when this flow is equal to the total allowable water flow goal calculated in Section 3.4 (see lower curve in Figure 3-12). After this time (~3,200 years after repository closure) the underground facility is assigned 99 percent of the total allowable water flow goal. This restricts the allowable flow to the shafts and ramps to 1 percent. Up to 3,200 years, the performance goal of the shafts and ramps is that portion of the total allowable flow that exceeds the 2,300 m³/year assigned as the performance goal of the underground facility. The 2,300 m³/year is the anticipated flow to the underground facility based upon an infiltration rate of 5 mm per year. The Performance Allocation for the Underground Facility and the Shaft/Ramp System is provided in Table 5-1 and shown in the curves of Figure 5-4.

Table 5-1. Performance Allocation for the Underground Facility and the Shaft/Ramp System

Time (Years)	Flow Goal (m^3/yr)	Underground (m^3/yr)	Shafts/Ramp (m^3/yr)
100	> 10^6	2,300	> 10^6
1,000	> 10^6	2,300	> 10^6
1,500	> 10^6	2,300	> 10^6
2,500	10,940	2,300	8,640
3,000	3,385	2,300	1,085
4,000	1,258	1,245	13
5,000	828	820	8
6,000	669	662	7
7,000	595	589	6
8,000	558	552	6
9,000	541	536	5
10,000	536	531	5

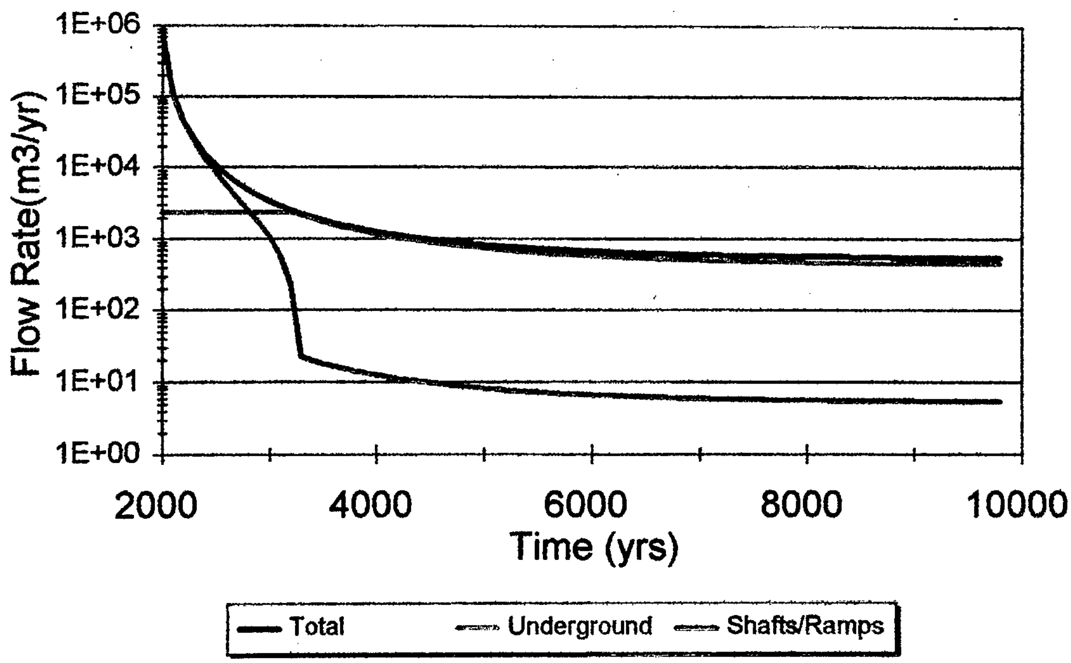

Figure 5-4. Performance Allocation

5.3 MODIFIED HYDROLOGICAL PERFORMANCE GOALS

The allowable water flow goals are modified to account for drainage at the base of the ramps and shafts. Fernandez et al. 1987, evaluated the potential storage capacities in the SCP-CDR design for different waste emplacement configurations. They found that a large volume could potentially be accommodated at the low points of the repository. Fernandez et al. 1987, considered increasing the allowable flow goal by 10,000 m^3 per year to account for this storage capacity at the repository horizon. Storage capacity is defined as a volume that could be retained, and allowed to drain into the rock in one year's time. This was the amount of water that could be stored and drained before contact was made with the waste packages.

An alternate approach is to evaluate the anticipated flows that would flow to the low point of the repository, and then to evaluate sump and drainage capacity on the basis of these flows. The maximum amount of flows considering shafts, ramps, and the underground for an infiltration rate of 30 mm per year is provided in Table 5-2.

Table 5-2. Summary of Anticipated Flows

Component	Anticipated Flow (m^3/yr)
Maximum Ramp	2,400
Maximum Shaft	170
Underground	14,000
Total	16,570

The infiltration capacity of the welded tuff at the repository horizon augments the sealing strategy of restricting flow to the repository. The actual storage capacity will be based on actual site conditions encountered as the ESF/repository is developed. The design goals for individual components can then be determined based upon the number of components needed to satisfy the performance goal for each subsystem. Expressing the modified hydrological relationships mathematically, the following relationships are obtained (CRWMS M&O 1997j):

$$Q(t) = S(t) + C_d(t) \tag{5-2}$$

$$C_t(t) = A_u(t) + C_d(t) \tag{5-3}$$

where

- $C_d(t)$ = Design margin storage capacity for the shaft and ramp seals subsystem per year,
- $C_t(t)$ = Total storage capacity for flow through the shafts/ramps, and underground facility
- $Q(t)$ = Seal design flow rate for the shaft and ramp seals subsystem,
- $A_u(t)$ = Anticipated flow from the underground system, (14,000 m^3/yr from Table 5-2)
- $S(t)$ = Allowable water flow goals allocated to seals in the shaft and ramp seals subsystem

The above design relations provide a flexible approach for developing design margin storage capacities and sealing requirements for the shaft and ramp seals subsystem. Figure 5-5 shows the relationship of required seal flow rate to design storage capacity at an early time following repository closure of 2,500 years when the total allowable flow can be high and for a time of 10,000 years when the allowable flow is small and most all of the allowable flow is allocated to the underground facility (99%). For example at 2,500 years after closure and considering a small design margin storage capacity of 3,500 m^3/year, the seal design flow requirement would be 12,140 m^3/year (Equation 5-2 or Figure 5-5) (CRWMS M&O 1997j). The total storage capacity required in the repository calculated from Equation 5-3 would be 17,500 m^3/year (3,500 + 14,000). Note that after 10,000 years, the seal design flow requirement would reduce to only about 3,500 m^3/yr (Equation 5-2 or Figure 5-5) and it would be nearly equal to the design margin storage capacity considered because the shafts/ramps system performance allocation (S(t)) is only 5 m^3/yr at 10,000 years (see Table 5-1).

If the design margin storage capacity of the shaft and ramp system is increased to 35,000 m^3/year (factor of 10 increase), the shaft/seal design flow requirement can be relaxed to permit greater flow through the seals (i.e. less stringent seal requirement) to 43,637 m^3/year at year 2,500 or 35,005 m^3/yr at year 10,000 after closure.

The relationship between the modified allowable water flow goals or the design flow rates for the shaft and ramp seal system as a function of time is presented in Figure 5-6. The analysis shows that the design requirement for the shaft and ramp seals subsystem is dominated by the performance of the EBS at early times from 2,000 to 3,500 years, and then by the design margin storage capacity of the shaft and ramp seals subsystem at later times.

For a shaft or ramp located near the low end of the repository, the design margin storage capacity could be incorporated into underground layout at the low end of the repository. Alternatively, drainage through sumps and the ramp floor could be used to provide the design margin storage capacity since a principal sealing strategy is to accommodate the infiltration into the Topopah Spring unit at the repository horizon. Sumps have potential for drainage near the base of the shafts or ramps. The Glover Solution (Fernandez et al. 1987) is a closed form solution for flow from a shaft or borehole. Drainage to the surrounding fractured tuff after standing water develops is evaluated for open or unlined shafts (CRWMS M&O 1997k). The Glover Solution is given by:

$$Q = K\,C_u\,r\,H \qquad (5\text{-}5)$$

$$C_u = \frac{2\pi\left(\dfrac{H}{r}\right)}{\operatorname{asinh}\left(\dfrac{H}{r}\right) - 1} \qquad (5\text{-}6)$$

where

Q = Flow rate
K = Hydraulic conductivity
r = Radius of the shaft
H = Height of the sump

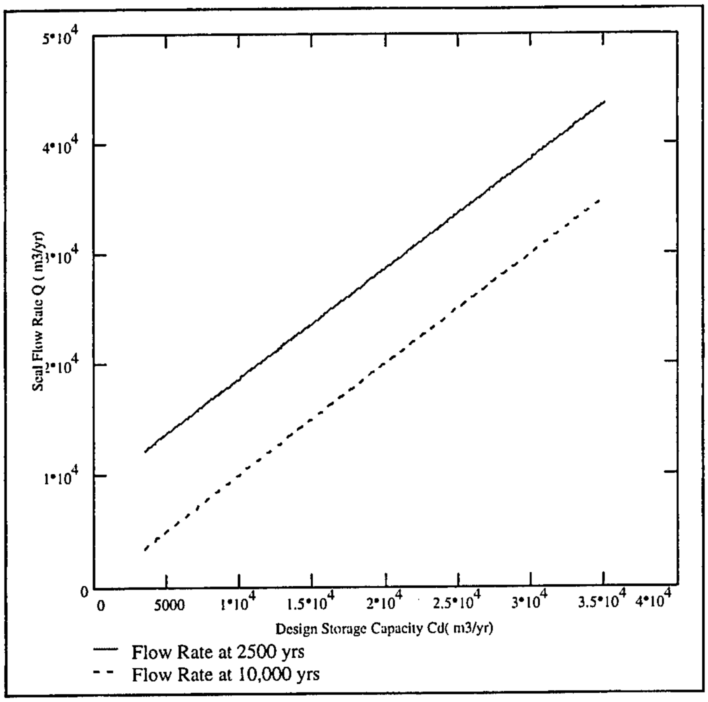

Figure 5-5. Design Flow Rate as a Function of Design Storage Capacity

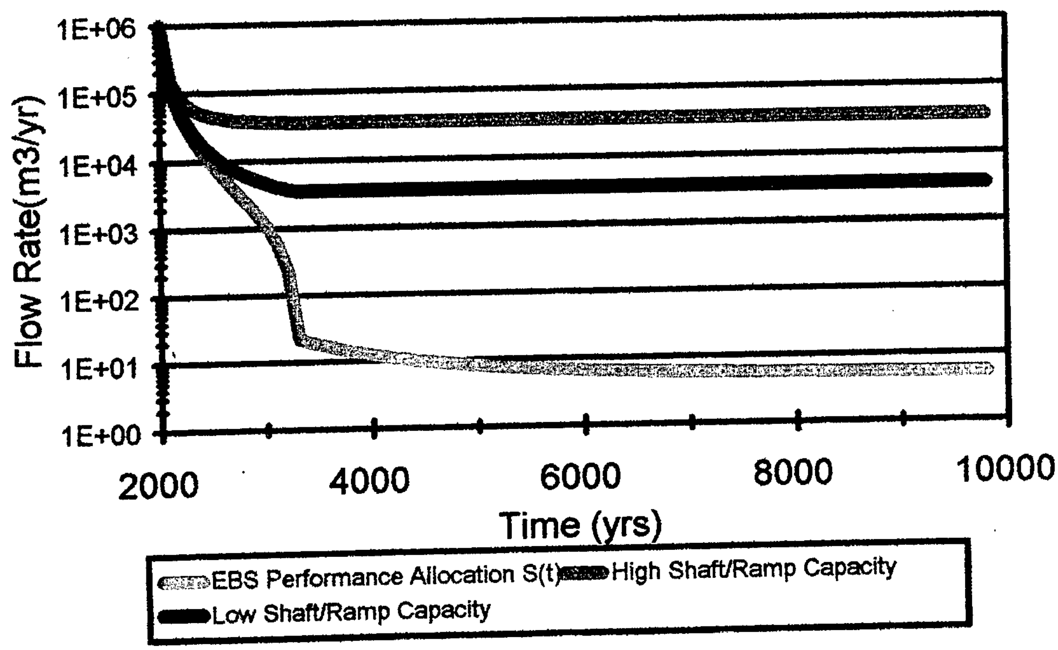

Figure 5-6. Modified Flow Rates for the Shaft/Ramp Seal System

The analyses suggest that the sump could be selected to provide drainage at the base of the repository.

