Program on Technology Innovation: Room at the Mountain

Analysis of the Maximum Disposal Capacity for Commercial Spent Nuclear Fuel in a Yucca Mountain Repository

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Technical Update, May 2006

EPRI Project Manager

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ABSTRACT

This report provides a preliminary analysis of the physical capacity of Yucca Mountain for the disposal of additional commercial spent nuclear fuel (CSNF). The result of this examination is that the current legislative limit on Yucca Mountain disposal capacity, 70,000 MTU of a combination of CSNF, DOE, and defense wastes (63,000 MTU CSNF; 7000 MTU or equivalent of DOE and defense wastes) is a small fraction of the actual available physical capacity of the Yucca Mountain system. EPRI is confident that at least four times this legislative limit (~260,000 MTU) can be emplaced in the Yucca Mountain system and hypothesize that, with additional site characterization, nine times the legislative limit (~570,000 MTU) could be emplaced. The minimum factor of four and possible factor of nine increase is based on the following:

- Within the proposed Upper Block area, a revised layout of the repository drifts could allow for two to three times the waste loading per unit area. Two examples of such a revised layout to accomplish the higher loading density are considered. For the options associated with these two layouts, peak rock temperatures are estimated to remain within acceptable thermal limits.

- At least a factor of two times more area is available for waste emplacement than the current Upper Block proposed for use by DOE to dispose of 70,000 MTU of waste. A factor of 2.6 to 3.5 times as much additional disposal area is potentially available with additional site characterization studies.

Thus, it is possible for Yucca Mountain to hold not only all the waste from the existing U.S. nuclear power plants, but also waste produced from a significantly expanded U.S. nuclear power plant fleet for at least several decades.
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LIST OF FIGURES

Figure 2-1  Borehole Log for UZ 14 (from Bodvarsson, et al., 1997) ................................................................. 2-2
Figure 2-2  A North-South Schematic Cross-Section Through the Upper Block of the
Primary Area  (from Robinson, 2004) .............................................................................................................. 2-3
Figure 2-3 East-West Cross-Section Through the Proposed Repository. Because of
the Dip of Units, the Proposed Host Rock for the Repository Changes from West to
East  (from Houseworth and Bodvarsson, 2004) .................................................................................................... 2-4
Figure 2-4 Schematic Diagram of Reference Yucca Mountain Repository Configuration
of Line-Loaded Waste Packages and Drift Spacing (from BSC, 2004a, Figure 6.2-2) ......................................... 2-7
Figure 2-5 Layout of the Proposed Repository and its Association with Key Geologic
Units.  Source: Underground Layout Configuration (BSC, 2003b) ................................................................. 2-8
Figure 2-6 Location of Faults at Yucca Mountain and in the Vicinity (BSC, 2004b) ........................................... 2-9
Figure 2-7 Calculated Lateral Extent of Boiling (96°C) Developed Around Emplacement
Drifts for Reference YMP Repository Design (from Figure 8f in Buscheck et al., 2006) ........................................ 2-11
Figure 3-1 Map Showing Potentially Usable Storage Areas (from Mansure and Ortiz, 1984) ............................ 3-2
Figure 3-2 Proposed Areas Potentially Available for Expansion of the Repository. Note that Optional Areas B, C, and D are Located West of Yucca Mountain. Descriptive
Details for the Six Areas are Provided in Table 3-1. (Modified from CRWMS M&O, 1994) .................................. 3-3
Figure 3-3 One Planning Scenario for a Proposed Repository with a Low Temperature
Operating Mode. Note Area 7 West of Fatigue Wash Fault. A Design Incorporating all
the Areas would Entail Approximately 23 km² (from US DOE, 2002b) .......................................................... 3-4
Figure 3-4 East-West Cross-Section Through the Proposed Repository. The Larger
Repository Footprints Extend the Repository Westward to the Left Boundary of the
Cross-Section (modified from BSC, 2004b) ....................................................................................................... 3-6
Figure 4-1 Waste Package Heat Generation Rate as a Function of Time with and without
Ventilation. The Ventilation Scenarios are Defined in Table 4-1. The Step Changes Correspond
to Assumed Sudden Changes in Ventilation Efficiency (Appendix C) ............................................................ 4-2
Figure 4-2 Illustration of the Conceptual Models Established for Screening Evaluation of
Thermal Capacity of Yucca Mountain Repository within the Current Design Footprint
(i.e., 81-m drift spacing) .................................................................................................................................. 4-3
Figure 4-3 Model Calibration Results. Temperature Profiles of “WP Temperature” and
“Drift Wall” from EPRI Analyses [bottom figure (b)] are Compared to “Waste Package”
and “Side” and “Crown” Profiles from BSC (2003e) Calculations [top figure (a)] ............................................. 4-5
Figure 4-4 Example of Temperature and Gas Saturation Contours at Different Times for
the Multi-Level Repository Concept (Case 1 Results) ....................................................................................... 4-13
Figure 4-5 Case 2 (Multi-Level Concept) Results: (a) Temperature Histories at the Waste
Packages, Drift Walls, and Centerlines between Drifts in the Top, Middle, and Bottom
Levels; (b) Gas Saturation Histories at the Drift Walls and Centerlines in the Three Levels ......................... 4-14
Figure 4-6 Example of Temperature and Gas Saturation Contours at Different Times for
the Grouped-Drift Repository Concept (Case 10 Results) ............................................................................... 4-15
Figure 4-7 Case 9 (Grouped-Drift Concept) Results: (a) Temperature Histories at the
Waste Packages (Center and Side), Drift Walls (Center and Side), as well as at the
Centerline Between Drifts; (b) Gas Saturation Histories at the Drift Walls (Center and Side)
and Centerline Between Drifts ......................................................................................................................... 4-16
Figure A-1 Mean Coefficient of Thermal Expansion (MCTE) vs. Temperature for Rock Samples from TSw2 Tuff (source: Brodsky et al., 1997) ................................................................. A-3
Figure A-2 Probability of Seeing Different Types of Rockfall in the Yucca Mountain Emplacement Drifts Due to a Single Seismic Event with a PGV of 2 m/s (for current repository design, source: EPRI, 2005a) .................................................................................................. A-6
Figure B-1 Temperature Profiles Used to Represent the Hottest and Coolest EBS for the EBSCOM Simulation of the Case A Optional Repository Design .......................................................... B-3
Figure B-2 Distribution of Peak EBS Temperatures in the EBSCOM Simulation of the Case A Alternative Repository Design .......................................................................................................... B-4
Figure B-3 Predicted Time Dependence of the Cumulative Fraction of Failed EBS Components for the Case A Alternative Repository Design Simulation. Failure Times are Shown for the Drip shield (DS), Waste Package (WP), and for the Combined EBS Comprising a WP and the Corresponding DS (EBS) ........................................................................................................ B-5
LIST OF TABLES

Table 3-1 Descriptive Summary of Six Potential Repository Areas Described in CRWMS M&O (1994).................................................................................................................................3-1
Table 3-2 Range of Estimated Expansion Factors for Option 1: Extending the Current YMP Repository Design to Characterized Areas of the Yucca Mountain Region .................3-7
Table 4-1 Ventilation Scenarios .................................................................................................................4-2
Table 4-2 Hydro-Thermal Properties .........................................................................................................4-6
Table 4-3 Initial Conditions.............................................................................................................................4-6
Table 4-4 Definition of Calculation Cases (horizontal spacing is 81-m for all Cases) ........................................4-7
Table 4-5 Results Summary.....................................................................................................................4-12
Table 5-1 Expansion Factors for Option 2: Multi-Level Repository (see Table 4-4) .......................................5-2
Table 6-1 Expansion Factors for Option 3: Grouped-Drift Repository (see Table 4-4) ...............................6-3

Table B-1 Peak EBS Temperatures and Corresponding Maximum Values for the EBSCOM Temperature Coefficients for the Four Optional Repository Design Temperature Profiles........................................................................................................................................... B-2
Table B-2 Predicted Time Dependence of the Cumulative Fraction of Failed Waste Packages for the Simulations of the Four Alternative Repository Designs .............................................. B-6
Table B-3 Predicted Time Dependence of the Cumulative Fraction of Failed Waste Packages for the Nominal Scenario and Two Elevated Temperatures with Different Assumed Threshold Temperatures for Aqueous Corrosion ................................................................. B-6
CONTENTS

1 INTRODUCTION ........................................................................................................................................1-1
  1.1 Purpose ............................................................................................................................................1-1
  1.2 Approach .........................................................................................................................................1-1
  1.3 Report Organization .....................................................................................................................1-3

2 CONSTRAINTS ON THE SPENT-FUEL DISPOSAL CAPACITY AT YUCCA MOUNTAIN .........................................................2-1
  2.1 Geologic Setting of Yucca Mountain .............................................................................................2-1
  2.2 Programmatic Decisions on Repository Location ......................................................................2-5
  2.3 Current Reference Repository Design .......................................................................................2-5
  2.4 Thermal Limits ...........................................................................................................................2-10
  2.5 Sub-boiling Pillars between Drifts ...............................................................................................2-10

3 OPTION 1: EXPANDED FOOTPRINT OF THE CURRENT YMP REPOSITORY DESIGN ...........................................................................3-1
  3.1 Previous Studies .........................................................................................................................3-1
  3.2 Evaluation .....................................................................................................................................3-5
  3.3 Conclusions ....................................................................................................................................3-5

4 THERMAL ANALYSES OF DESIGN OPTIONS .........................................................................................4-1
  4.1 Introduction .....................................................................................................................................4-1
  4.2 Data on Decay Heat and Ventilation ..........................................................................................4-1
  4.3 Conceptual Models .......................................................................................................................4-3
  4.4 Calibration of Calculational Model .............................................................................................4-4
  4.5 Calculation Cases for Design Options .......................................................................................4-5
  4.6 Results of Thermal Calculations ..................................................................................................4-8

5 OPTION 2: MULTI-LEVEL REPOSITORY BASED ON THE CURRENT REFERENCE REPOSITORY DESIGN ..............................................................5-1
  5.1 Introduction .....................................................................................................................................5-1
  5.1.1 Upper-Level Evaluation........................................................................................................5-1
  5.1.2 Second- and Third-level Evaluations ...................................................................................5-1
  5.2 Conclusions ...................................................................................................................................5-2

6 OPTION 3: GROUPED-DRIFT REPOSITORY BASED ON THE CURRENT REFERENCE REPOSITORY DESIGN ................................................6-1
  6.1 Evaluation ......................................................................................................................................6-1
  6.2 Conclusions ....................................................................................................................................6-2
1
INTRODUCTION

1.1 Purpose

A deep geological repository at Yucca Mountain has been proposed for the disposal of spent fuel from the nation’s commercial reactors and other radioactive waste. The reference capacity of 70,000 MTHM of initial heavy metal, as mandated by the Nuclear Waste Policy Act of 1982 (NWPA), includes 63,000 MTHM of commercial spent nuclear fuel (CSNF), the projected amount of CSNF that will be produced by about 2014. It is clear, however, that a large percentage of reactors in the United States will continue to operate beyond 2014, and that new initiatives are underway to expand the base capacity of nuclear power to meet both energy and environmental imperatives.

Several options are being considered for the future generation, management, and disposition of spent nuclear fuel. EPRI’s sponsors recently requested that EPRI explore the potential expansion of the amount of CSNF that can be disposed at Yucca Mountain above the 63,000 MTHM value that is presently the basis for USDOE’s planned license application to the USNRC. While EPRI is fully aware that to expand Yucca Mountain’s capacity above 70,000 MTHM would require legislation, it seems technically feasible to do so. Considerable resources have been devoted over nearly 30 years to characterize the Yucca Mountain site with respect to nuclear waste disposal and to identify potential repository designs. This characterization and design work suggests that additional, suitable tuff formations exist adjacent to the “primary” block, and that higher density repository designs are possible. In addition, several independent analyses by the USDOE, USNRC and EPRI indicate that the current repository design based on spent fuel as a waste form will meet regulatory compliance goals by the USNRC and the USEPA.

The purpose of this report, therefore, is to present an initial analysis of the maximum amount of commercial spent nuclear fuel that could be emplaced into a geological repository at Yucca Mountain. This analysis identifies and uses programmatic, material, and geological constraints and factors that affect this estimation of maximum amount of spent fuel for disposal.

1.2 Approach

There are two key physical assumptions made in this preliminary analysis:\1:

- Only the currently characterized rock area at Yucca Mountain as reported by US Department of Energy’s Yucca Mountain Project (USDOE/YMP) is considered.

\1 A third, legal assumption made in this report is, of course, that Congress would take the necessary action to allow additional CSNF disposal at Yucca Mountain. However, this report focuses exclusively on the physical assumptions and limitations.
• The USDOE/YMP’s current ‘line-load’ high-temperature operating mode (HTOM) for a repository design, in which the temperature of waste packages rise above boiling for up to 1800 years, is adopted².

By using these two assumptions, the results of this analysis of the maximum amount of spent fuel capable of disposal at Yucca Mountain will eliminate the need for additional, up-front design or site characterization work prior to the construction license application for the initial 70,000 MTHM, hence, minimize near-term schedule or funding impacts to the YMP. Options such as (a) an expanded amount of site characterization and/or (b) extended surface storage or ventilation period prior to repository closure, and/or (c) alternative designs (for example, the previous HTOM mode considered by YMP with the more space-efficient 29-m pitch between emplacement drifts, BSC, 2003a) would further increase the maximum spent-fuel disposal capacity at Yucca Mountain. Potential implications of these additional options are discussed in this report in a qualitative manner but not included in the present quantitative analyses.

Based on these constraints, factors and assumptions, three basic strategies or ‘Options’, for maximizing the amount of spent fuel for disposal are explored:

• Expanding the current line-load/HTOM design over the maximum rock area at Yucca Mountain considered suitable for spent fuel disposal by the USDOE/YMP.

• Constructing a multi-level set of emplacement drifts in which the exact same geometrical configuration of emplacement drifts of the line-load/HTOM design would be constructed at three different levels.

• Constructing a single-level repository by grouping three emplacement drifts (triad) in which two additional emplacement drifts, each with virtually identical properties as the current line-load/HTOM emplacement drifts, would be emplaced at 20-m horizontal offsets on either side of each of the currently planned emplacement drifts.

Impacts on post-closure repository performance, notably thermal impacts and potential degradation of barrier functions arising from thermal effects, are evaluated for each of these strategies. Opportunities for hybrid combinations of these options are discussed, but no formal analyses of such hybrid options have yet been made.

A reoccurring term calculated in this report is the ‘expansion factor,’ which is equal to the amount of CSNF that could be emplaced at Yucca Mountain for a specific option divided by the current 70,000 MTHM legislative limit of waste, which is composed of 63,000 MTHM of CSNF and 7,000 MTHM of defense high-level waste (DHLW) and naval reactor spent fuel, that could be emplaced in the reference repository design. This formulation of an expansion factor is conservative, because it is anticipated that in expanded designs, essentially all of the increased amount of waste disposed would be CSNF. One of the primary physical constraints to potential expansion of Yucca Mountain capacity is the decay-heat load. In general, CSNF decay heat on a per-MTHM basis is larger than that for non-CSNF wastes. Hence, the assumption that any Yucca

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² This is the so-called high-temperature operating mode, HTOM, design with a 1450 Watts/m line-load and an 81-m pitch between line-loaded emplacement drifts (BSC, 2003a).
Mountain capacity expansion is occupied by 100% CSNF is conservative. This assumption is made to avoid any issues with speculations on co-expansion of non-CSNF wastes or differences in dimensions and heat loadings of various radioactive wastes.

1.3 Report Organization

Section 2 of this report discusses various programmatic, material and geological constraints and limits that affect consideration of maximizing the amount of spent fuel capable of disposal at Yucca Mountain. In Section 3, the straightforward strategy of expanding the current HTOM design over the repository area previously identified as suitable for spent fuel disposal by the USDOE/YMP is examined. Specific multi-level and grouped-emplacement drift designs and the detailed thermal calculations conducted for each of these designs are presented in Section 4. Based on these thermal analyses, Section 5 and Section 6, respectively, contain evaluations of the post-closure consequences of maximizing spent fuel disposal for the multi-level and grouped emplacement-drift options. Other factors and options, including the potential for hybrid designs, which could lead to even greater amounts of spent fuel being disposed at Yucca Mountain, are presented in Section 7 in order to identify possible future refinements to this present preliminary report. Finally, Section 8 contains a summary of results and recommendations based on the reported analyses, followed by cited references in Section 9. Appendices A, B and C contain supplemental information on thermal impacts on natural barrier performance, thermal impacts on corrosion behavior of reference waste packages, and possible ventilation strategies to manage heat in the Yucca Mountain repository, respectively.
2
CONSTRAINTS ON THE SPENT-FUEL DISPOSAL
CAPACITY AT YUCCA MOUNTAIN

There are several important physical constraints on potential expansion of Yucca Mountain capacity. These include the geologic setting of Yucca Mountain itself, programmatic decisions on repository location, use of the current repository design, and thermal constraints. Each of these constraints is discussed in more detail in this chapter.

2.1 Geologic Setting of Yucca Mountain

Figure 2-1 is a geologic log for UZ 14, a borehole that is located in a wash near the Drill Hole Wash Fault in the north end of the Primary Block (Figure 2-5). Most designs locate the repository within Topopah Spring Tuff over the section shaded yellow from the bottom of the upper lithophysal zone to the lower lithophysal zone (Figure 2-1). The repository host horizon (yellow shading) cuts across the stratigraphy because the rock units are dipping while the drifts remain somewhat horizontal (Figure 2-2).

At the location of UZ 14, the top of the host horizon is about 200 m from the ground surface. The requirement that all portions of the facility be located 200 m or more below the ground surface was established in the Final General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories (U.S. Department of Energy, 1984). This somewhat arbitrary, but conservative minimum depth below the surface was specified to provide a buffer against erosion that could lead to nuclide releases. It is unlikely that even one million years of erosion will come close to causing the full 200 meters of rock over the proposed repository to be removed. Projections on erosion estimate less than 1 meter per 10,000/years in canyons above the repository, and less than 0.02 m of slope retreat (U.S. DOE, 1995). Furthermore, it is not yet clear whether there are lithologic preferences guiding the selection of the lower part of the Topopah Spring Unit. It may be possible, therefore, to expand the repository horizon upward into the upper reaches of the upper lithophysal and possibly even into the upper non-lithophysal units.