Drainage through the floor of a ramp can be estimated from Darcy's law using an equivalent, porous-medium, saturated hydraulic conductivity to account for fractures. Under saturated conditions after steady state flow has been reached, the drainage is estimated by:

$$Q = K \cdot A \tag{5-7}$$

where

Q = Ramp floor drainage,
K = Hydraulic conductivity of the fractured tuff, and
A = Floor area.

Because the bulk rock conductivity varies due to the density of the fractures in the rock a range of bulk rock conductivities was investigated.

The shaft and ramp drainage is presented in Figures 5-7 and 5-8 respectively, over a range of rock conductivities from 10^{-6} (low) to 10^{-4} (high) cm/s. The analysis shows that enhanced drainage can be easily attained.

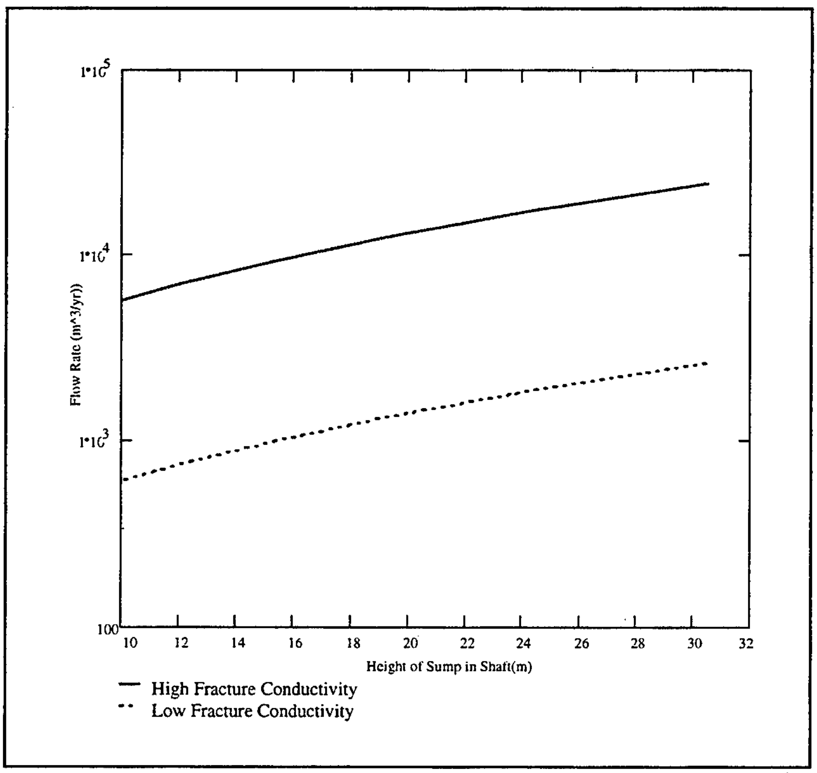

Figure 5-7. Shaft Sump Drainage

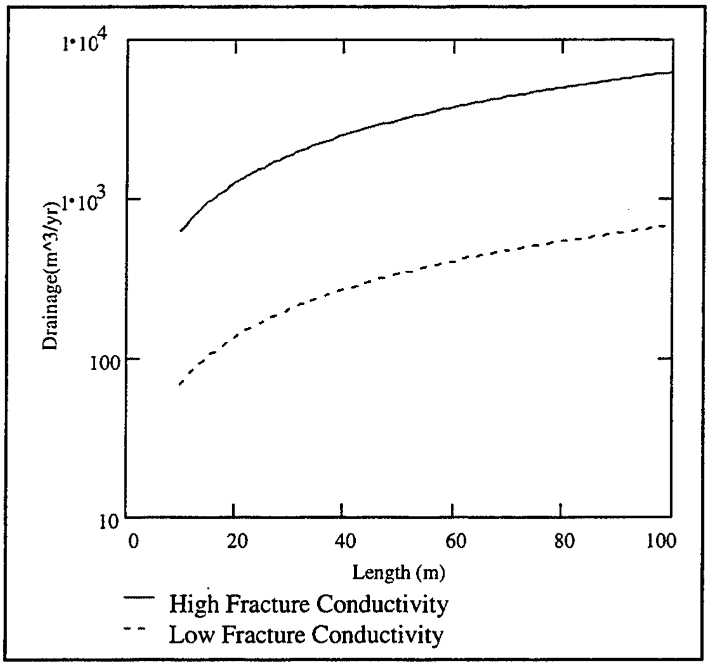

Figure 5-8. Ramp Floor Drainage Capacity

The design goals as a function of time for the shaft and ramp seals subsystem are evaluated at repository closure and may be stated as

$$DG_a(t) = \frac{Q(t)}{X_a} \tag{5-8}$$

where

Q(t)	= Seal Design flow rate for shaft and ramp seals subsystem
$DG_a(t)$	= Design goal of a specific seal component at time t
X_a	= Number of shafts and ramps accessing the repository

In Section 5.4.3 various sealing concepts are presented for consideration. The components include an anchor to bedrock plug located at the contact zone between the TCw and the alluvium, upper seals located in PTn and TSw, and backfill.

The sealing objectives can be accomplished through the placement of shaft and ramp seals to limit the water that can enter the repository via man-made penetrations. The provision of sump drainage immediately below the repository horizon will divert any water entering from the shaft away from the waste emplacement areas. Table 5-3 presents the design requirements for the seals at two extreme times of 2,500 and 10,000 years after closure showing the range of the requirements. Note that the larger performance goal at year 2,500 is due to the engineered barriers being still intact and hence little release of radionuclides occurs at this time as compared to the release from the waste package

Table 5-3. Summary of Hydrologic Design Requirements for the Shaft and Ramp Seals

Item	Flow Rate 2,500 Years After Closure	Flow Rate 10,000 Years After Closure
EBS Performance Allocation	8,637	5
Storage	35,000	35,000
Modified Performance Goal	43,637	35,005
Number of Shafts/Ramps	4	4
Design Goal for Components	10,909	8,751

at 10,000 years. A design margin storage capacity shaft and ramp system of 35,000 m^3/yr, is considered with access to the repository from two shafts and two ramps.

If consideration is given to four shafts and ramps, and the design of a seal near the base of the repository that is approximately 9 m long under a hydrostatic head of 370 m, the required hydraulic conductivity is 10^{-6} cm/s to restrict flow to 3,500 m^3 per year. For an order of magnitude increase in flow rate, 35,000 m^3 per year, the required hydraulic conductivity is 10^{-5} cm/s which would be more easily achieved. These sealing requirements are flexible such that flow rates and total storage capacities can be selected.

5.4 REPOSITORY SEALING STRATEGY AND PREFERRED OPTIONS

The following discussion presents a repository sealing strategy for where, when and how to seal the shaft and ramp system and exploratory boreholes. The strategy addresses specific technical issues that have been identified and evaluated for the repository design studies.

5.4.1 Where to Seal

This section presents a discussion of the seal locations within the shafts, ramps, and exploratory boreholes. The discussion considers existing information on developing categories for boreholes from the surface based exploratory borehole program and how this information is applied to the selection of sealing locations.

The general locations of exploratory borehole seals or shaft and ramp seals are based on the assessed condition of borehole walls from video logging of existing exploratory boreholes penetrating through the welded and nonwelded tuffs (Fernandez et al. 1994). Borehole video logs have been previously reviewed in detail, and sections of the boreholes were placed in categories as shown in Table 5-4.

Table 5-4. Categories of Boreholes (After Fernandez et al. 1994)

Category Criteria	Description
C1	Excellent, typically symmetrical hole with a smooth surface; no hole enlargement; no to few lithophysae; no pronounced fractures; minor "pluckouts."
C2	Good, typically symmetrical holes with a smooth surface; hole enlargement small or intermediate but infrequent; no to few fractures; uniform lithophysae can be present.
C3	Poor-- typically a rough surface; hole enlargement is intermediate and frequent, but it is possible for hole to be symmetrical; lithophysae can be prevalent, large, and nonuniformly distributed; fractures are frequent.
C4	Extremely poor, typically a nonsymmetrical hole having an extremely irregular surface; hole enlargement is large; large lithophysae can be present; fractures are frequent and pronounced.

Based upon these categories, the generalized hole conditions found were as follows:

- Most of the Categories C3 and C4 occur in the densely welded, devitrified tuff in the Tiva Canyon and Topopah Spring units.
- Category Cl occurs in the Paintbrush nonwelded tuff.
- Categories Cl and C2 occur in the upper portion of the Topopah Spring unit.
- Categories Cl and C2 occur in the nonwelded vitric and zeolitic portions of the Calico Hills unit.

These evaluations suggest that in order to meet the sealing requirements developed in the previous section of this report, shaft and ramp seals should be placed in the Paintbrush nonwelded tuffs, and in the upper portion of the Topopah Spring unit. Exploratory boreholes seals as discussed subsequently, should be placed in the nonwelded vitric and zeolitic portions of the Calico Hills unit outside the high temperature zones of the underground repository.

Upper seals include seals emplaced in the Paintbrush and the top of the more fractured Topopah Spring unit to reduce the entry of water from a shallow fracture system, and backfill to provide a capillary barrier for unsaturated flow. While borehole classifications show more favorable conditions in the nonwelded tuffs that are relatively free of fractures, the assessed rock-mass strength for nonwelded tuffs is lower. The potential exists for induced fracturing from drilling in the lower strength nonwelded tuff. The borehole classifications show that sealing locations with high rock mass quality can be selected in both the Paintbrush and the top of the more fractured Topopah Spring unit. Seals placed in these locations would provide redundant design for flow in the upper zones from direct infiltration of water in fracture zones, or from perched water.

5.4.1.1 Exploratory Borehole Sealing Locations

The strategy for sealing the exploratory borehole system (boreholes of concern, the current concepts for sealing exploratory boreholes, and methods of seal emplacement) has been described previously by Fernandez et al. 1994. These exploratory boreholes range from shallow (penetrating into alluvium only) that would only require backfilling to deep (penetrating into the groundwater table) that would require sealing. The current repository design intersects several deep existing boreholes that require sealing.[1] The primary areas in which to place borehole seals are: (1) away from high-temperature zones to prevent degradation of the cementitious materials. This would be in the PTn nonwelded tuff at a vertical distance from the repository horizon; (2) the upper portion of the Topopah Spring unit, and (3) in the tuffaceous beds of the Calico Hills unit.

5.4.1.2 Upper Shaft/Ramp Sealing Locations

A number of redundant seals are proposed for the shaft and ramp system. These sealing locations are illustrated in Figure 5-9.

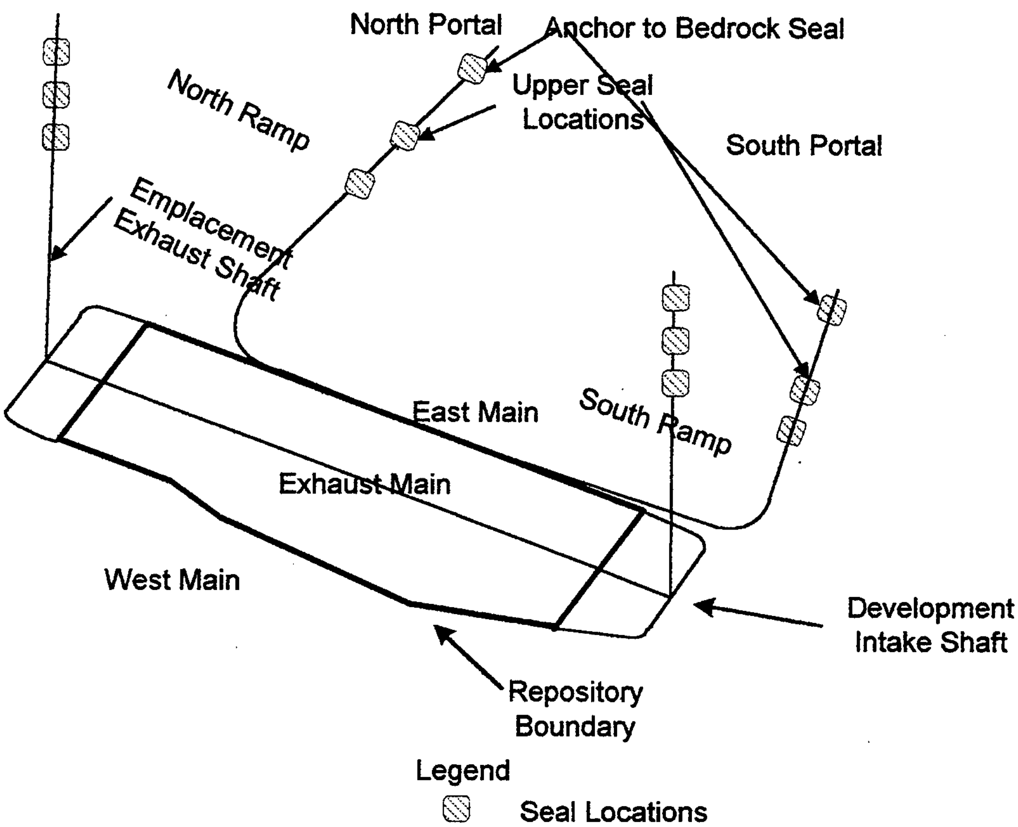

Figure 5-9. Repository Sealing Locations

[1] Note that the exploratory borehole program and repository may change resulting in more or fewer boreholes being intersected.