Figure 2-2 is a north-south cross-section through the Primary Block, which provides a schematic representation of the geologic setting. The proposed repository is consistently located in the lower part of the Topopah Spring Tuff. The repository zone shown on Figure 2-2 is thicker than the diameter of a planned drift. A 100-meter thick repository zone created with stacked drifts could be accommodated along this plane.
Figure 2-1
Borehole Log for UZ 14 (from Bodvarsson, et al., 1997)
Figure 2-2
A North-South Schematic Cross-Section Through the Upper Block of the Primary Area
(from Robinson, 2004)

Figure 2-3 is a schematic east-west cross section through the proposed repository. When the repository is shown in this view, it becomes clear why the repository host horizon transitions from the lower part of the Topopah Spring to the Upper Lithophysal Zone because of the dip. A 100-meter thick repository would, as a first approximation, span most of the entire Topopah Spring Tuff from top to bottom.
Because this cross-section is blocky, it is difficult to discern that the current design results in the top of the repository being nearly within 200 meters of the ground surface near the Solitario Canyon Fault. For a stacked (100 m) repository design (see Section 4 of this report) to work and maintain some separation from the ground surface, either the left (west) end of the upper portions of the stacked repository would need to be extended further eastward, or the somewhat arbitrary, 200-meter minimum ground cover administrative constraint would need to be revised. In effect, less of the current design footprint would be available for the stacked repository design if the 200-meter minimum ground cover constraint was retained.

Figure 2-3
East-West Cross-Section Through the Proposed Repository. Because of the Dip of Units, the Proposed Host Rock for the Repository Changes from West to East (from Houseworth and Bodvarsson, 2004)
2.2 Programmatic Decisions on Repository Location

Various studies in the past (e.g., Mansure and Ortiz, 1984; CRWMS M&O, 1994) have examined the question of how large an area at Yucca Mountain might be suitable for development as a repository. Mansure and Ortiz, 1984 (pg. 8) developed criteria used in both its own study as well as in CRWMS M&O (1994), namely:

- “It is preferable that the underground facility be in the moderately to densely welded devitrified zone of the Topopah Spring Member containing less than 15-20% lithophysal cavities above the basal vitrophere.”
- “All portions of the underground facility must be at least 200 m below the directly overlying ground surface.”
- “The underground facility should be above the water table.”

The first criterion bears on mineability (e.g., ease of excavation, stability of excavations, need for ground support, etc.) and the effect of lithophysal cavities that formed during the initial ash-fall event that created each tuff unit. Some reasonable depth below the ground surface assures that normal erosion will not expose the repository over regulatory timeframes, although a 200-meter minimum depth criterion appears conservative. Finally, a site above the water table is implied as providing better performance, although back in 1984 this concept was not yet well developed.

The application of the criteria listed above is useful for generating theoretical areas, usable for repository placement. Selection of a more realistic usable area(s), however, requires consideration of other factors such as natural boundaries provided by major faults, needs to maintain flexibility in the design, and safety issues.

Performance assessment provides the tool for understanding the impact of various factors of waste package and repository design, thermal loading, and physical and climatic settings in estimating how a repository is likely to behave. Thus, criteria like those above, while useful for screening and preliminary assessments, are not sufficient in and of themselves to fully validate the efficacy of expanding the repository area. As subsequent discussions indicate, the most comprehensive set of performance assessments have been carried out for the reference design outlined in the following section.

2.3 Current Reference Repository Design

The current line-load/high-temperature operating mode (HTOM) repository design is shown in Figures 2-4 and 2-5. Figure 2-4 shows the basic dimensions and geometry for the current repository design, with a 10-cm spacing between each nuclear waste package within an emplacement drift, and an 81-m pitch between emplacement drifts. The fundamental aspects of this design include:

- Close spacing causes each drift to simulate a ‘line-load’ of radiogenic heating with intense but uniform heating along the entire length of each emplacement drift.
- Radiogenic heating causes localized boiling and removal of water within the emplacement drift and to a limited extent within the surrounding tuff.
• Extended spacing between drifts and limited extent of boiling around drifts assures that a
  sub-boiling pillar of tuff rock persists for all time between the neighboring emplacement
drifts.

Taken together, this design results in a reduced number of drifts (by about 30) but over
approximately twice the area compared to ‘point load’ configurations, an extended dry period of
1000-2000 years within the drifts, the potential formation of locally saturated regions in the tuff
above emplacement drifts, and an avenue for gravitationally driven flow to safely drain water
from the saturated regions in the cool region between emplacement drifts. Continuous
mechanical ventilation is required during the pre-closure period to meet pre-closure logistical
and temperature requirements.

It is important to stress that while this design is treated as a fixed constraint in this analysis, it is
merely the latest reference design option in a long sequence of viable repository designs that
have been explored and evaluated by the USDOE/YMP. This extremely large 81-m pitch is a
recent conservative design modification, which is relatively space-inefficient compared to other
designs that are within rock-mechanical constraints determined by the need for mechanical
stability of the drifts (Appendix A). There is no legal or regulatory ‘criterion’ for such a space-
inefficient 81-m pitch between emplacement drifts. Modeling the behavior of such a layer of
condensate (e.g., Buscheck et al., 2006a) has proved difficult due to the interaction of
computational limitations with the complex physics of two-phase porous-medium flow in
regimes where instabilities may occur. It has been speculated (see Section 2.5 for more detail)
that such a saturated layer of condensate water might later lead to a temporary period of water
flow into emplacement drifts as boiling isotherms eventually contract inwards and the repository
system returns to sub-boiling conditions. Thus, the prime motivation for this modification of an
81-m spacing between drifts is to allow drainage of any layer of condensate water from above
the repository through a sub-boiling pillar of tuff between the drifts.

The current repository ‘footprint’ in plan view (Figure 2-5) covers an area of about 6.5 km² or
1600 acres with emplacement of 70,000 MTHM of initial heavy metal mostly in the Upper Block
of the so-called ‘Primary Area’ except for that portion north of the Drill-Hole Wash Fault. The
Upper Block of the Primary Area is commonly considered to be located between the Solitario
Canyon Fault on the west, and the Ghost Dance Fault to the east, and the Drill-Hole Wash Fault
to the north (see Figure 2-6 and 3-2). Because of these fault boundaries, the design incorporates
setbacks from the actual faults. The present design (Figure 2-5) also includes an area between the
Drill-Hole Wash Fault and the Pagany Wash Fault. The importance of the Drill-Hole Wash
Fault, which cuts the proposed repository footprint, has been de-emphasized because “tunneling
in 1995 showed the structure to be less prominent than originally thought.” (CRWMS M&O,
1996). Thus, more recent designs usually extend the repository through the Drill-Hole Wash
Fault to the Pagany Wash Fault (e.g., Figure 3-3). There is confusion in that recent reports
redefine the larger area, extending north to Pagany Wash Fault as the Primary Area (e.g., Figure
3-3). For the purposes of this report, we consider the Primary area considered to have the Drill-
Hole Wash Fault as the northern boundary (Figure 3-2).
There has been considerable emphasis on repository designs that focused on the Upper Block of the Primary Area. Some designs have also envisioned the same quantity of waste distributed over a larger footprint, a strategy designed to provide lower thermal loading. Some of the area requirements associated with these designs, because they demonstrate the possibilities of expanding the repository footprint beyond the Upper Block, are examined in Section 3.

Figure 2-4
Schematic Diagram of Reference Yucca Mountain Repository Configuration of Line-Loaded Waste Packages and Drift Spacing (from BSC, 2004a, Figure 6.2-2)
Figure 2-5
Layout of the Proposed Repository and its Association with Key Geologic Units.
Source: Underground Layout Configuration (BSC, 2003b)
Figure 2-6
Location of Faults at Yucca Mountain and in the Vicinity (BSC, 2004b)
2.4 Thermal Limits

Of primary concern to evaluations of maximizing the CSNF disposal capacity at Yucca Mountain is consideration of thermal limits to natural and engineered barriers. Increasing the thermal loadings within repository blocks could lead to higher than previously anticipated temperature. Elevated temperature, in turn, could engender and accelerate thermally activated degradation processes that could compromise the long-term isolation functions and performance of such barriers.

Detailed thermal analyses for the multi-level design option and the grouped-drift design option are presented in Section 4. Based on these analyses, Appendices A and B examine possible thermally activated degradation processes and thermal constraints for tuff and engineered barrier system components, respectively.

A cladding thermal limit of 350°C has been established to avoid rod failures due to creep. Analyses performed by the Project (CRWMS 2000) indicate that the 350°C cladding criterion is not violated if the WP surface temperature does not exceed 250°C after emplacement in the repository. Thermal analyses performed here for alternative multi-tier and grouped-drift repository designs indicate that the peak EBS temperature will not exceed 229°C (Table 4-4). Therefore, it seems unlikely that in-package fuel rod creep failures will occur following emplacement for any of the optional repository designs considered. However, for the current analysis, the 350°C cladding thermal limit has not been deemed to represent a constraint on the optional repository designs considered for expanded fuel capacity at YM.

2.5 Sub-boiling Pillars between Drifts

A recent design perspective is preservation of a sub-boiling region, or ‘pillar’, between emplacement drifts for all times after waste emplacement and repository closure. Such a design concept would allow drainage of any condensate water (regions with 100% saturation in the rock) that might arise in the region above multiple emplacement drifts. A wide 81-m spacing, or ‘pitch’, between drifts has been proposed to preserve a sufficient portion of the pillars would be at sub-boiling conditions below at the repository elevation. This design would always allow drainage of thermally mobilized water through the central portion of the pillars and ensure the hydrologic independence of individual emplacement drifts.