The proposed designs for the various shaft and ramp seal components include the following options:

- Anchor-to-Bedrock Plug is located in the TCw, and would be protected from surface temperature and superficial geologic processes. The objective of this plug would be to limit direct surface water infiltration.

- Upper Seals are located in the PTn and TSw formations. As discussed below, these sealing locations are selected based upon rock mass quality and the assessed conditions from borehole logging, and upon restricting flow from the potential perched water zone of the PTn.

- Shaft/ramp Backfill selected with a backfill hydraulic conductivity of 10^{-2} cm/s or less (Discussed per the airflow calculation of Section 4.1).

There is potential for surface water to enter by direct infiltration into the dominantly vertical fracture system that in turn could enter the ramps. The imbricate fault zone or the Bow Ridge Fault Zone represents such a fracture system for the North Ramp. For potential flows from these zones, two redundant seals located in the bedded tuffs (Figure 5-10) that are relatively free of fractures, and in the top of the Topopah Spring unit welded tuff are proposed. These seals would prevent water from fault zones from entering the ramps. Also, these seals would prevent perched water, that might form near the contact zone, from entering the ramps, and encourage the lateral flow of perched water to the east of the repository on this contact zone.

5.4.2 When to Seal

For shafts and ramps that provide access for materials handling and ventilation of the repository, seals would be constructed upon retreat from the repository. For borehole seals, access needs to be maintained at preferred sealing locations to prevent potential collapse of the casing, accelerated corrosion of casing due to collapse of the formation around the casing (which would result in higher corrosion rates than those for atmospheric corrosion), and due to potential synergistic effects between stress and corrosion. Further, the potential collapse of the borehole after casing removal and just prior to seal emplacement needs to be prevented.

The high-temperature environment at the potential repository horizon could result in casing failure prior to sealing or in failure of the open borehole during sealing; this would limit access to the lower sealing locations. Even for cased boreholes, the high temperature environment might increase formation stress and result in formation collapse against the casing and accelerate corrosion. These considerations suggest casing removal and seal placement prior to waste emplacement to assure the placement of high-quality seals.

In some cases exploratory boreholes may be used for performance confirmation testing after waste emplacement. For existing boreholes, studies will be conducted, and certain borehole casing may be reworked to assure casing integrity prior to seal emplacement. If certain deep exploratory boreholes are intended to be used for post waste emplacement monitoring within the waste emplacement areas, a separation distance between the borehole and the nearest waste emplacement drift should be maintained to assure borehole stability.

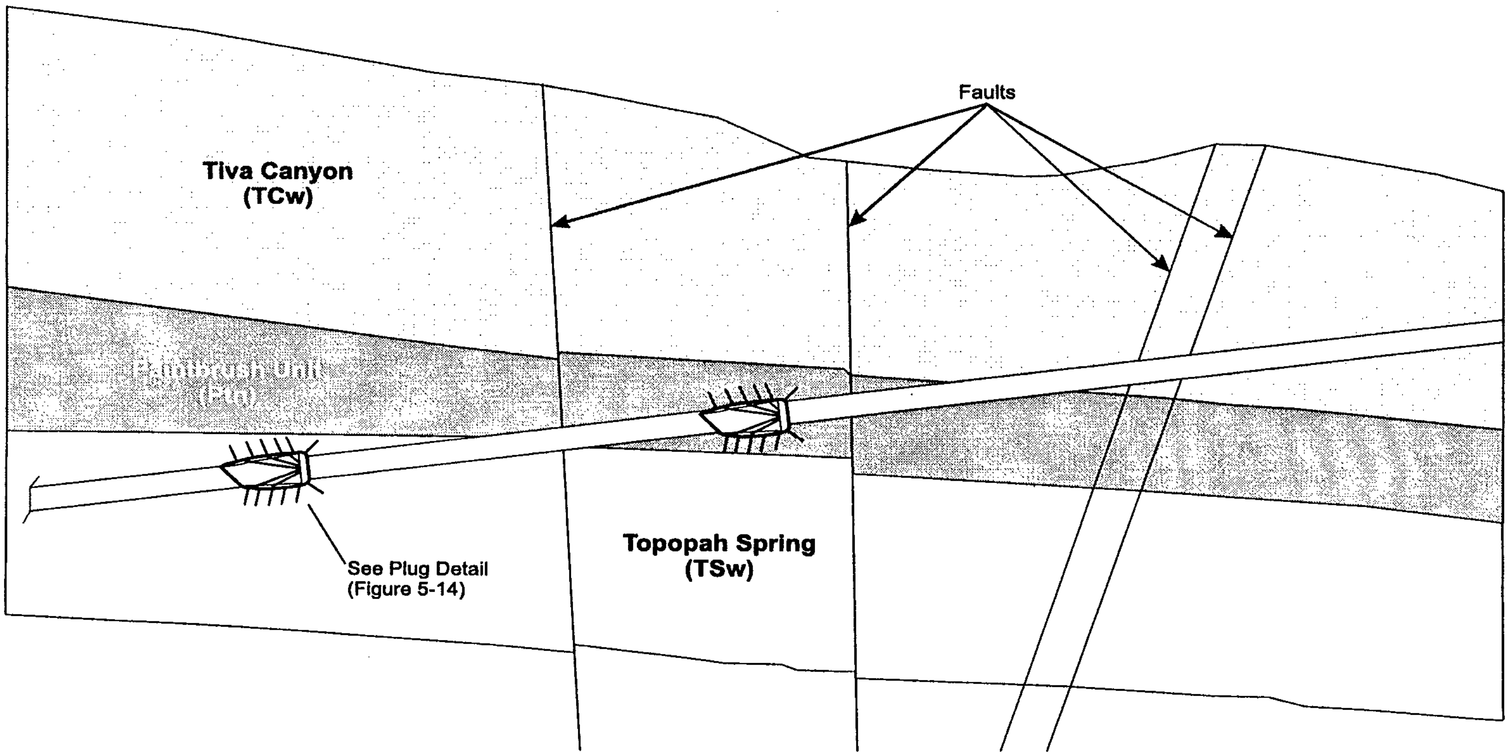

FIG-5-10.CDR.TPM.DOCS.M&O.DOCUMENT.5705.00018/5-29-97

Figure 5-10. Locations of Upper Ramp Seals

5.4.3 How to Seal

A conceptual model for flow through a seal system is presented in Figure 5-11. The flow paths include the seal itself (seal matrix), the interface zone, and the surrounding MPZ. Flow could occur through the interface zone between the seal matrix and the host rock. Flow could also occur in a zone of increased permeability that develops due to excavation and stress relief across fracture systems.

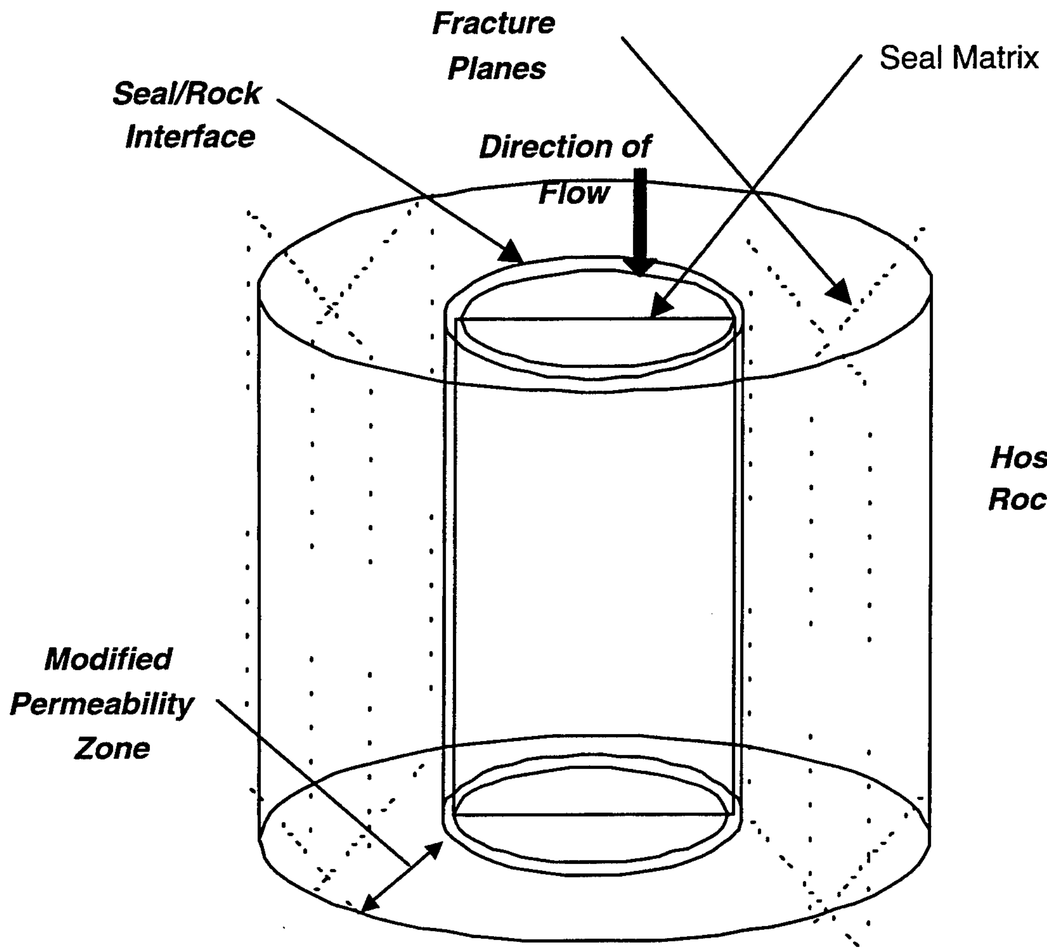

Figure 5-11. Conceptual Model for Flow through a Repository Seal

For boreholes, laboratory tests (Fernandez et al. 1994) showed the importance of the interface-zone permeability (DOE 1988). For sealed boreholes, flow occurs either through the seal matrix or through the interface zone. These tests showed that the "effective plug permeability" for flow through the interface zone to be 1 to 2 orders of magnitude greater than the permeability of the seal material. This result supports the theory that the interface zone behaves like a fracture, in that at low effective stress levels, the interface opens and exhibits high conductivity. At higher stress levels, the interface closes and exhibits a much lower conductivity that is independent of effective stress.

The excavation of underground shafts and tunnels creates an MPZ in the rock mass surrounding penetrations (see Figure 5-11). The extent and nature of the MPZ is not well known at this time, however, information regarding the MPZ will be obtained during site characterization and ESF construction. To restrict interface flow and flow in the immediate surrounding formation, the MPZ would be treated by pressure grouting at specific seal locations.

It is postulated that the dominant processes which may lead to the MPZ of the rock mass are stress redistribution and damage by excavation. It should be noted that while care might be taken to limit damage due to mechanical excavation, the redistribution of stress will occur regardless of the excavation method used. The redistribution of stresses around an opening in fractured tuff might affect the permeability of the rock mass in two ways; namely, (1) by the fracturing of intact rock due to excessive compressive or tensile stresses, and (2) by the opening or closing of preexisting fractures due to changes in the normal stresses acting across the fractures, or to shearing along the fractures. Case and Kelsall (1987) postulated that these mechanisms for modifying permeability would occur in fractured, welded tuff. Figure 5-12 shows the results of their analysis for relative permeability, which is defined as the permeability of the rock mass divided by the in situ permeability. The results of their analysis suggest that MPZ due to stress relief might be one to two orders of magnitude greater than the undisturbed rock.

The conceptual design of the shaft and ramp seals involves primary grouting to restore the MPZ, the construction of a plug consisting of cementitious and/or earthen materials, and secondary grouting of the interface zone (for cementitious materials) that would reduce permeability of the interface zone.

The selection of materials for grouting, the plug materials, and plug length can be made based on simple hydrologic models. The effective seal conductivity is expressed as an equivalent hydraulic conductivity for the seal, the interface zone, and the surrounding MPZ. The overall hydrologic performance of the shaft and ramp seals can be enhanced by increasing the plug length.[2] For example, since flow is proportional to the effective seal conductivity and inversely proportional to plug length, an order of magnitude increase in plug length results in an order of magnitude reduction in the conductance of the seal.

The potential repository sealing program concentrates on selected cementitious and earthen-based materials for sealing applications (Fernandez et al. 1987; Hinkebein and Fernandez 1989). Cementitious materials are the primary materials that have been considered for fracture grouting and borehole, shaft and ramp seal emplacement. The use of smectite clays (bentonite) is also being considered, because it may possess longevity as it is a ubiquitous alteration product at Yucca Mountain. There are two zones of abundant smectite: one is at the top of the vitric, nonwelded base of the Tiva Canyon that contains 7 to 35 percent smectite, and the other is at the tops of the basal vitrophyre of the Topopah Spring Member that contains 5 to 45 percent smectite (Bish and Vaniman 1985). The discussion below summarizes the logic that was used to select specific, cementitious and earthen materials.

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[2]The flow resistance is proportional to plug length; an order of magnitude increase in plug length results in an order of magnitude increase in the permissible conductivity for a specified flow rate.

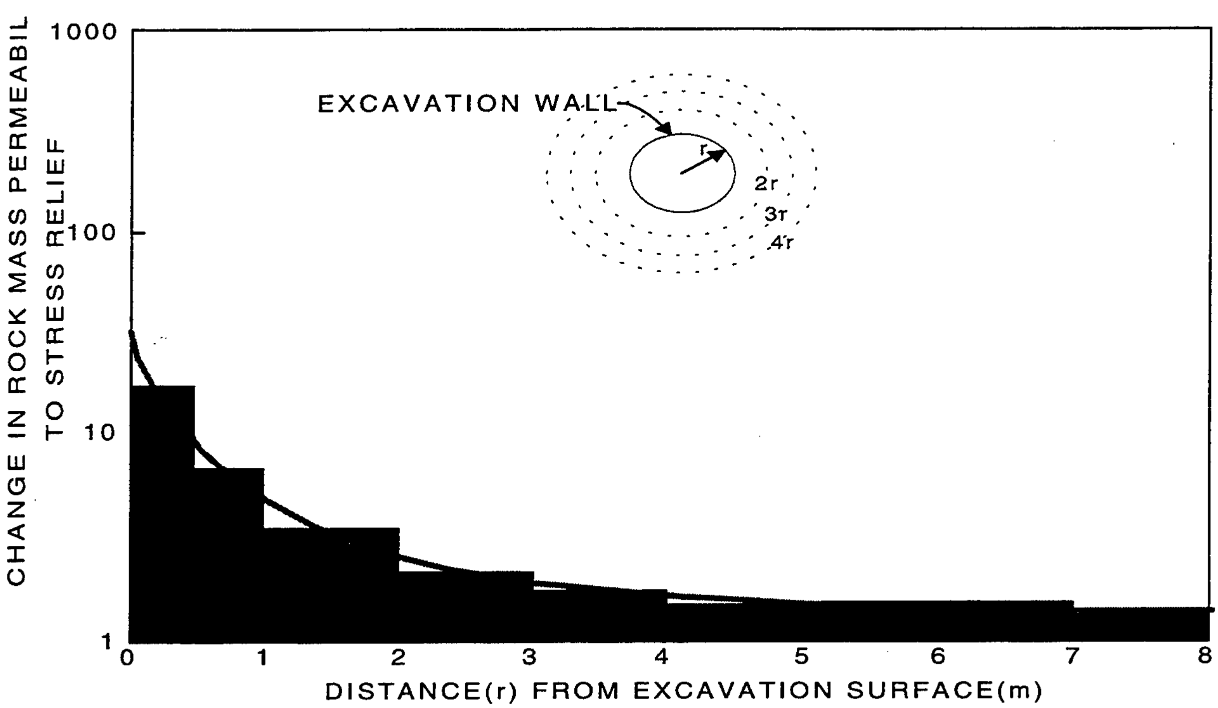

Figure 5-12. Modified Permeability Zone in Welded Tuff
(Modified from Case and Kelsall 1997)

The current concepts for sealing exploratory boreholes can be traced back to the early repository-sealing program for the Office of Nuclear Waste Isolation (Kelsall et al., 1986). The concepts are based on the requirement of 10 CFR 60.134 that boreholes should not become preferential pathways for radionuclide migration that was generic to different rock types. Kelsall et al. (1986) developed the concept that water flow in boreholes should be limited to a small percentage of the total flow occurring through the repository host rock formation. The percentage would be selected on the basis of conservatism and engineering judgement.

Fernandez et al. (1987, 1994) presented the sealing requirements for exploratory boreholes that adopted the "preferential pathways" criterion as stated above but refined the conceptual design for borehole seals based upon exploratory borehole classification, and the selection of sealing locations. The evaluations in this report suggested that sealing locations could be selected in relatively unfractured rock below the repository horizon. This led to the development of performance goals and conductivity of the seals considering interface zone flow, and the seal matrix flow.

This report presents recommended requirements for borehole sealing that are based on Fernandez et al. 1994. It used expert engineering judgement and conservatively recommends requirements to restrict water flow in boreholes to one percent of the potential for water flow through the rock.

The one percent criterion can be translated to an effective seal conductivity (CRWMS M&O 1997o) for the current set of deep boreholes penetrating the repository block. If consideration is given to unsaturated flow through the rock mass ranging from 5 to 30 mm per year, and the potential occurrence of perched water near seals in exploratory boreholes, the calculated effective seal permeabilities range from 10^{-4} to 10^{-3} cm/s. This is considered achievable.

A borehole sealing criterion based upon a percentage of the potential flow through the rock, the borehole-sealing requirement provides flexibility as new information is developed about flow in the unsaturated zone at Yucca Mountain. If additional boreholes are identified within the repository block, the permeability would become more stringent. Since flow in boreholes is limited to a small percentage of the flow through the rock mass, total systems performance should not be affected by the presence of sealed boreholes since flow through these sealed boreholes is not significant.

5.4.3.1 Cementitious Materials

Unlike the smectite clay, the cementitious materials, including the grouts, are not native to the volcanic tuffs at Yucca Mountain. The potential repository sealing program developed cementitious materials that are similar in bulk chemistry to the tuff forming more stable calcium-silica-hydrate (C-S-H) (Licastro et al. 1990). The strategy to increase long-term durability by minimize the presence of the expansive agent ettringite and reduce the presence of calcium hydroxide by including reactive silica to form a C-S-H such as tobermorite.

Geochemical analyses were conducted on three cementitious materials in the presence of water and tuff (Hinkebein and Gardener 1991) at temperatures ranging from 25°C to 76°C. Two of these materials were variations of an ordinary Portland cement (OPC)-based concrete. One material was a variation of an ettringite-rich concrete. The analysis showed that OPC containing a balance of calcium and silica produces the least volume change. The analysis suggests the least modification to the overall structure and the resulting permeability for the OPC balanced cement.

Two possible cementitious formulations are presented for sealing the repository, a standard grout formulation for sealing fractures with apertures greater than 1 cm and borehole seals, and a standard concrete formulation for placement in the larger cross-sections of the boreholes. Formulation 84-12 (Licastro et al. 1990) was used as a starting point for the cements. Changes were then made to the formulations to achieve the geochemical goals defined previously.

5.4.3.2 Earthen Seal Materials

Fernandez et al. 1987, presented a review of the hydrologic properties for crushed tuff and rock-clay mixtures. A wide range of properties can be obtained depending on particle size distribution, clay type and content, water content, and degree of compaction. Values for conductivity range from 100 cm/s to 10^{-5} cm/s. Fernandez et al. 1987 also discussed the addition of 30 percent bentonite for a variety of materials resulting in the achievement of hydraulic conductivities of 10^{-10} cm/s.

For tuff/clay mixtures, the primary factors controlling hydraulic conductivity are the type and percentage of clay, degree of saturation, and the degree of compaction. The addition of clay results in a large reduction of hydraulic conductivity. Hydraulic conductivity values of the order of 10^{-7} cm/s can be achieved with all clays with low to moderate clay contents.

A crushed tuff backfill consisting of the Topopah Spring tuff plus a smectite clay would be beneficial for redundant seal components if the repository were to experience saturated conditions in isolated areas. At saturated or near saturated conditions, clinoptilolite forms increasing the volume and decreasing the hydraulic conductivity of the backfill. A decrease in grain size, pore size, and a decrease in the hydraulic conductivity will limit the flow of water in the backfill and will prevent the backfill from becoming a preferential pathway for flow. Under unsaturated or dry conditions, a backfill consisting of crushed Topopah Spring tuff would be desirable since clinoptilolite will not form and the volume of the backfill may decrease. This would increase the porosity of the backfill and provide a capillary barrier to unsaturated flow as noted previously. For saturated flow, the use of crushed Topopah Spring tuff plus a smectite clay for a sealing material would reduce hydraulic conductivity to the degree necessary for sealing.

5.4.3.3 Possible Design Options for Shaft/Ramp Seals

Seal locations, material properties, and placement methods for shaft and ramp seals can be selected that provide adequate structural serviceability for sealing components to resist various loading combinations. These loading combinations include:

- Static loads from overlying seal materials and interactions with the host rock.
- Thermal loads due to the hydration of the cement and radioactive waste decay.
- Settlement of backfill, due to seismic events.
- Differential volumetric expansion or contraction, due to placement methods, cement hydration, temperature changes, and differences in selected material properties.

Either cementitious materials, or earthen materials or combinations for redundancy can be used for the shaft and ramp seals. Cementitious materials would provide both hydrologic flow and structural load resistance (Figures 5-13 and 5-14). The construction sequence for shafts and ramps includes grouting the MPZ, removing the shotcrete lining, or artificial support, constructing the seal, grouting the interface zone, and then resuming backfilling. Note that the option to install keys for seals would be evaluated through design tradeoff studies. Primary grouting would be performed prior to lining removal. After primary grouting, the ramp lining or artificial support would be removed at the seal locations and the primary seals emplaced after backfilling to the lower side of the seal. The seal concrete is placed in one or a few continuous pours with cold joints normal to the direction of flow. Water may be circulated to reduce temperatures in the concrete during the cement-hydration stage. Alternatively, the placement temperature may be lowered by cooling the aggregate. The interface zone could be contact grouted following emplacement of the seal. Additional stages of grouting with higher pressures and with finer grouts might be employed as required.