Designs as recent as the 2002 Final Environmental Impact Statement or FEIS (USDOE, 2002a), however, did not incorporate such a sub-boiling pillar preserved for all time. Instead, it was assumed that the eventual formation of sub-boiling pillars as the rate of radiogenic heating decreased, with lateral water diversion along fractures in tuff, would adequately assure drainage of early-formed condensate water above emplacement drifts that had pitches much smaller than 81-m. For example, a 29-m pitch between emplacement drifts was used in the FEIS design (USDOE, 2002a; 2002b) and acceptable repository performance as obtained for such a design.
Furthermore, it should be noted that drift-scale thermal calculations by the USDOE/YMP indicate that the mean average lateral extent of boiling is about 8 m from the drift waters for representative infiltration rates and thermal conductivity ($K_{th}$) values for tuff (Figure 2-7). Thus, the 81-m pitch between drifts represents nearly a 4- to 5-fold engineering conservatism compared to the reasonably expected value for lateral extent of boiling, and this 81-m pitch appears considerably larger than is needed to accommodate the expected variability of rock conditions.

In conclusion, the current YMP repository HTOM design concept with an 81-m pitch between drifts is adopted for these preliminary analyses of the maximum capacity for CSNF disposal at Yucca Mountain. However, the 81-m value is based on a 4- to 5-fold conservative engineering analysis for the purpose of achieving a drainage pillar for condensate water that will eventually form for much smaller drift pitches. Future analyses of the maximum amount of CSNF that could be disposed at Yucca Mountain could examine repository designs with significantly smaller pitch between emplacement drifts, resulting in potentially higher disposal capacities (see Section 7).
3

OPTION 1: EXPANDED FOOTPRINT OF THE CURRENT YMP REPOSITORY DESIGN

3.1 Previous Studies

Previous studies have examined the subsurface area that might be available for waste storage at Yucca Mountain. A study by Mansure and Ortiz (1984) formed the basis for much of the follow-on work in the 1990s. Their work identified six potentially usable areas in and around Yucca Mountain (Figure 3-1). Area 1 is the Primary Area discussed in the previous section, including both the Upper and Lower Blocks. Area 2 comprises approximately 9.11 km$^2$ (2250 acres), west, north and east of the Primary Area. The present repository design includes part of Area 2. As is evident in Figure 3-1, the boundaries for Area 2 are mostly determined by major faults. Area 3 is relatively small (1.62 km$^2$, 400 acres) bounded by the Sever Wash and Pagany Wash Faults. Area 4 is located immediately west of the Primary area and contains about 6.07 km$^2$ (1500 acres). Area 5 is located south of the primary area and is also quite small (2.02 km$^2$, 500 acres). Area 6 is the largest of the areas (10.72 km$^2$, 2650 acres) but also is the most complicated structurally. It incorporates rocks to the east of the Primary Area to the Bow Ridge Fault. Overall, the Mansure and Ortiz study identified 37.03 km$^2$ that theoretically might be suitable for waste disposal.

CRWMS M&O (1994) examined the possibilities of using areas outside the Primary Area in order to accommodate a wider distribution of waste to provide lower thermal loads. That analysis started with the Mansure and Ortiz (1984) study and went on to define repositories of different areas. The largest repository design encompassed approximately 10.90 km$^2$ and involved six separate areas. This total area is about 30% of the theoretical area outlined by Mansure and Ortiz (1984). The informal names for these six areas are given in Table 3-1 together with information on areas and physical settings. Their locations in relation to major faults are shown in Figure 3-2. The report (CRWMS M&O, 1994) reiterates that there is a paucity of data north and west of the Primary Area.

Table 3-1

Descriptive Summary of Six Potential Repository Areas Described in CRWMS M&O (1994)

<table>
<thead>
<tr>
<th>Potential Emplacement Area</th>
<th>Estimated Area (km$^2$)</th>
<th>Depth to Repository (m)</th>
<th>Water Table Below Repository (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Area (Upper Block)</td>
<td>3.76</td>
<td>200-400</td>
<td>260-365</td>
</tr>
<tr>
<td>Primary Area (Lower Block)</td>
<td>0.88</td>
<td>215-320</td>
<td>260-290</td>
</tr>
<tr>
<td>Optional Area A</td>
<td>0.63</td>
<td>290-450</td>
<td>110-250</td>
</tr>
<tr>
<td>Optional Area B</td>
<td>1.78</td>
<td>200-460</td>
<td>180-300</td>
</tr>
<tr>
<td>Optional Area C</td>
<td>1.47</td>
<td>200-270</td>
<td>200-270</td>
</tr>
<tr>
<td>Optional Area D</td>
<td>2.37</td>
<td>160-250</td>
<td>160-250</td>
</tr>
</tbody>
</table>
Figure 3-1
Map Showing Potentially Usable Storage Areas (from Mansure and Ortiz, 1984)
A comparison of Figures 3-1 and 3-2 indicates that of the areas defined by Mansure and Ortiz (1984), Area 6 is least represented in the more recent design (Figure 3-2). The area east and southeast of the Upper Block of the Primary Area is still considered quite complicated from a structural viewpoint. The numerous fault traces on Figure 3-2 in this region labeled as ‘Area of Interest’ reflects this structural complexity.

Generally, evaluations examined potential areas as far west as the Fatigue Wash Fault, which is located about 1.5 to 2 km west of the Solitario Canyon Fault and Yucca Mountain (Figure 2-6). There are references in more recent documents to areas even further west. For example, Figure 3-3, taken from Figure 5 from the Yucca Mountain Science and Engineering Report (USDOE, 2002b) envisions a repository footprint of about 23 km$^2$. This larger region (compared to Figure 3-2) is created mainly by adding Area 7 (1.7 km$^2$), by extending the Primary Area southward and by increasing the size of the Lower Block (from 0.88 to 5.16 km$^2$). With little geologic data available west of Yucca Mountain, exploration would be necessary to confirm the suitability of this area. However, it does suggest the possibility for more usable blocks amongst the north-south major fault zones.
Figure 3-3
One Planning Scenario for a Proposed Repository with a Low Temperature Operating Mode. Note Area 7 West of Fatigue Wash Fault. A Design Incorporating all the Areas would Entail Approximately 23 km$^2$ (from US DOE, 2002b)
3.2 Evaluation

The current design for the repository encompasses about 6.5 km², including the Upper Block of the Primary Area and a northward extension. There are relatively detailed geologic and hydrogeologic characterizations indicating relatively minor structural disturbance of this block. The anticipated repository horizon in the Upper Block is 200-400 meters above the water table and 200-400 below the ground surface. Other areas exist that also satisfy siting criteria. The addition of these five other areas, including the Lower Block of the Primary Area, approximately doubles the area for the proposed repository (13 km²) (Figure 3-2). The designs for this larger repository become more complex because of the number of areas involved and because, generally, the repository levels would be at different elevations. The cross-section (Figure 3-4), for example, shows that rocks west of the Solitario Canyon Fault occur at a lower elevation than those to the east of the fault.

The cross-section (Figure 3-4) also makes it apparent how far west these enlarged footprints would extend. In effect, the repository is better described as being in the Yucca Mountain region, because of the extension to the west. The main uncertainty for establishing the suitability of the area to the west of Solitario Canyon Fault is that areas north and west of the Upper Block are not as well explored geologically as the Upper Block, and few, if any, performance assessments have been run.

There is some possibility of increasing the repository area up to about 23 km². This area is about 60% of the potential usable storage estimate of Mansure and Ortiz (1984). This area size is speculative because it includes a relatively large usable area in the Lower Block in regions of apparent structural complexity (Area 6; Figure 3-1) and farther west, beyond Fatigue Wash Fault. Any proposed repository design of this size may be logistically more complicated because, beyond the Primary Area, no single intact block between major faults is very large. The design would require linking a number of smaller areas together. Likely, the major constraint on repository size is not running out of potential expansion areas but the increasing potential difficulties in using an ensemble of small undisturbed blocks bounded by faults, spread out over a large area.

Petersen (2006) suggested the feasibility of a maximum design area of ~17 km² or 4200 acres, based on a low temperature design from the Draft Environmental Impact Statement. This estimate incorporates six of the seven blocks of Figure 3-3, with a smaller area of the Lower Block. This suggested area is in line with estimates discussed herein.

3.3 Conclusions

The current proposed repository design has focused on the Upper Block of the Primary Area and a northward extension that encompasses about 6.5 km² or 1600 acres. Table 3-2 shows various expansion factors (the ratio of possible repository area divided 6.5 km²) based on the analyses described in this section.
There are several key points to note from Table 3-2. First, the estimates of area available for a repository at Yucca Mountain generally decrease with increasing information, reflecting earlier area estimates based on limited characterization to areas estimates that are now based on more complete site characterization. Second, area estimates may also be based on assumed repository designs, especially areal heat loading and thermal limits, prevailing at the time that the estimates were made. Third, while it is prudent to not assume too favorable a set of hydrogeologic characteristics in less well-characterized blocks of Yucca Mountain, the possible presence of fractures in such tuff blocks, by itself, may not prevent safe emplacement of waste packages in such areas.
Table 3-2
Range of Estimated Expansion Factors for Option 1: Extending the Current YMP Repository Design to Characterized Areas of the Yucca Mountain Region

<table>
<thead>
<tr>
<th>Source</th>
<th>Extended Area (km²)</th>
<th>Expansion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mansure and Ortiz (1984)</td>
<td>37.03</td>
<td>5.7</td>
</tr>
<tr>
<td>CRWMS M&amp;O (1994)</td>
<td>10.90</td>
<td>1.7</td>
</tr>
<tr>
<td>Yucca Mountain Science and Engineering Report (USDOE, 2002b)</td>
<td>23</td>
<td>3.5</td>
</tr>
<tr>
<td>FEIS (2002a and earlier drafts, Section 2.1.2.2)</td>
<td>10</td>
<td>1.5</td>
</tr>
<tr>
<td>Peterson (2006)</td>
<td>17</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>This Study</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Confident</td>
<td>13</td>
<td>2.0</td>
</tr>
<tr>
<td>• Possible</td>
<td>17-23</td>
<td>2.6-3.5</td>
</tr>
</tbody>
</table>

Based on Table 3-2, there are good prospects for at least doubling the capacity for CSNF disposal at Yucca Mountain by taking advantage of well-characterized, structurally intact blocks that adjoin the current Upper Block for the current repository design. With additional work, there are possibilities of a maximum design footprint of 17 km² to 23 km² (4200 acres to 5700 acres) based on the level of site characterization information regarding the Yucca Mountain area presently available. For these larger prospective areas, the repository design will require linking together numerous small blocks. Any larger repository footprints, approaching the early estimate of Mansure and Ortiz (1984), will probably require expansion south and southeast of the Primary Area. This area has positive features but is associated with distributed structural features that may require significant additional study to evaluate.