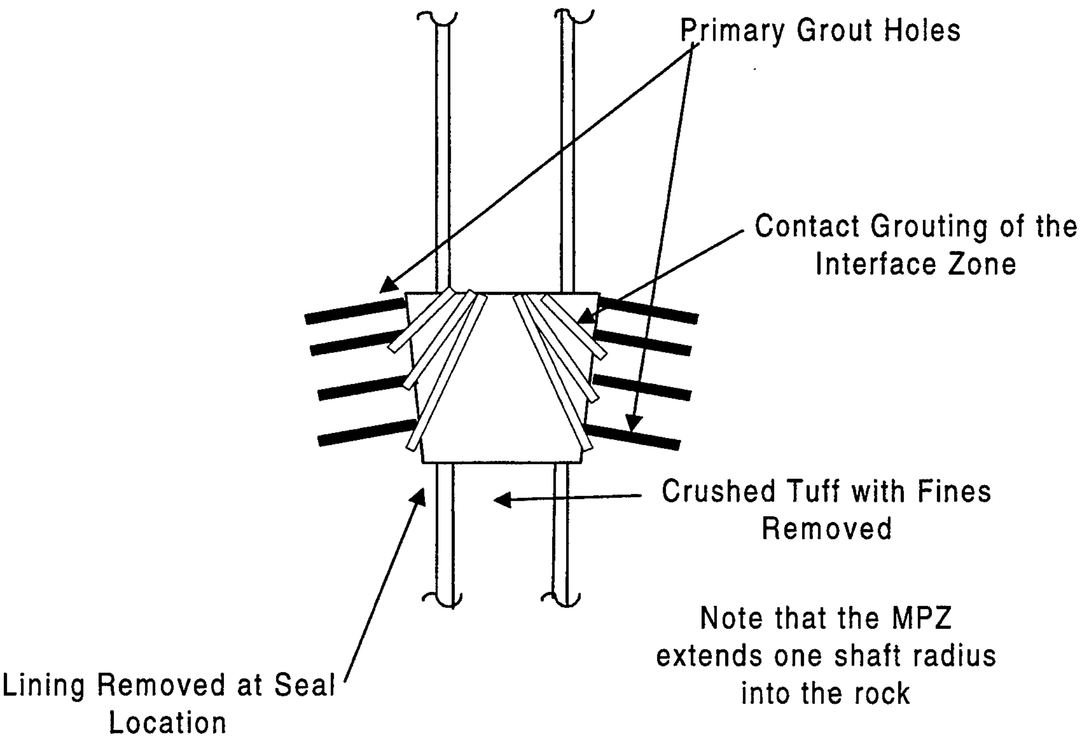

Figure 5-13. Conceptual Design for a Shaft Seal

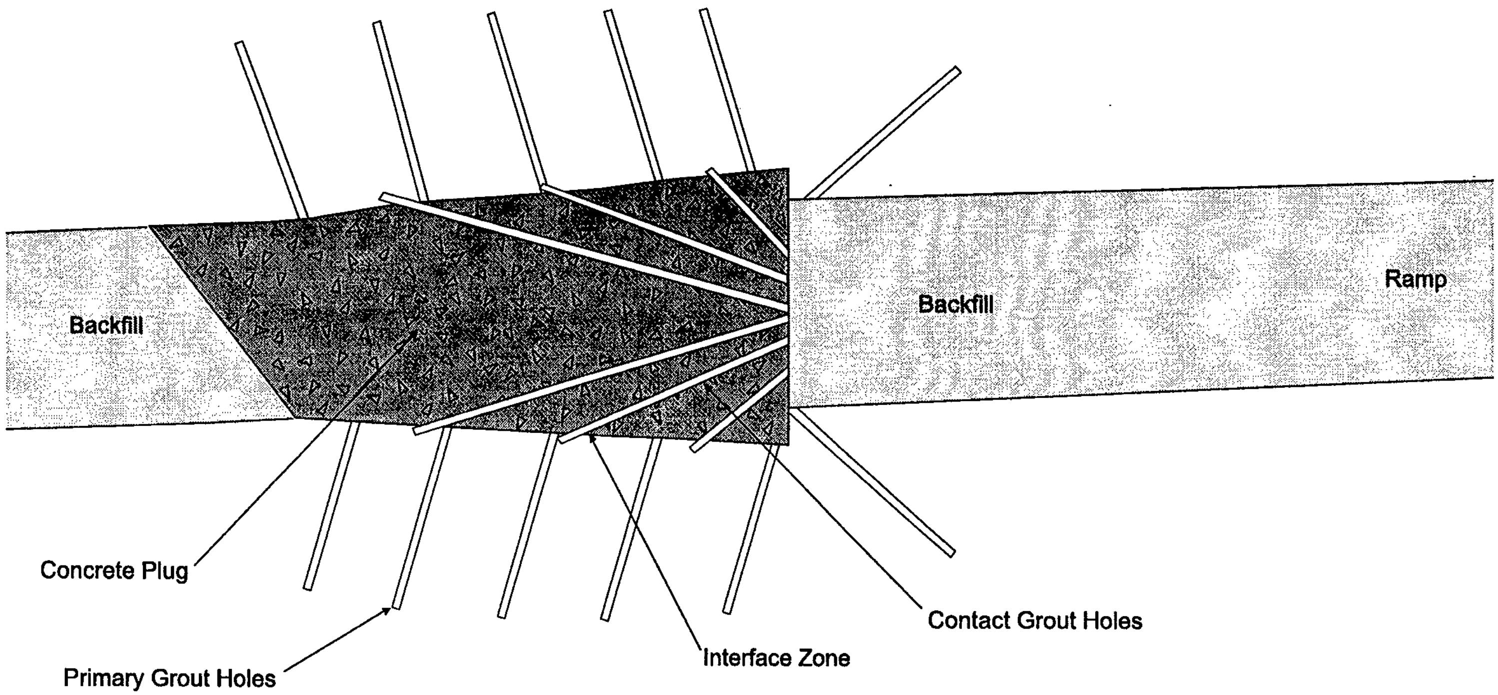

FIG-5-14.CDR.TPM.DOCS.M&O.DOCUMENT.5705.00018/5-30-97

Figure 5-14. Conceptual Design of a Cementitious Ramp Seal

The design of the typical ramp seals as illustrated in Figures 5-14 can follow a similar construction sequence as for shaft seals. The ramp seals are located within the bedded tuffs and the welded tuff of the Topopah Spring unit. The selection of the plug length will be based upon the necessary flow path length tailored to site specific conditions to meet the allowable water-flow goals for ramp seals.

Contact grouting will be important for the ramp seal because of the difficulty of concrete placement near the crown. In the design of construction barriers for the Waste Isolation Pilot Plant (WIPP), grout tubes were used to distribute grout to the interface zone (DOE 1995).

Earthen materials are comparatively weaker, and would probably need to be supported by "settlement plugs" of cementitious materials that would provide resistance to load. The earthen materials could provide added confidence in the longevity of the shaft and ramp seals due to their greater geochemical compatibility compared with the cementitious materials. Sawyer and Daemen 1987, suggest that the swelling potential of confined compacted clay (bentonite) upon wetting is sufficient to close or "heal" cracks or voids in a seal.

The typical construction sequence for a composite cementitious/earthen shaft seal (Figures 5-15 and 5-16) can commence with the construction of a concrete settlement or confinement plug below the earthen seal and backfill with crushed tuff with fines removed. Grout forming the primary grout curtain is injected into the MPZ as with the cementitious seal. Following removal of the liner at the seal location, the earthen seal is emplaced in a series of lifts. The lift size would be selected to optimize compaction efficiency. After emplacement of the earthen seal, a second concrete plug might be emplaced above providing confinement for the earthen seal.

5.4.3.4 Possible Design Options for Exploratory Boreholes

The conceptual design for sealing exploratory boreholes (Figure 5-17) might involve the placement of porous backfill below denser cementitious or earthen seals in which the contrast in matrix potential is at least equivalent or greater than the contrast in matrix potential between the welded and nonwelded host rocks. Further, the porous backfill would be engineered to provide a capillary barrier for unsaturated conditions with the host formation to restrict potential flow into the borehole. The porous backfill with the specified porosity, grain-size distribution, and hydrologic properties can be selected to satisfy these dual objectives.

Well abandonment procedures and plans for boreholes exist and are used in water well, oil/gas well, and deep well injection to eliminate physical hazards, prevent groundwater contamination, conserve aquifer yield and hydrostatic head, and prevent intermixing of subsurface water. Many states regulate well abandonment. For example NAC 445.4277 contains the State of Nevada's injection well plugging requirement, while NAC 534.420 contains the requirements for plugging water wells. For those wells that do not penetrate to the groundwater, the State of Nevada (NAC 534.421.01 (a)) allows backfilling of the well with soil cuttings drilled from the well or inorganic fill matter; but, the top 50 ft must be filled with cement grout, concrete grout, or neat cement. It is therefore recommended that a general sealing plan as outlined in Fernandez et al. 1994 be developed for all exploratory boreholes as well as a detailed borehole-specific sealing plan.

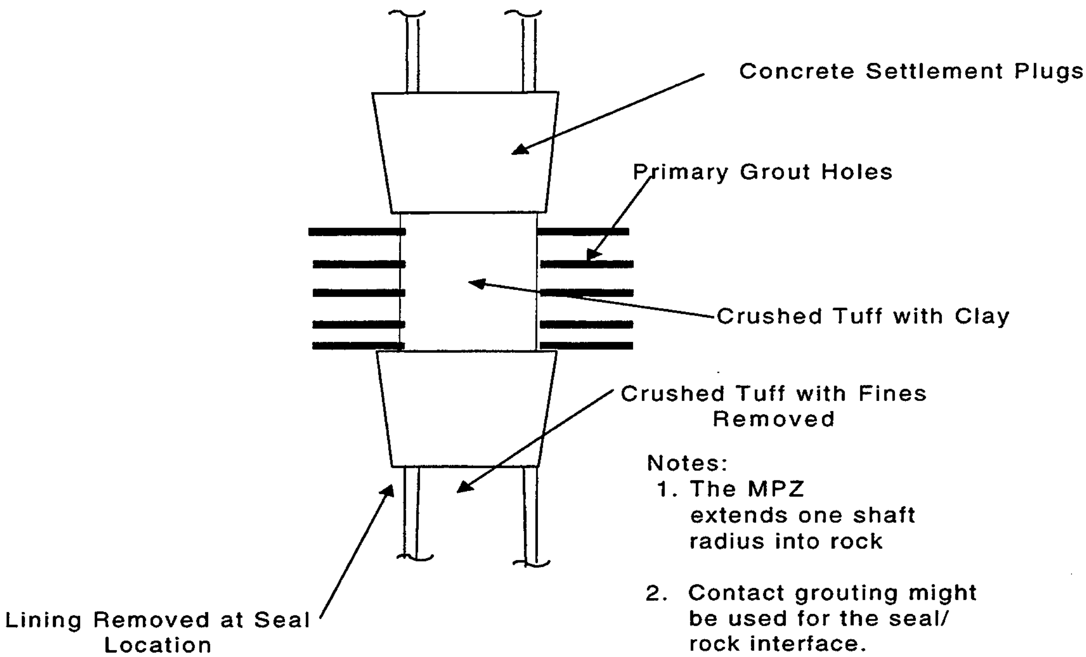

Figure 5-15. Design Concept for an Earthen Seal in a Shaft

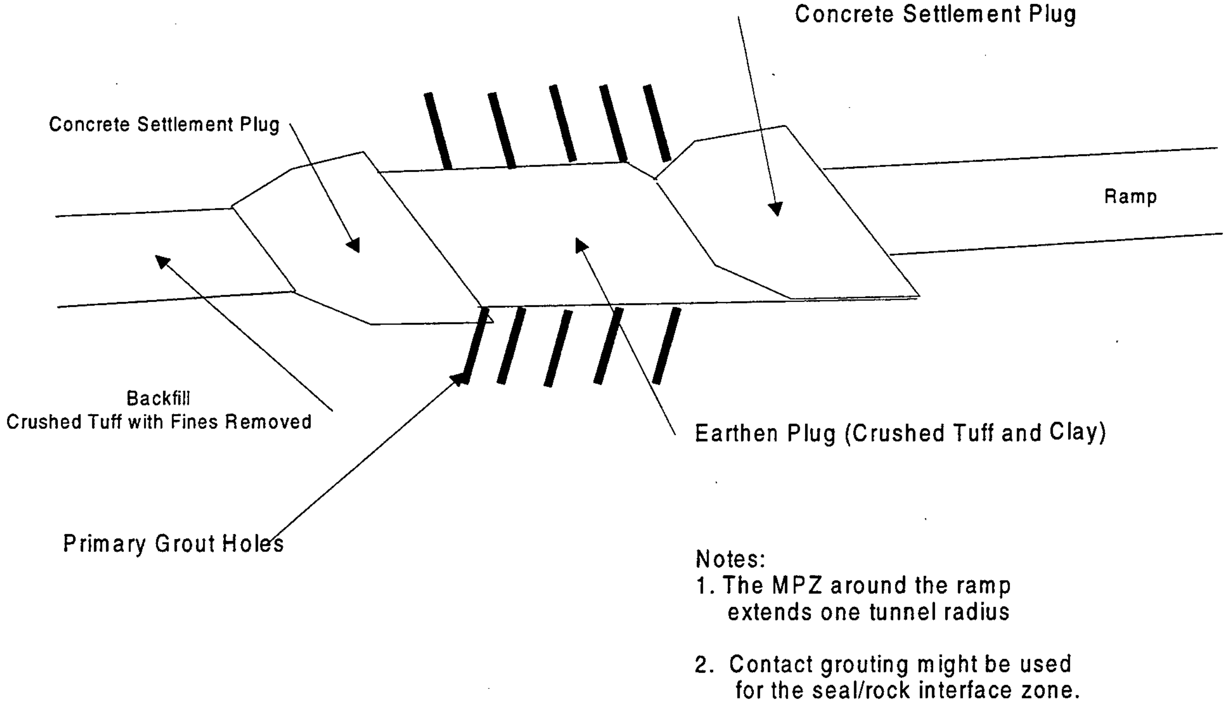

Figure 5-16. Design Concept for an Earthen Seal in a Ramp

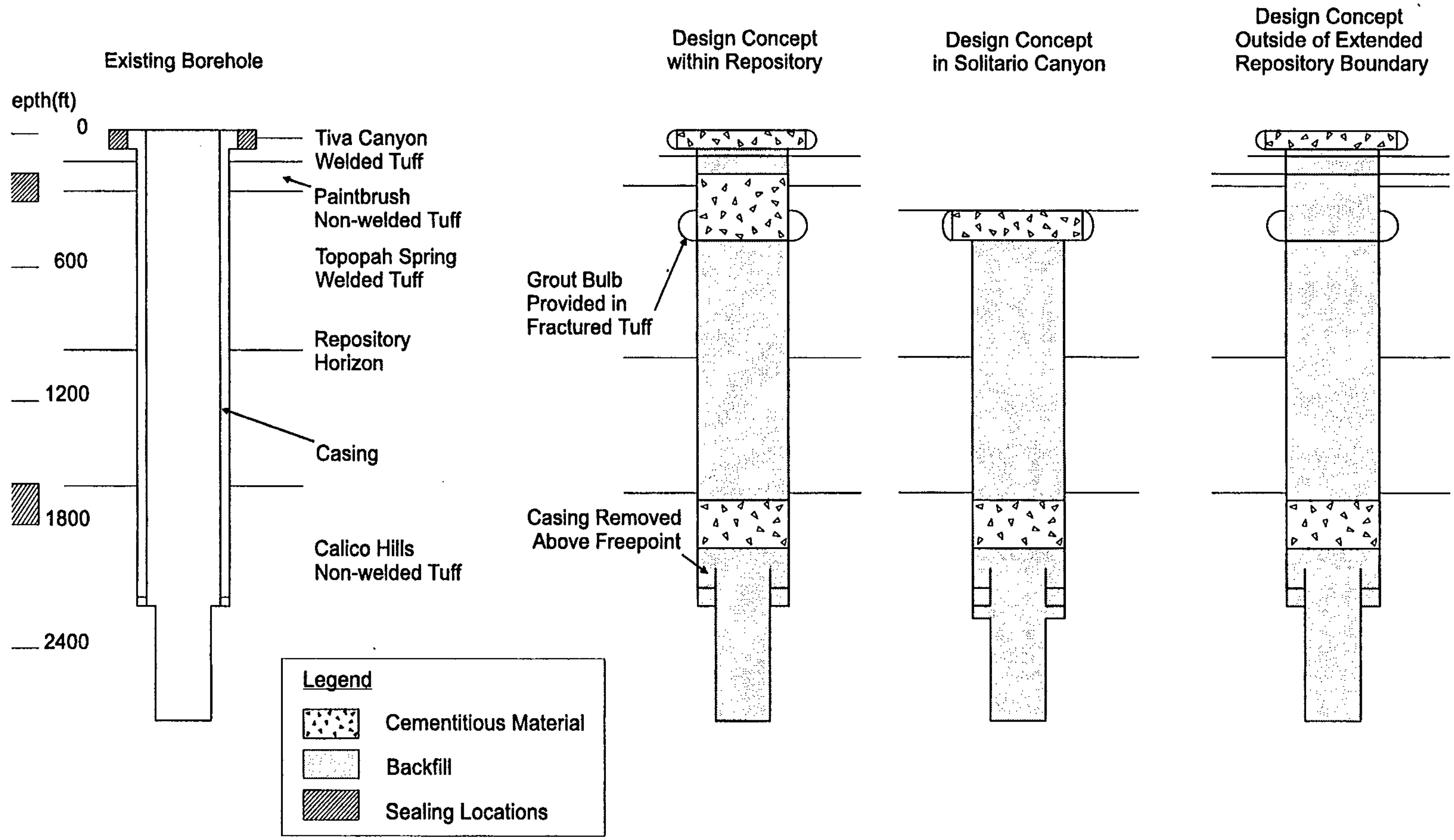

FIG-5-17.CDR.TPM.DOCS.M&O.DOCUMENT.5705.00018/5-30-9

Figure 5-17. Design Concepts for Sealing Exploratory Boreholes (After Fernandez et al. 1994)

For compliance with Nevada Administrative Code requiring a low permeability backfill, the use of low permeability cementitious or earthen seals might be used in certain zones that would be subject to saturation such as at or just above the zeolitic zones in the Calico Hills Formation. These seals would provide a reduction of permeability for vertical flow down the borehole to the groundwater table under saturated flow conditions. The Code requires that all boreholes be capped and surface casing cemented at the entrance to each borehole.

Seals should be emplaced in zones showing higher quality hole conditions such as in the PTn nonwelded tuffs, in the upper portion of the TSw, and in the nonwelded vitric and zeolitic portions of the CHn Unit as was discussed previously. This design is reflected for boreholes within or near the potential repository in Figure 5-17.

In contrast to the design of shaft and ramp seals that can be located away from the high temperature zones of the repository, exploratory borehole seals may be subject to higher temperatures than shaft and ramp repository seals. Previous thermal stress analyses (Fernandez et al. 1994) predicted a smaller rise in temperature and thermally induced stresses at the potential repository boundary or just outside the potential repository boundary than for boreholes within the repository boundary.

5.4.3.5 Period of Performance for Repository Sealing

The project has established a basic requirement (CRWMS M & O 1996a) for the Mined Geologic Disposal System (MGDS) that the system shall be designed to provide a reasonable expectation of containing radionuclide releases to the accessible environment for 10,000 years after repository closure. Also, previous sealing studies (Fernandez et al. 1987) established the sealing period of performance at 1,000 years based on the performance allocated water inflow to the shaft and ramp subsystem exceeding the maximum computed inflows to this subsystem at the end of the sealing period. In performing a similar analysis for this study to assess the design period of performance for seals, it has been noted that the release of ^{99}Tc was the critical radionuclide in establishing the allowable water flow goal for this study. The release of ^{99}Tc was calculated to reach a peak value after about 10,000 years. Therefore, the current recommended sealing period based upon the release of ^{99}Tc should be at least 10,000 years since seals would be required to restrict the water inflow for this time period. This corresponds to the basic requirement of the MGDS. The requirement for seal design life adopted is 10,000 years.

5.4.4 Performance Confirmation Testing

The current regulations define requirements for a field testing program. The primary regulatory requirements, 10 CFR 60, provide a basis for testing sealing components. The sealing requirements fall into three areas: seal component testing (both performance confirmation and design); performance criteria for the complete repository system; and general criteria for the sealing system. The design requirements for the repository sealing system have been defined as constraints on the complete repository system and general criteria in this report. The requirements pertinent to seals testing are given below:

- The performance confirmation program shall provide data that indicate whether the natural and engineered systems and components required for repository or that are designed or assumed to operate as barriers after permanent closure, are functioning as intended and anticipated.

- The program shall start during site characterization and continue until permanent closure.
- The program shall include in situ monitoring, laboratory and field testing, and in situ experiments as appropriate to accomplish the above objectives.

In considering the sealing components that might be developed to comply with the sealing requirements presented in this report, performance testing might also be required to determine the effectiveness of testing instrumentation, including the range, sensitivity, and accuracy of the instruments (This is particularly true for the surface backfill tests.) that will be used to conduct the seal tests.

The project has developed several field testing concepts for seal component tests and performance confirmation tests (Fernandez et al. 1993). Table 5-5 presents a summary of seal component tests. Table 5-6 presents a summary of the proposed tests for performance confirmation testing. The intent is to understand the basic performance of sealing components initially and then apply this understanding to subsequent more complex tests. Seal component tests will evaluate specific structural or hydrological issues and emplacement issues associated with seal installation. Performance confirmation tests will evaluate the overall performance of the seal system in a specific geologic environment.

Note that sealing concepts, and their associated seal design requirements presented in this report stress flexibility and robustness and can be modified as the results of the site characterization and repository design are made available. The planned site specific investigations will determine the geologic and hydrologic characteristics at sealing locations. These investigations may require more specific investigations for seal components as outlined in Table 5-5. On the basis of these tests, designs will be developed to support the Viability Assessment and the subsequent License Application. These designs will then require performance confirmation testing as outlined in Table 5-6.

Table 5-5. Summary of Seal Component Tests

Test	Objective
Small-Scale In Situ Test	Characterize the thermal and stress response of the hydration of the grout or concrete placed in nonwelded and welded tuff environments.
Intermediate-Scale Seal Test	Characterize the hydrologic performance of borehole seals in the nonwelded Paintbrush tuff and the upper portion of the Topopah Spring Member.
Fracture Grouting Test	Understand the hydrologic effectiveness of grout penetration in a number of different fractured environments, including the Tiva Canyon, possibly the Paintbrush nonwelded tuff, and the Topopah Spring Member.
Backfill Tests	Establish the consolidation behavior and the preliminary hydrologic performance of drift and shaft fill, including nonwelded and welded rockfill, due to emplacement techniques. Determine the extent of fines migration.
Grouted Rock Mass Test	Assess the thermal effects on permeability of a fractured rock mass, as well as the thermal effects on a fractured rock mass that is grouted.

Table 5-6. Summary of Performance Confirmation Tests and Associated Objectives

Test	Objective
Seepage Control Test	Understand the hydrologic performance of the ramp fill and filter designs together with the drainage through the underlying fractured rock, the potential migration of fines and subsequent clogging of the underlying fractures, the drainage enhancement provided by various drainage designs, the effects of saturation and partial saturation on the rock fill properties, and thermal effects on the rockfill/rock interface and the rockfill itself. This testing should be done in the Topopah Spring Members.
Shaft Seal and Shaft Fill Tests	Characterize the hydrologic behavior of rigid shaft seals (including the interface zone, the MPZ, and the seal itself) in the Paintbrush tuff, and the Topopah Spring Member. Characterize the hydrologic performance and the consolidation behavior of rockfill comprise of nonwelded and welded tuff with and without additives.
Remote Borehole Seal Test	Understand the hydrologic performance of borehole seals in the nonwelded Paintbrush, the welded Topopah Spring, and the nonwelded Calico Hills units.

5.5 SUMMARY OF DESIGN REQUIREMENTS

Allowable water flow goals are the allowable amounts of water that can enter the waste disposal areas. Air flow goals are the allowable amounts of air flow that can leave the repository. Air flow goals are established for air flow from the repository horizon to the ground surface. In developing these performance goals, specific criteria in 10 CFR 60 were considered. The qualitative design criteria for seals for shafts and boreholes are given in 10 CFR 60.134. The quantitative criteria given in Section 60.113 are used to develop the performance goals for the shafts, ramps, and exploratory boreholes. The performance goals are derived by computing the volume of water required to release radionuclides in amounts equal to the annual release rate established by the NRC in 10 CFR 60 (Section 3.2) for the radionuclides of concern and then modifying the goals as discussed previously to provide design margin and design flexibility. The following recommendations are made for seal requirements.

Primary seal design requirements for individual components are presented for air and water flow. The water flow requirements are to seal the boreholes within the extended repository boundary so that water flow through the sum of all boreholes that intersect the repository is less than 1 percent of the water flow through the rock. The requirement for sealing shafts and ramps is expressed as a mathematical relationship that accounts for EBS performance, the design storage capacity of the shaft and ramp seals subsystem, and the determination of the total storage capacity at the low end of the repository for flow from several sources.

5.5.1 Water Flow Sealing Requirements

- Boreholes

  Seal the deep exploratory boreholes within the extended repository boundary so that water flow through the sum of all such boreholes[3] (Section 5.1) is less than one percent of the water flow through the rock. (This can be achieved by providing effective seal conductivity for sealing components of 10^{-5} to 10^{-6} cm/s for the deep existing boreholes. Theses values are based on the number of boreholes in Figure 3-1).

- Shafts/Ramps

  Seal the shafts and ramps to meet the combination of seal flow and storage capacity determined in Figure 5-18 from the line or below. (For four shafts and ramps in the current design this can be achieved with effective seal conductivities of 10^{-5} to 10^{-6} cm/s).

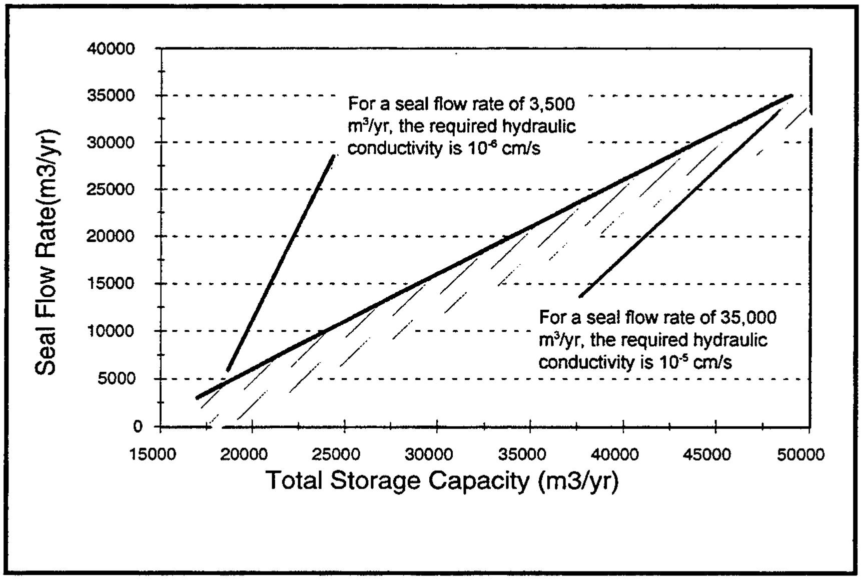

Figure 5-18. Design Chart for Shafts and Ramps Seals

[3]Deep exploratory boreholes are boreholes that penetrate to at least the contact between the TSw and PTn or below, and within 400 m of the repository boundary or the extended boundary.