A credible planning expansion factor for the footprint of the proposed repository would be three times the present design or 19.5 km², which is close to that independently derived by Petersen (2006).
4 THERMAL ANALYSES OF DESIGN OPTIONS

4.1 Introduction

A screening model has been established to evaluate the thermal capacity at Yucca Mountain. The model considers two different repository conceptual design options proposed by the EPRI team in order to investigate the Yucca Mountain potential to accommodate more spent nuclear fuel:

- Constructing a multi-level set of emplacement drifts in which the exact same geometrical configuration of the emplacement drifts of the line-load/HTOM design would be constructed at three different levels (Figure 4-2).

- Constructing a single-level repository with triad-grouped drifts in which two additional emplacement drifts, each with virtually identical properties as the current line-load/HTOM emplacement drifts, would be emplaced at 20-m horizontal offsets on either side of each of the currently planned emplacement drifts. This design option is shown in Figure 4-2.

Both repository design options assume the same footprint as the current design, i.e., maintain a framework of wide pillars spaced on 81-m centers, the same drift lengths, and the total disposal area. The difference is that the first option involves emplacing three levels of the same layout, while the second option involves adding additional drifts within the same repository level.

Modeling of both options is based on coupled heat transfer and two-phase flow with boiling and condensation as simulated by the TOUGH2 code, which is also used by the Yucca Mountain Project (YMP) (Pruess et al., 1999).

4.2 Data on Decay Heat and Ventilation

Data on decay heat history used in this study is from BSC, 2003a. The initial loading of the current design for spent fuel is 1450 W/m per waste package. Various ventilation scenarios are considered (see Appendix C), which are defined as the ventilation efficiencies and time durations. In the model, the ventilation efficiency is equivalent to reduced heat generation rate from spent fuel waste package (BSC 2003a). The ventilation scenarios considered are summarized in Table 4-1. Figure 4-1 shows the decay heat histories with and without ventilation. Note that the heat generation rate is based on unit length per waste package.
Table 4-1
Ventilation Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Heat Removal Efficiency and Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>86.3% 0 – 50 yrs</td>
</tr>
<tr>
<td>II</td>
<td>87.3% 0 – 50 yrs; 93% 50 – 300 yrs.</td>
</tr>
<tr>
<td>III</td>
<td>91% 0 – 50 yrs; 96% 50 – 300 yrs.</td>
</tr>
</tbody>
</table>

Figure 4-1
Waste Package Heat Generation Rate as a Function of Time with and without Ventilation. The Ventilation Scenarios are Defined in Table 4-1. The Step Changes Correspond to Assumed Sudden Changes in Ventilation Efficiency (Appendix C)
4.3 Conceptual Models

The conceptual models established for the two repository concepts are only different in geometry at the repository horizon, mostly involving the drift arrangement, as illustrated in Figure 4-2. The horizontal extent is from the center of the waste package to the centerline between two adjacent sets of drifts, thereby bounding the model horizontally by two symmetry boundaries. The vertical domain spans approximately 760 m. In these two-dimensional models, the unit length is used in the direction perpendicular to the picture in order to correctly apply the decay heat generation rates shown in Figure 4-1. The top boundary is maintained at constant temperature and pressure and is treated as permeable to gas. Furthermore, a constant infiltration rate of 16 mm/yr is imposed at the top boundary. The bottom boundary of the domain is treated as fully saturated (representing water table) and kept at constant temperature and pressure.

There are five geological layers considered in the model as shown in Figure 4-2, each is assumed to be horizontal and homogeneous. Fractured rock is treated as an equivalent continuum.

Figure 4-2
Illustration of the Conceptual Models Established for Screening Evaluation of Thermal Capacity of Yucca Mountain Repository within the Current Design Footprint (i.e., 81-m drift spacing)
The waste package is represented by a single element in the model. The drift, including invert, drip shield and void space, is represented by another single element. The drift properties are adjusted in model calibration in order to approximate complicated geometry and materials within a drift as accurately as possible. There are a total of 1648 elements for the multi-level model and 1502 elements for the multi-drift model.

The model is first simulated without heating until steady state is reached. The obtained steady-state solution is used as initial conditions to simulate coupled heat and flow processes when heat is applied.

4.4 Calibration of Calculational Model

As a first step, EPRI’s calculational model is calibrated against the published 2-D thermal calculations of a reference repository at Yucca Mountain (BSC 2003a). This calibration is achieved by adjusting hydro-thermal properties within their reported uncertainty ranges (BSC 2003a; Glascoe et al., 2004; BSC 2004a). The property values of the equivalent continuum fractured formations are obtained by volume-weighting fracture and matrix property values, including different units in one formation. To ensure adequate gas phase movement, fracture permeability and capillary pressure values are given higher weightings. The parameter values used in the model are shown in Tables 4-2 and 4-3. The calibration results are shown in Figure 4-3.

It can be seen that the calibrated and reported peak waste package temperatures and temperature histories are in excellent agreement. The calibrated average drift-wall temperature also matches satisfactorily with the reported drift-wall temperatures at the crown and side positions. The current EPRI model does not have the same spatial discretization as the earlier model, and hence, there is no equivalent comparison for the drift-base location.

Figure 4-3 also shows the gas saturation in rock immediately surrounding the drift, an important parameter from the EPRI model, to evaluate and compare various options for maximizing the capacity of the Yucca Mountain repository for disposal of CSNF. Figure 4-3 shows the general relationship in which dry-out corresponds to the time period of temperature exceeding boiling point that lasts from shortly after 50 years following waste emplacement, when ventilation is turned off, to approximately 1300 years. Note, it is assumed that emplacement of all wastes within the repository occurs simultaneously, and both the BSC and the EPRI models used ventilation Scenario I listed in Table 4-1.
4.5 Calculation Cases for Design Options

EPRI’s calibrated calculational model is used to simulate the hydro-thermal behavior of the two repository conceptual designs (Options 2 and 3). A total of twelve Cases have been considered, covering a range of design, heating and ventilation scenarios. The definitions of these Cases are given in Table 4-4.
Table 4-2
Hydro-Thermal Properties

<table>
<thead>
<tr>
<th>Domain</th>
<th>Density [kg/m³]</th>
<th>Permeability [m²]</th>
<th>Porosity</th>
<th>Thermal conductivity (wet/dry) [W/m-K]</th>
<th>Heat capacity [J/kg-K]</th>
<th>λ</th>
<th>(\alpha/\rho g) [1/Pa]</th>
<th>(S_{\text{spr}})</th>
<th>Initial Water Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste Package</td>
<td>8189</td>
<td>0</td>
<td>0</td>
<td>14.42</td>
<td>489</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Drift¹</td>
<td>2530</td>
<td>(10^{-10})</td>
<td>0.9</td>
<td>1.5 – 14.41</td>
<td>901</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.1</td>
</tr>
<tr>
<td>TCw</td>
<td>2511</td>
<td>(1.19\times10^{-12})</td>
<td>0.196</td>
<td>1.96/1.6</td>
<td>844</td>
<td>0.6081</td>
<td>1.26\times10^{-1}</td>
<td>0.1867</td>
<td>0.7</td>
</tr>
<tr>
<td>PTn</td>
<td>2316</td>
<td>(4.65\times10^{-13})</td>
<td>0.4517</td>
<td>1.027/0.47</td>
<td>1185</td>
<td>0.6104</td>
<td>9.26\times10^{-4}</td>
<td>0.095</td>
<td>0.5</td>
</tr>
<tr>
<td>TSW</td>
<td>2500</td>
<td>(3.91\times10^{-12})</td>
<td>0.1272</td>
<td>2.418/2.08</td>
<td>901</td>
<td>0.6079</td>
<td>1.46\times10^{-1}</td>
<td>0.191</td>
<td>0.8</td>
</tr>
<tr>
<td>CHn</td>
<td>2358</td>
<td>(2.36\times10^{-13})</td>
<td>0.3132</td>
<td>1.343/0.75</td>
<td>1141</td>
<td>0.5098</td>
<td>4.61\times10^{-4}</td>
<td>0.3032</td>
<td>0.7</td>
</tr>
<tr>
<td>CFU</td>
<td>2410</td>
<td>(2.5\times10^{-15})</td>
<td>0.259</td>
<td>1.36/0.74</td>
<td>633</td>
<td>0.6079</td>
<td>5.42\times10^{-4}</td>
<td>0.01</td>
<td>0.7</td>
</tr>
</tbody>
</table>

1. The drift domain includes invert, drip shield, and void space.

Table 4-3
Initial Conditions

<table>
<thead>
<tr>
<th>Pressure [bar]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top boundary</td>
<td>0.84</td>
</tr>
<tr>
<td>Bottom boundary</td>
<td>0.92</td>
</tr>
<tr>
<td>Infiltration rate (constant)</td>
<td>16 mm/yr</td>
</tr>
</tbody>
</table>

Also shown in Table 4-4 is the ‘expansion factor,’ the expanded capacity of the repository for the disposal of CSNF for each Case compared to the current design. For example, in Case 1, all three levels are configured the same as the current repository design, hence, the total increase in capacity is three times the current design within the current footprint (i.e., 81-m horizontal drift spacing).