5.5.2 Air Flow Sealing Requirements

Limit air flow through the sum of all deep boreholes (within the extended repository boundary that intersect the repository) and shafts and ramps to less than 1 percent of the air flow through the rock (Section 5.1). (For four ramps and shafts this can be achieved with a backfill in the shafts, ramps, and boreholes with a hydraulic conductivity of 10^{-2} cm/s).

5.5.3 Seal Design Requirements

The following design requirements are identified for the shaft and ramp seals subsystem and deep exploratory boreholes system within the extended repository perimeter (within 400 meters of the waste emplacement areas):

Seal locations designs shall augment the natural characteristics of the host rock formations in reducing the potential flows to the repository or from the repository to the groundwater table. The seal locations include the unfractured PTn unit, the upper portion of the TSw unit and in the non welded vitric and zeolitic portion of the CHn (Section 5.4.1).

The seal design for the shafts, ramps and exploratory boreholes will provide earthen and cementitious materials to provide redundant design in preventing flow to the repository horizon (Section 5.4.3).

Seal designs shall provide for impoundment of water at the low end of the repository horizon to prevent flow into the waste emplacement areas from shafts and ramps, and shall divert water to provide vertical infiltration below the repository (Section 5.3).

Seal designs to prevent flow into the repository shall consider both anticipated and unanticipated flows from fault systems to assess the maximum hydraulic potential for flow through the seal matrix and the surrounding interface and modified permeability zones (Section 5.1).

Seal designs to divert and drain flow at or near the repository horizon shall consider both anticipated and unanticipated flows from the upper seals and fault systems below the upper seals to assess hydraulic potential for drainage, and water impoundment to comply with the requirements for water flow (Section 5.3).

Seal designs shall mitigate against seal degradation and channeling around the seal through the interface zone and the modified permeability zone (Section 5.4.3).

Seals shall be designed to resist loadings due to backfill, saturated backfill due to perched water, thermal hydration during seal emplacement, thermal stresses during repository heating, and seismic loading for a period of 10,000 years (Section 5.4.3).

Pressure grouting of fracture systems for a seals in an exploratory borehole interface zone between the seal and the surrounding host rock formation and modified permeability zone shall be done in such a manner as to assure that hydrofracturing of the host rock formation and modified permeability zone shall not occur (Section 5.4.3).

Seals shall be designed for the in-situ and induced thermal and geothermal environmental conditions expected at the site (this temperature is not anticipated to exceed 90°C at sealing locations).

Seals shall be designed for a hydrostatic head from the sealing location to the ground surface (Section 5.3).

Deep exploratory boreholes within the repository boundary that are not intended for post-waste emplacement monitoring shall be sealed prior to underground excavation and waste emplacement.

For the case of deep exploratory boreholes within the extended boundary of the repository that are not sealed prior to repository excavation and waste emplacement, borehole integrity shall be maintained to the extent practical. One method of maintaining borehole integrity is to provide an established separation distance between the borehole and the underground drift. The established separation distance (based on structural analysis) for borehole and casing stability for such boreholes shall be maintained between the borehole and the waste emplacement drifts.

For deep exploratory boreholes within the repository block that are intended to be used for post closure monitoring, an established separation distance adequate (based upon structural analysis) for borehole and casing stability shall be maintained between the borehole and waste emplacement drifts.

5.5.4 Seal Environment

The requirements for sealing of shafts, ramps and boreholes must consider the natural sealing environment and the elevated temperature environment after waste emplacement. Table 5-7 summarizes hydrologic related site parameters that were stated previously in the SCP-CDR (DOE 1988) needed to support seals design. Table 5-8 summarizes other miscellaneous parameters needed to support seals design.

As discussed in Section 1.4 (Figure 1-1), geologic and hydrologic characterization within the underground repository and the exploratory boreholes will provide detailed information within each shaft and ramp as to the optimum seal locations. The emphasis in Table 5-7 is on hydrologic and geologic information that would support design. The information contained in Table 5-7 will assist the project in identifying performance scenarios. This will include the hydraulic potential for inducing flow through seals that would be necessary for developing designs with a selected geometry and effective seal conductivity. After completion of the major hydrologic and geologic investigations that would identify alternate seal locations. The final location, geometry, and materials selection would be selected through detailed design studies. The development of detailed seal designs would consider the geochemical environment and the potential for seal degradation in selecting sealing materials.

Table 5-7. Hydrologic-Related Site Parameters Needed to Support Seals Design

Performance Or Design Parameters	Modifiers	Parameters	Needed Confidence	Current Confidence
Saturated bulk rock hydraulic conductivity of Tiva Canyon Member		3.1×10^{-8} to 1.5×10^{-6} cm/s	Medium	Medium
Continuous saturation profile of soil to bedrock-soil interface	At shaft and borehole locations	$\pm$10% of natural saturation every meter	Medium	Low
Gradation of Soil	At shaft locations predominantly within 15 m from shaft and borehole locations	Determination through standard sieving analyses	Not applicable	Low
Extent and hydraulic conductivity of the modified permeability zone (MPZ)	MPZ in TCw and TSw2	20 to 60 times the undisturbed, rock mass hydraulic conductivity (saturated), averaged over one radius from the wall of the shaft	Medium	Low
Unsaturated hydraulic, matrix properties	TSw2, especially in vicinity of shafts	1×10^{-10} to 1×10^{-17}cm/sec	Medium	Medium
Drainage capacity (saturated bulk rock hydraulic conductivity)	TSw2 at selected drift floor locations at repository horizon	2.7×10^{-6} to 2.6×10^{-5} cm/sec	High	Medium
Drainage capacity (saturated bulk rock hydraulic conductivity)	TSw2 at base of shaft	2.7×10^{-5} to 2.6×10^{-4} cm/sec	High	Medium
Saturated, bulk rock hydraulic conductivity	CHn1 at base of boreholes	8.7×10^{-7} to 2.2×10^{-6} cm/sec	Medium	Medium
Magnitude of water entering shafts	shafts and ramps	170 m^3/yr per shaft considering anticipated processes	High	Low
Hydraulic potential for flow through seal system	Episodic flow from fault zones	340 m	High	Low

TSw2 = Topopah Spring, welded (repository horizon)
TCw = Tiva Canyon, welded
CHn1 = Calico Hills, nonwelded

Table 5-8. Miscellaneous Information Needed to Support Seals Design

Performance Or Design Parameters	Modifiers	Parameters	Needed Confidence	Current Confidence
Compressive strength of the rock mass	TCw, PTn, TSw1, TSw2, CHn1	See CRWMS M&O 1996b for values	Medium	Medium
In Situ Stress	TCw, PTn, TSw1, CHn vertical & horizontal	None	Medium	Low
In Situ Stress	TSw2 horizontal and vertical	See *Stress Measurement Data and Analysis*, TDIF 305878, SNL January, 1997" for values.	Medium	Medium
Fracture characteristics	no modifier	See "Sweetkind, D.S., Williams-Stroud, S.C., *Characteristics of Fractures at Yucca Mountain, Nevada: Synthesis Report*, U.S. Geological Survey Administrative Report, Denver, CO, 1996 (in prep. for values)	Medium	Medium
Seismic response spectra	At shaft and ramp location (surface and repository horizon)	To be determined through design studies	High	Low
Temperature variations at ground surface	At ground surface at shaft and ramp entry points	To be determined by laboratory testing and activities	To be determined by laboratory and design activities	Low
PH of rainfall	At shaft and ramp location	>4.5	Medium	Low
Dissolved sulphates SO^{2}-	At end upgradient from shaft location	<0.10% soluble SO^{2}- in soils or surface water <150 ppm dissolved SO^{2}-	Low	Low
Geochemistry	TCw, TSw2, CHn1v, CHn1z	TBD	Medium	Low
Maximum temperature at seal locations	Upper portion of TSw and PTn	<90°C	High	Medium
	At repository and horizon around shaft	To be determined through thermal performance studies at selected sealing location	TBD	TBD
	At selected locations near repository horizon	To be determined through thermal performance studies it selected sealing location	TBD	Low
	Calico Hills unit in boreholes below the repository	<90°C	High	Medium

Table 5-8. Miscellaneous Information Needed to Support Seals Design (Continued)

Performance Or Design Parameters	Modifiers	Parameters	Needed Confidence	Current Confidence
Thermal expansion, heat capacity, and thermal conductivity of seal emplacement environment	TSw2 CHn1	See "CRWMS M&O Site Geotechnical Report, B00000000-01717-5705-00043	Medium	Low
Saturated hydraulic conductivity	Shaft or ramp fill	1x10^{-2} cm/s	High	Low
Gradational analyses, angle of internal friction, compressibility	Shaft or ramp fill	To be determined through design studies		
Fracture characteristics	TCw	<20 fractures/m	High	Low
	TSw2	<40 fractures/m	High	Low
	CHn1 at base of ES-1	<5 fractures/m	High	Low
	PTn	<10 fractures/m	High	Low
Chemistry of waters (if any) in fault including sediment content		Elemental concentration	Medium	Low
Grade of emplace-ment drifts and drift dimensions	In repository	0.5%	Medium	High
Casing location and condition for exploratory boreholes	All boreholes in extended repository bounded	Location of casing to $\pm$5 m. Conditions determined by logging and drilling records	High	Medium
Unit contacts in exploratory boreholes	All boreholes in the extended repository boundary	Contact location $\pm$5 m	High	High

6. RESULTS AND RECOMMENDATIONS

A repository sealing requirements study was conducted to identify design requirements for the repository sealing system. The repository sealing study considered repository sealing to be defined as those components that would reduce potential inflows of water or air into the repository, or that would divert water flow near the repository horizon to allow drainage into the TSw. The repository sealing strategy thus includes the underground design of facilities that would impound water at the low end of the repository or near the base of the ramps or the shafts, and allow drainage to occur into the underlying formation as well as sealing of shafts, ramps, and boreholes.

6.1 AIR FLOW

The potential for convective air flow and the release of gaseous radionuclides from the repository were evaluated for compliance to the NRC regulation (10 CFR 60) for restricting or limiting radionuclide releases from the EBS to one part in 100,000. This regulation established an allowable air flow goal for the release of gaseous radionuclides. The allowable air flow goal for flow through shafts and ramps was based on meeting the NRC allowable release for ^{14}C and ^{129}I from the engineered barrier of the waste packages. This allowable air flow for the shafts and ramps was expressed as a percentage of the flow through the rock above the repository. The NRC criteria was met with allowable air flows through the shafts and ramps calculated to be less than 5 percent. For a conservative goal, an allowable flow of one percent was used (CRWMS M&O 1997e and CRWMS M&O 1997f).

The convective flow of air was evaluated by considering that cool air is drawn in through the North Ramp, South Ramp, and the Development Intake Shaft. The air enters the repository and rises over the central block of the repository through boreholes, the Emplacement Exhaust Shaft and the overlying welded and nonwelded tuff units. The analyses show that if a general backfill is selected to restrict flow to one percent of the flow through the rock, the required ramp or exploratory borehole backfill hydraulic conductivity is 10^{-2} cm/s. A backfill with a hydraulic conductivity of 10^{-2} cm/s thus would suffice to restrict the release of gaseous radionuclides to within NRC limits and is recommended as a design requirement for air flow.

6.2 WATER FLOW

The repository sealing requirements study assessed the need for sealing shafts, ramps and boreholes to prevent water inflows to the repository. The approach considered the current NRC requirements for radionuclides release from the EBS. This approach included developing relationships for the release of specific radionuclides from the EBS for comparison to the NRC limits. The assessment considered the current repository design with a thermal loading of 83 MTHM/acre. Allowable water flow goals were developed for the repository isolation system for the most critical radionuclides in the inventory.