Cases 1 to 6 provide the basis for sensitivity analyses of various design factors for the three-level repository option, including the effect of lower thermal loading for each of the three levels, vertical spacing of levels, and the effect of an extended period of ventilation after 50 years following emplacement. Cases 7 to 12 present the basis for sensitivity analyses of same design factors for the grouped-drift design option.
Table 4-4
Definition of Calculation Cases (horizontal spacing is 81-m for all Cases)

<table>
<thead>
<tr>
<th>Case</th>
<th>Repository Concept</th>
<th>Initial Loading</th>
<th>Expansion Factor</th>
<th>Ventilation Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Three-level, 30-m vertical drift spacing</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>2</td>
<td>Three-level, 30-m vertical drift spacing</td>
<td>1000 W/m for all waste packages</td>
<td>2 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>3</td>
<td>Three-level, 50-m vertical spacing</td>
<td>1000 W/m for all waste packages</td>
<td>2 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>4</td>
<td>Three-level, 50-m vertical spacing</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>5</td>
<td>Three-level, 30-m vertical spacing</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 87.3%; 50 – 300 yrs: 93%</td>
</tr>
<tr>
<td>6</td>
<td>Three-level, 30-m vertical spacing</td>
<td>1000 W/m for all waste packages</td>
<td>2 times</td>
<td>0 – 50 yrs: 87.3%; 50 – 300 yrs: 93%</td>
</tr>
<tr>
<td>7</td>
<td>Single-level, 3-drifts 20-m apart</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 87.3%; 50 – 300 yrs: 93%</td>
</tr>
<tr>
<td>8</td>
<td>Single-level, 3-drifts 20-m apart</td>
<td>1450 W/m for center waste package, 725 W/m for side waste packages</td>
<td>2 times</td>
<td>0 – 50 yrs: 87.3%; 50 – 300 yrs: 93%</td>
</tr>
<tr>
<td>9</td>
<td>Single-level, 3-drifts 20-m apart</td>
<td>1450 W/m for center waste package, 725 W/m for side waste packages</td>
<td>2 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>10</td>
<td>Single-level, 3-drifts 20-m apart</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>11</td>
<td>Single-level, 3-drifts 20-m apart</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 91%; 50 – 300 yrs: 96%</td>
</tr>
<tr>
<td>12</td>
<td>Single-level, 3-drifts 20-m apart</td>
<td>1450 W/m for center waste package, 725 W/m for side waste packages</td>
<td>2 times</td>
<td>0 – 50 yrs: 91%; 50 – 300 yrs: 96%</td>
</tr>
</tbody>
</table>
4.6 Results of Thermal Calculations

Figure 4-4 shows an example of temperature and gas saturation evolutions for the multi-level repository concept using the Case 1 design. It can be seen that the top drift essentially performs as the current design, with an above-boiling, dry-out zone that expands to a maximum distance of approximately 10 m away from the drift before contracting and dissipating within the waste package as the rate of radiogenic heating decreases (BSC 2003a).

For all three repository levels, the high temperature contours first expand from the drifts both horizontally and vertically. In the vertical direction, the outward migration of the contours tends to increase with progressively deeper drift levels at any given point in time. This is attributable to heating by the top-level drift that shields infiltrating water from evaporative cooling of the lower drifts. This causes the temperature profiles associated with lower-level drifts to be higher than the profiles of the top drift, creating more extensive, both laterally and vertically, boiling zones than the top-level drift. The boiling front extends to the centerline of the ‘pillar’ between lower-level drifts, which causes temporary dry-out for the second and third levels. In more detailed 3-D thermal models supporting the License Application for the Yucca Mountain repository (Buscheck et al., 2006; Hardin, 2006), condensate water immediately above the dry pillar is predicted to preferentially flow towards the end of the emplacement drifts and the edge of the repository panels where temperatures are sub-boiling due to edge cooling effect. This more realistic thermal effects are not captured by 2-D models similar to EPRI’s model that also are being used in thermal modeling supporting the License Application (Buscheck et al., 2006; Hardin, 2006). The absence of such anticipated drainage of condensate water represents a conservatism in EPRI’s current thermal modeling, hence, EPRI’s results are more representative of restricted areas in the center of the repository.

The boiling in the centerline ‘pillar’ locations for the second and third levels, however, does not last longer than boiling above the waste package, as shown in Table 4-5 and Figure 4-5. Thus, sub-boiling pillars between second- and third-level emplacement drifts, which allow drainage of condensate water located at the boiling front within the tuff, will form long before any condensate water in likely to drain directly into emplacement drifts. Thus, the temporary loss of sub-boiling pillars between second- and third-level emplacement drifts is not expected lead to enhanced drainage of an overlying layer of condensate water into these drifts.

As an example, Figure 4-5 shows Case 2 temperature and saturation histories at the waste packages, rock immediately surrounding the drift (denoted as “Drift Wall” in the figure), and centerline of the pillars between drifts (denoted as “Centerline” in the figure) in all three levels. It can be seen that the waste package in the middle level has the highest temperature, followed by the waste package in the bottom level. The drift-wall temperatures are also plotted in order to study the heating effect on host rock. It can be seen that the above-boiling period of the pillar centerline is much shorter than the above-boiling period of the drift.

Similar hydro-thermal behavior is also observed for other multi-level Cases. In all Cases the temperature at the pillar centerline temporarily reaches the boiling point and, in some Cases, exceeds it. The spatial extent and duration of dry-out depends on the initial heat loading and ventilation efficiency. Results of Cases 3 and 4 demonstrate that heat transfer in the multi-level
repository option can be improved by increasing the vertical spacing between drifts from 30-m to 50-m. A summary of results is given in Table 4-5, which lists the peak waste package temperatures, peak temperature in host rock near the drift, above boiling time duration near the drift, as well as maximum temperature and dry-out period at the centerlines of pillars between drifts.

An example of temperature and saturation contours at different times for the grouped-drift option is given in Figure 4-6. Similar to the multi-level concept, in the grouped-drift Cases, the center drift experiences the most heating. The duration of at-boiling and above-boiling temperatures that occurs at the centerline of the pillar between drifts, depends on the initial heat loading, ventilation efficiency and duration after repository closure. An example of time histories of the obtained results is shown in Figure 4-7. Key results are summarized in Table 4-5.

It should be noted that this model conservatively assumes that all of the CSNF is fully emplaced within the repository instantly at the start of model simulation. Therefore, any times shown in Figures 4-4 through 4-7 and Table 4-5 refer to the time after full emplacement.

It can be seen from Table 4-5 that peak drift temperatures above the peak drift temperature of the current repository design correspond to Cases with a total expansion factor of three (Case 1 and 10) and with the current ventilation design (Scenario I in Table 4-1). As presented in Appendices A and B, however, these higher peak temperatures are expected to no adverse effect on the tuff or waste package, respectively. Table 4-5 also shows that in some Cases (Cases 5, 6, 8, and 12) the peak drift temperatures are below the current-design peak temperatures. These latter Cases correspond to either increased ventilation efficiencies (Cases 5 and 12) or the combination of increased ventilation efficiencies and lowered initial heat loading (Cases 6 and 8), as explained in Table 4-4.

Table 4-5 also shows that for some Cases the temperatures at the centerlines of the pillars approximately 40-m away from drifts are at, or slightly above, the boiling point for 150-200 years. For Cases where the temperature is at boiling, equilibration of vaporization and condensation processes (heat-pipe effects) that are modeled prevents complete dry-out. In the single-porosity model used here, the tuff continues to have a non-zero effective permeability in this situation, but in reality, at-boiling conditions corresponds to a situation where fractures are completely dried out while the matrix is not, which virtually shuts off any liquid flow. If this occurs, multi-scale 3-D thermal models supporting the License Application (Buscheck et al., 2006) indicate that the liquid water would preferentially flow along the drift pillar towards the end of the drift or the edge area of the repository where temperatures are sub-boiling due to the edge-cooling effect.

The 2-D thermal models and assumptions made here are in accordance with similar thermal analyses made by the Yucca Mountain Project (BSC 2003a; Glascoe et al., 2004; BSC 2004a; Buscheck et al., 2006). As shown in Section 4.4 of this report, results from the EPRI model closely match those published by the YMP. There are, however, limitations to both 2-D scoping analyses such as those presented here and multi-scale 3-D thermal analyses (e.g., Buscheck et al., 2006). For example, in 3-D analyses, the cooler ends of emplacement drifts will act as preferentially sites for condensation of evaporated water, allowing 50% or more of the
condensate water to be removed at the edges of the repository (Buscheck et al., 2006; Hardin, 2006) without further interaction with emplacement drifts. Thus, the 2-D model results here should be conservative (i.e., lead to predictions of higher degrees of gas saturation for more prolonged boiling periods within Yucca Mountain than would occur in reality), and are perhaps more representative of thermal effects at the midpoints of the emplacement drifts rather than being representative of the entire length of the emplacement drifts.

Also, tuff has a dual-porosity behavior, which is approximated in the model by a single porosity with equivalent properties, an approximation also used by YMP (Buscheck et al., 2006). While the Section 4.4 calibration shows that the model is able to reasonably reproduce the global behavior of the system, it may not reproduce detailed behavior at a time and place where significant differences between the single-porosity and double-porosity arise, in particular, in regions of tuff where the temperature stays at the boiling point for a long time. In a dual-porosity model of tuff, all the permeability would be in the fractures and almost all the porosity would be in the matrix. The fractures drain first. As soon as the moisture content drops very slightly, the fractures are drained and the permeability drops to zero. This behavior, predicated on a dual porosity model for tuff, is not reproduced by this single permeability model that uses a van Genuchten relative permeability and predicts a non-zero permeability when the water content has dropped below its initial value but has not reached zero. Thus, because tuff can be more realistically represented by a dual-porosity model in which essentially all flow goes through fractures, rock at the boiling point have zero permeability except in a “heat pipe” region whose extent is not determined by the approximate single-porosity model used here. Using the approximate thermohydrologic model used in this study, for all cases (Table 4-5) the pillar centerlines reach or exceed the boiling point. For the cases in which only the boiling temperature is reached, drainage fractures could dry out.

Fracture dry out will obstruct downward drainage of condensate; in such a situation, condensate behavior is difficult to predict. Condensate water that is not preferentially drained at the cooler ends of emplacement drifts (e.g., Buscheck et al., 2006, see previous discussion) will begin to collect above the upper repository level and along the V-shaped trough between emplacement drifts (see Figure 4-4b). Drainage of such condensate water via sub-boiling pillars at the second- and third-levels of a multi-level repository may be blocked for 200-300 years (Table 4-5). The exact behavior of the condensate along this boundary, until pillars re-open, is difficult to predict because cold fluids that are located above hotter fluids in systems capable of flow are inherently gravitationally unstable. A second instability could arise when the relative humidity at the pillar centerline reaches 100%. In models, buoyant upward flow of the soil gas could be blocked by the presence of this zone where the partial pressure of nitrogen and oxygen is zero. Upward flow of hot air could occur, and temperature inhomogeneities could form where the upward flow breaks through. The nonlinearity of the two-phase flow system in a dual-porosity medium makes these instabilities difficult to analyze.

For such potential blocked drainage in pillars to be a relevant and significant factor in these analyses, however, several conditions must be met. First, the blocked water must somehow be transported as a liquid phase from the area of condensation to the emplacement drifts before the blockage in the pillars is alleviated. Heat-pipes effects have been suggested as one such mechanism. For the heat-pipe mechanism to transport liquid waste all the way into the drifts
from the pillar region, there must be sub-vertical, through-going features (e.g., fracture zones) with appropriate transport properties sufficient to enable heat-pipe effects to form, persist and carry water through the above-boiling dry-out zone (a distance of 20-30 meters, see Figure 4-4b, for example) into intersected emplacement drifts. The necessary properties of such an enabling heat-pipe feature or fracture have not been determined, so at this time the ‘heat pipe’ scenario leading to significant inflow of water during the thermal dry-out period must be considered speculative.

Second, assuming such heat-pipe-enabling fractures do occur, such fractures would need to be numerous, wide-spread and preferentially oriented toward intersecting emplacement drifts in order that a large number of waste packages might experience earlier-than-expected inflow of condensate water; no evidence of such numerous or wide-spread fracture zones at Yucca Mountain has previously been cited (USDOE, 2002a; 2002b), nor is it credible that the orientation of such fractures would preferentially lead to intersection between the zone of potential instability and emplacement drifts rather than being uniformly distributed within the Yucca Mountain block.

Finally, the hypothetical inflow of condensate water at early times would need to have a deleterious effect on the containment and release performance of the waste packages for instability of overlying condensate water to be of concern with respect to regulatory compliance. Analyses presented in Appendix B of this report clearly show that any hypothetical early inflow of water during the nominal thermal dry-out period would not have any adverse impact on long-term containment. Furthermore, even if there were early failures of waste packages, the 160-180°C temperatures within emplacement drifts during this period (see Table 4-4) would lead to evaporation of all water within the drifts, preventing any early release of radionuclides via advective or diffusive pathways. Thus, while there are acknowledged uncertainties and potential instabilities of limited condensate water forming above certain multi-level and grouped-drift repository configurations during a 200-300 year period in which sub-boiling drainage pillars are not maintained, further analyses are likely to confirm that the overall risk-consequence of such a hypothetical scenario are insignificant to regulatory compliance.
### Table 4-5
Results Summary

<table>
<thead>
<tr>
<th>Cases</th>
<th>Maximum WP Temperature</th>
<th>Maximum Drift Wall Temperature</th>
<th>Above-Boiling Time Duration at WP and Near Drift [yrs]</th>
<th>Maximum Temperature at Centerlines of Pillars Between Drifts</th>
<th>Location and Duration of Dry-Out at Centerline of Pillars between Drifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>214 °C at 90 yrs</td>
<td>197 °C at 94 yrs</td>
<td>53 – 12,700</td>
<td>142 °C at 300 yrs</td>
<td>Lower two drifts; 112 – 414 yrs</td>
</tr>
<tr>
<td>2</td>
<td>158 °C at 113 yrs</td>
<td>150 °C at 122 yrs</td>
<td>57 – 6,550</td>
<td>113 °C</td>
<td>Lower two drifts; 155 – 406 yrs</td>
</tr>
<tr>
<td>3</td>
<td>138 °C at 182 yrs</td>
<td>132 °C at 186 yrs</td>
<td>65 – 6,200</td>
<td>100 °C</td>
<td>Bottom drift; 245 - 344 yrs</td>
</tr>
<tr>
<td>4</td>
<td>184 °C at 118 yrs</td>
<td>172 °C at 121 yrs</td>
<td>54 – 12,100</td>
<td>129 °C</td>
<td>Lower two drifts; 142 – 396 yrs</td>
</tr>
<tr>
<td>5</td>
<td>128 °C at 576 yrs</td>
<td>124 °C at 608 yrs</td>
<td>400 – 12,100</td>
<td>96 °C</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>111 °C at 844 yrs</td>
<td>109 °C at 844 yrs</td>
<td>500 – 6,500</td>
<td>96 °C</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>147 °C at 519 yrs</td>
<td>139 °C at 519 yrs</td>
<td>340 – 3,840</td>
<td>111 °C</td>
<td>433 – 593 yrs</td>
</tr>
<tr>
<td>8</td>
<td>115 °C at 744 yrs</td>
<td>112 °C at 746 yrs</td>
<td>490 – 3,600</td>
<td>96 °C</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>184 °C at 88 yrs</td>
<td>171 °C at 115 yrs</td>
<td>60 – 3,600</td>
<td>116 °C</td>
<td>148 – 362 yrs</td>
</tr>
<tr>
<td>10</td>
<td>229 °C at 67 yrs</td>
<td>198 °C at 227 yrs</td>
<td>56 – 3,870</td>
<td>154 °C</td>
<td>107 – 382 yrs</td>
</tr>
<tr>
<td>11</td>
<td>146 °C at 523 yrs</td>
<td>138 °C at 525 yrs</td>
<td>330 – 3,660</td>
<td>110 °C</td>
<td>441 – 603 yrs</td>
</tr>
<tr>
<td>12</td>
<td>115 °C at 718 yrs</td>
<td>111 °C at 805 yrs</td>
<td>520 – 3,500</td>
<td>96 °C</td>
<td>No</td>
</tr>
</tbody>
</table>

1. The listed above-boiling time period is the longest among all the drifts.
2. In cases where more than one pillars experience dry-out, the listed is the longest among all the pillars.
Figure 4-4
Example of Temperature and Gas Saturation Contours at Different Times for the Multi-Level Repository Concept (Case 1 Results)
Case 2 (Multi-Level Concept) Results: (a) Temperature Histories at the Waste Packages, Drift Walls, and Centerlines between Drifts in the Top, Middle, and Bottom Levels; (b) Gas Saturation Histories at the Drift Walls and Centerlines in the Three Levels
Figure 4-6
Example of Temperature and Gas Saturation Contours at Different Times for the Grouped-Drift Repository Concept (Case 10 Results)
Figure 4-7
Case 9 (Grouped-Drift Concept) Results: (a) Temperature Histories at the Waste Packages (Center and Side), Drift Walls (Center and Side), as well as at the Centerline Between Drifts; (b) Gas Saturation Histories at the Drift Walls (Center and Side) and Centerline Between Drifts.
5
OPTION 2: MULTI-LEVEL REPOSITORY BASED ON THE CURRENT REFERENCE REPOSITORY DESIGN

5.1 Introduction

Sensitivity analyses of thermal calculations for various Cases of a three-level repository design are presented in Section 4. In this section, it is assumed that each of the three levels is configured identically to the current reference repository concept for Yucca Mountain. Each emplacement drift has closely spaced waste packages to achieve a ‘line-load’ behavior in which the entire length of each drift experiences a uniform heating. The current 81-m spacing between the center drifts in each level is also maintained. Thus, the multi-level repository option considered here would occupy exactly the same 6.5 km² ‘areal footprint’ as the current repository concept and would be located in the well-characterized Upper Block (see Sections 2 and 3).

5.1.1 Upper-Level Evaluation

As shown in Section 4 (see Figures 4-4 and 4-5), the upper level of the three-level repository option would evolve and behave essentially the same as the single-level reference design. The boiling front would extend a maximum of about 10 meters into the surrounding tuff, leaving a large sub-boiling ‘pillar’ region between adjoining emplacement drifts. Thus, any layer of condensate water that might form during the pro-grade heating and boiling period that dries-out the emplacement drifts would always have a pathway for drainage. This would eliminate any possibility of enhanced condensate water from entering drifts in the upper-level, the exact same situation that is anticipated to exist for the current repository design.