Various performance scenarios were developed for estimating flows to the underground repository through the shafts, ramps, and exploratory boreholes. The range of potential anticipated flows considered infiltration rates ranging from 5 mm per year to 30 mm per year. The inflow rates to the underground facility reflect the infiltration rates and capture zone area under anticipated and unanticipated conditions.

The results showed that anticipated water inflows through shafts were of the order of 1 to 170 m^3 per year, and would not likely exceed the drainage flow capacity of backfilled shafts.

Water inflow rates under unanticipated conditions were also considered. Under unanticipated conditions, flows might be higher for short episodic events. However, the flows are still relatively small since shafts and ramps are located outside of flood plain areas. The flows investigated considered potential transient flow from a perched water zone, and flow through intersecting fault zones. The potential flow through the fault zone under unanticipated conditions was reflected by a high rock conductivity (10^{-2} cm/s).

An assessment of the need for sealing shaft and ramp components was performed by comparing the allowable flow goals to the anticipated water flows to the underground repository. The comparisons showed that for the range of anticipated flows from the shafts, ramps, and underground facility, the flows from the underground shafts and ramps at an infiltration rate of 5 mm per year might not exceed the allowable flow rate as determined from the requirement for release of radionuclides from the EBS. For these anticipated flows, seals would not be necessary. At an infiltration rate of 30 mm per year, the allowable flow rates would be exceeded and there would be requirements for seals. For unanticipated flows, there is also the potential that flows through shafts and ramps might exceed the allowable water flows over short periods of time.

For deep exploratory boreholes that intersect or go below the repository horizon, the need for repository seals is established on the basis that they could represent preferential pathways from the repository horizon to the groundwater table. The potential exists for perched water zones near the zeolitized zones where a significant permeability contrast would exist. The potential exists for perched water to enter the deep exploratory boreholes below the repository horizon, and transmit water and radionuclides to the groundwater table.

Various seals design concepts were proposed in each of the shafts and ramps and deep exploratory boreholes. These components included an Anchor-to-Bedrock Plug, Upper Seals located in the PTn and TSw formations, and shaft backfill. These proposed seals provide redundancy in using multiple seals with different materials for sealing in several host rock formations. Flexible seal design requirements for the shafts, ramps and boreholes were developed and presented in Section 5.5.

6.3 REPOSITORY SEALING STRATEGY AND DESIGN REQUIREMENTS

A repository sealing strategy considered where, when and how to seal. The prime sealing locations above the repository include the upper portion of the Topopah Spring welded tuff, of high compressive strength and the relatively unfractured Paintbrush nonwelded tuff of lower compressive strength. Seals might be emplaced in the Paintbrush and the top of a Topopah Spring unit to prevent the entry of water from a shallow fracture system. Shaft/ramp fill is also suggested to be used to provide a capillary barrier for unsaturated flow.

The strategy presents information on when to seal exploratory boreholes. The strategy includes sealing of exploratory boreholes within an extended repository boundary (400 m) prior to repository excavations, and waste emplacement. For several selected boreholes that might be used for monitoring post waste emplacement performance, the casing would have to be designed to provide access to repository sealing locations at the time of repository closure. For these several boreholes, a design requirement is established to maintain a separation distance between the borehole and the surrounding waste emplacement drifts adequate to maintain borehole and casing stability.

Various repository concepts for cementitious and earthen materials are presented to illustrate how to seal. These concepts show possible primary grouting of the fracture system in the MPZ prior to seal installation, seal installation using selected seal materials, and contact grouting of the interface zone.

Other secondary seal design requirements were developed from the primary seal design requirements. These requirements address the need to develop designs that augment the natural characteristics of the host rock, and the need to provide redundancy through the use of different materials sealed against different host rock formations. The seal design requirements assess the hydraulic potential for drainage, and water impoundment to comply with the requirements for water flow. Additional information from hydrologic and geologic and repository design studies on the sealing environment is presented in Tables 5-7 and 5-8.

The seals study concentrated on establishing recommendations for sealing shafts, ramps, and boreholes and did not consider any potential sealing of emplacement drifts, subsurface water diversion, or engineered drainage of the potential repository. The recommendations for sealing the shafts, ramps, and boreholes do involve the subsurface design in that they require that subsurface water storage be included. The recommended subsurface water storage capacities would be adequate for not only the water which was allowed to go through the shaft, ramp, and borehole seals but for the water that entered the repository through the host rock. In the process of the evaluations, issues were raised regarding the amount of water flow which might occur into the drifts (fracture and matrix) and the potential performance issues associated with concentrating water flow in a localized area of the north end as a result of the proposed engineered drainage. It is recommended that these issues regarding flow into the drifts and concentration of flow in the repository be addressed. Performance Assessment indicated that their codes should be sufficiently robust to perform those calculations by about January 1998. Estimates were made as to what potential impacts would result if it became necessary to seal the emplacement drifts with either grout or the use of diversion dams. Should such measures be required there would need to be changes in the slope of the drifts and the costs to do that work would be added but it does not appear that there would be any impact to Subsurface Design from the standpoint of requiring more emplacement drifts/area.

6.4 RECOMMENDATIONS FOR SEAL PLANS, SEAL TESTING, AND ADDITIONAL REPOSITORY STUDIES

While no specific plans for sealing the shafts and ramps are called out in the state statutes, it is clear that such plans should be prepared since many of the same issues as for wells and boreholes will need to be addressed. For example, in developing seal designs using the guidance in this report, seal locations would need to be selected on the basis of subsurface repository design and subsurface investigations detailing rock mass quality and other pertinent properties for sealing locations in each shaft and ramp.

The seal plans developed by the project should exist as controlled documents with design specifications and construction drawings and should consider the general and specific problems encountered at specific sealing locations after completion of site investigations. The plans for sealing exploratory boreholes should provide detailed information from a combination of mechanical caliper and video logging to search for any obstructions. Injection pressures may be determined by controlled hydrofracturing in zones near seal locations. In areas where primary grouting is necessary, grout designs will be tailored to provide materials performance at specified grout-injection pressures, viscosity, and strength. The plans for sealing shafts and ramps should provide detailed drawings illustrating seal geometry, the extent of key excavations, and grout holes. The plans should detail any requirements for removal of artificial support and provide construction quality control during emplacement of seals. Materials specifications should provide the properties such as hydraulic conductivity or unconfined compressive strength to be developed by the sealing materials such as grouts, concrete and earthen backfill. Performance confirmation testing should be included as part of the detailed design, and seal plans to provide additional information on construction quality control.

For exploratory boreholes, it is recommended that sealing plans be prepared for all proposed deep boreholes within the extended repository boundary. These boreholes should be evaluated prior to drilling to define the specific seal design. Work plans should address issues with respect to well abandonment and borehole access.

This report presented information on repository seal component and performance confirmation testing. Previous sealing studies (Fernandez et al. 1994) identified these tests and provided a schedule for testing to support the License Application. As design concepts are developed, it is recommended that in situ testing of seal components be performed to support design efforts. In addition, it is recommended that geochemical studies be conducted to assess the long-term performance of sealing materials. This testing might utilize different earthen and cementitious sealing materials in both fractured and unfractured tuff to support seal design efforts.

This report addresses repository seals in shafts, ramps, and exploratory boreholes. Other sealing requirements for sealing components in the underground facility may need to be developed to control water flows from the perimeter mains, and to direct this flow to areas where water can be drained into the fractured tuff below the repository. Further, water flows into waste emplacement areas may need to be restricted from flowing to the low end of the repository. Previous studies (Fernandez et al. 1987) have shown that there would be more difficulty in achieving water flow goals in the higher temperature environment. Thus, it is recommended that additional performance assessment and sealing evaluations be conducted to develop sealing requirements within the underground repository. These studies should evaluate the current repository design and the potential for water to concentrate in the low points of the repository and increase saturation levels with the potential for an increased flux rate to the groundwater table. Should the recommended evaluations indicate the need to seal emplacement drifts or modify drainage flows, it should not impact the amount of emplacement drifts/area required. It may, however, affect the slopes of the drifts and the cost to add such measures as diversion dams or grouting of cracks, if needed, may increase.

The following is a summary of the recommendations for requirements for the seals system that were developed based on the results of this study:

Boreholes

The seals system for boreholes should be designed to meet the following criteria:

- The system shall provide sealing to boreholes that meet the criteria of coming within 100 m of the repository horizon or deeper and for those boreholes that are within an area bounded by a distance of 400 m from the repository emplacement area perimeter.

- To ensure that boreholes should not become preferential pathways for radionuclides, the system shall limit vertical water flow through the sum of all boreholes that intersect the repository to less than one percent of the vertical water flow through the rock mass that extends 400 m beyond the repository perimeter drifts. Based on the current expected number of boreholes that meet the above criteria (six existing and one planned), the one percent or less flow can be achieved by sealing the boreholes with an effective seal conductivity of between 10^{-4} to 10^{-3} cm/s. This criterion is flexible in that if additional boreholes are drilled the permeability requirement would become more stringent.

- Borehole seals shall limit airflow consistent with the criteria listed below for shafts and ramps.

Shafts and Ramps

The seals system for shafts and ramps would be designed to meet the following criteria:

- The system shall limit air flow through the sum of all of the subsurface openings (i.e., boreholes, ramps, and shafts) to less than one percent of the air flow through the rock mass over the area that extends to 400 m beyond the repository perimeter. This can be readily achieved with the sealing permeabilities specified above for the boreholes and below for the shafts and ramps.

- The system shall be designed to provide for a total storage capacity of water at the repository horizon which will accommodate a rate of 17,000 to 49,000 m^3/yr. Storage capacity is defined as a volume that could be retained and allowed to drain into the rock in one year's time without contacting the waste packages.

- To achieve the subsystem requirement of limiting the release rate of any radionuclides to less than one part in 100,000 per year, the system shall limit the total flow rate through shaft and ramp seals equal to or less than the value computed from the following equation. The storage capacity is based on the value used in the above criterion.

$$\text{Flow rate} = (0.98 \bullet \text{Total Storage Capacity in } m^3/\text{yr}) - 13{,}234\ m^3/\text{yr}$$

This flow rate can be achieved by providing seals that have conductivities 10^{-5} to 10^{-6} cm/s with the higher conductivity corresponding to the higher flow.

Operating Conditions

The system shall be designed for the following environmental conditions and lifetime:

- The system shall be designed for the following applicable environmental conditions:

Subsurface Environments	Minimum and Maximum Conditions
In-situ Rock Temperature	13 to 90 °C
Water Infiltration	5 to 30 mm/year
pH of Infiltration Water	4.5 to 10.5

- To provide reasonable expectation of meeting the MGDS radionuclide release requirements, the system shall be designed for permanent installation with a design life goal of 10,000 years.

If, in the regulatory process, a decision is reached to make the borehole or shaft/ramp seals more robust, the design can be easily changed by scaling the work done in this report. Lower conductivity seal material, backfill, or larger seal plugs could all be considered to increase the robustness of the seal.

Subsurface Sealing and Water Diversion

Some additional evaluations of the performance impact of repository engineered water drainage, which may concentrate radionuclides in a localized area and possible flow into emplacement drifts, should be done. The capability to perform such evaluations should exist after January 1998.

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7.2 REGULATIONS

10 CFR 60, *Disposal of High-Level Radioactive Wastes in Geologic Repositories*

40 CFR 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level Waste and Transuranic Radioactive Waste*

7.3 NEVADA STATE

NAC 534A.150, Sealing of Holes

NAC 534A.490, Abandonment of Geothermal or Injection Well

NAC 534A.500, Casing Strings to be Cut Off and Capped; Removal of Structures and Other Facilities.

8. ACRONYMS AND ABBREVIATIONS

BWR	Boiling Water Reactor
CFR	Code of Federal Regulations
CRWMS	Civilian Radioactive Waste Management System
DHLW	Defense High Level Waste
EBDRD	Engineered Barrier Design Requirements Document
EBS	Engineered Barrier System
ESF	Exploratory Studies Facility
MGDS	Mined Geologic Disposal System
M&O	Management and Operating Contractor
MPZ	Modified Permeability Zone
MTHM	Metric Tons Heavy Metal
NAC	Nevada Administrative Code
NRC	U. S. Nuclear Regulatory Commission
OPC	Ordinary Portland Cement
PWR	Pressurized Water Reactor
RDRD	Repository Design Requirements Document
SCP	Site Characterization Plan
SCP-CDR	Site Characterization Plan - Conceptual Design Report
SNL	Sandia Naitonal Laboratories
TBD	To Be Determined
TBV	To Be Verified
TSPA	Total Systems Performance Assessment
UZ	Unsaturated Zone
WIPP	Waste Isolation Pilot Plant
YMP	Yucca Mountain Project
YMSCO	Yucca Mountain Site Characterization Office

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