The peak wall-rock temperature of emplacement drifts in the upper-level is always less than 160°C (Figure 4-5), which is well below the ~250°C thermal limit for rock failure arising from thermal effects (Appendix A). The peak waste package temperature and the integrated temperature-time profile for waste packages in upper-level drifts (Figure 4-5) is also significantly lower than values previously shown by EPRI’s IMARC/EBSCOM model to not lead to any significant acceleration in waste package corrosion or failure (Appendix B).

5.1.2 Second- and Third-level Evaluations

For the lower second- and third levels of the multi-level repository option, the general heating and boiling behavior is the same as for the upper level of emplacement drifts, as discussed in Section 4. One difference in behavior is that for some Cases, the sub-boiling pillar between emplacement drifts of the lower two levels temporarily disappears for several hundred years (See Figure 4-4 and Table 4-4). As indicated in Section 4, however, the temporary loss of sub-boiling pillars in the lower levels is not expected to lead to any adverse consequence on repository performance or regulatory compliance, even if ‘heat pipe’ fractures were to occur between the
condensate zone and the emplacement drifts. Indeed, EPRI analyses indicate that the total dry-out period for emplacement drifts in the lower levels may be 2-3 times longer than the same period experienced in the upper level emplacement drifts (Figure 4-5b), which could attenuate long-term radionuclide release rates from these lower drifts compared to the upper-level emplacement drifts.

With respect to possible adverse thermal impacts on mechanical properties of the repository host rock, the peak drift-wall temperatures of the second- and third-levels (Figure 4-5a) are below 160°C, which is well below the thermal limits for the surrounding tuff (Appendix A). Although the temperature-time profiles for waste packages in the second- and third levels are somewhat elevated above the temperature-time profiles of the waste packages in the upper level (Figure 4-5a), these peak temperatures are well below conditions evaluated by EPRI’s IMARC/EBSCOM that show no significant adverse impact on corrosion behavior of waste packages (Appendix B).

5.2 Conclusions

Detailed thermal analyses of the multi-level repository option (Section 4) indicates that each level would achieve the same, or better, performance with respect to initial dry-out than for the current repository concept. Temporary loss (200-300 years) of sub-boiling pillars between drifts in the second- and third-levels is predicted in all cases, and follow-up analyses involving 3-D, dual-porosity models could be applied to further evaluate this effect, although no regulatory compliance impacts are anticipated to arise from such temporary effects. For example, calculated peak temperature profiles for the range of Cases considered (See Table 4-4) would not lead to adverse impacts on the performance or properties of the natural rock (Appendix A) and engineered barriers (Appendix B). Therefore, it is concluded that a three-level repository option (Option 2) could be directly implemented based on current site characterization and materials studies already conducted by the USDOE/YMP.

Table 5-1
Expansion Factors for Option 2: Multi-Level Repository (see Table 4-4)

<table>
<thead>
<tr>
<th>Case</th>
<th>Repository Concept</th>
<th>Initial Loading</th>
<th>Expansion Factor</th>
<th>Ventilation Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Three-level, 30-m vertical drift spacing</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>2</td>
<td>Three-level, 30-m vertical drift spacing</td>
<td>1000 W/m for all waste packages</td>
<td>2 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>3</td>
<td>Three-level, 50-m vertical spacing</td>
<td>1000 W/m for all waste packages</td>
<td>2 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>4</td>
<td>Three-level, 50-m vertical spacing</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td>5</td>
<td>Three-level, 30-m vertical spacing</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 87.3%; 50 – 300 yrs: 93%</td>
</tr>
<tr>
<td>6</td>
<td>Three-level, 30-m vertical spacing</td>
<td>1000 W/m for all waste packages</td>
<td>2 times</td>
<td>0 – 50 yrs: 87.3%; 50 – 300 yrs: 93%</td>
</tr>
</tbody>
</table>
Table 5-1 shows an ‘expansion factor’ of 2-3 within the Primary Block alone could be achieved by adopting the Option 2 multi-level repository design. The lower expansion factor value is associated with lower (by a factor of 2/3) thermal line-loading compared to the current reference repository design. Better isolation performance for lower levels of a multi-level repository might arise, for example, from diversion of infiltrating water by overlying emplacement drifts, reducing the potential long-term release rate of radionuclides from these lower levels.
6

OPTION 3: GROUPED-DRIFT REPOSITORY BASED ON THE CURRENT REFERENCE REPOSITORY DESIGN

6.1 Evaluation

Another potential means of increasing the capacity of the proposed repository is to include additional, grouped emplacement drifts on a single level. In the design option analyzed here, the drifts are grouped with each group consisting of three drifts separated by two 20-meter pillars, with a 41-meter pillar between groups (See Figure 4-2b). The purpose of the larger pillar between groups is to maintain a zone that always remains below boiling temperatures, allowing condensate to drain between the groups.

It is anticipated that initially, the central drift in each group would be loaded with waste and mechanically ventilated with 15 m$^3$/s of air. Because the 81-meter spacing of these “central” drifts and the ventilation rate match the plans for the baseline repository, the initial loading has a capacity of 70,000 MTHM and the performance with 50 years of forced ventilation is known to be acceptable based on thermal analyses already completed by DOE.

During the initial loading, which will take at least ten years, the amount of heat removed by mechanical ventilation can be monitored as part of the Performance Confirmation Program. This will allow the ventilation models to be recalibrated against this data. A thermal analysis, using ventilation heat removal efficiencies from the recalibrated model, would then be used to determine the rate and duration of ventilation that would be required after the side tunnels are loaded with waste. The side tunnels would then be loaded.

EPRI's preliminary calculations (Section 4) indicate that each of the side drifts could be loaded with the at least half the waste density of the center emplacement drift, and possibly with an equal or greater density. This would result in a total repository capacity of at least 140,000 MTHM and possibly 210,000 MTHM or more. However, at present there are large uncertainties in predictions of the amount of residual heat that would exist in the mountain if there is long-term ventilation. There is a hierarchy of additional measures that could be implemented to ensure sufficient heat removal would occur to ensure that the design criteria are met. (Preservation of a below-boiling zone in the pillars between the drift groups is likely to be the limiting thermal criterion for designs based on long-term ventilation, because thermal gradients lessen over time due to heat conduction in the rock and the decline of the heat output of the waste).
The first set of potential heat removal measures that could be implemented to improve heat removal efficiency with a higher total waste material loading includes:

- Natural ventilation for up to 250 years after the initial 50 years of forced ventilation.
- Forced ventilation for up to 250 years after the initial 50 years.
- Surface storage of spent fuel prior to placement in the side drifts of each group.

If it is determined that these measures would not ensure compliance with the repository design criteria, the side drifts could be loaded at a reduced density.

Additionally, a design change could be incorporated in the repository design to improve heat removal so as to increase repository capacity or provide additional confidence in the compliance with repository design criteria. The drift design could be altered so that the ventilation air would be introduced at both ends of the drift and flow towards an exhaust in the drift center. The resulting reduction of the effective drift length for ventilation from 600 m to 300 m would significantly increase ventilation efficiency. Figure 6-8 of the Ventilation AMR indicates that implementation of such a design change would result in an increase in the amount of heat that would be removed from the mountain during the ventilation period by an amount in the range of 30% to 50%. Obviously, a decision to implement this design change would have to be implemented prior to initial loading of the central drifts.

6.2 Conclusions

Table 6-1 presents a summary of the ‘expansion factors’ ranging between 2-3 evaluated for the grouped-drift design option. Extended ventilation represents a promising method for increasing the storage capacity of Yucca Mountain by increasing the allowable number of emplacement drifts. As discussed in Appendix C, extended ventilation can greatly reduce the amount of fission-product decay heat delivered to the rock mass. The thermal analyses in Section 4 show that even less aggressive extended ventilation strategies move the occurrence of peak temperature both in the drift and at the pillar centerline out to a time on the order of 800 to 1000 years after emplacement.
Table 6-1
Expansion Factors for Option 3: Grouped-Drift Repository (see Table 4-4)

<table>
<thead>
<tr>
<th>Case</th>
<th>Repository Concept</th>
<th>Initial Loading</th>
<th>Expansion Factor</th>
<th>Ventilation Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Single-level, 3-drifts</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 87.3%; 50 – 300 yrs: 93%</td>
</tr>
<tr>
<td></td>
<td>20-m apart</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Single-level, 3-drifts</td>
<td>1450 W/m for center waste package, 725 W/m for side</td>
<td>2 times</td>
<td>0 – 50 yrs: 87.3%; 50 – 300 yrs: 93%</td>
</tr>
<tr>
<td></td>
<td>20-m apart</td>
<td>waste packages</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Single-level, 3-drifts</td>
<td>1450 W/m for center waste package, 725 W/m for side</td>
<td>2 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td></td>
<td>20-m apart</td>
<td>waste packages</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Single-level, 3-drifts</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 86.3%</td>
</tr>
<tr>
<td></td>
<td>20-m apart</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Single-level, 3-drifts</td>
<td>1450 W/m for all waste packages</td>
<td>3 times</td>
<td>0 – 50 yrs: 91%; 50 – 300 yrs: 96%</td>
</tr>
<tr>
<td></td>
<td>20-m apart</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Single-level, 3-drifts</td>
<td>1450 W/m for center waste package, 725 W/m for side</td>
<td>2 times</td>
<td>0 – 50 yrs: 91%; 50 – 300 yrs: 96%</td>
</tr>
<tr>
<td></td>
<td>20-m apart</td>
<td>waste packages</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This represents a significant change in the physical regime that determines maximum temperature. In scenarios with 50 years ventilation, like the baseline repository, maximum temperatures are determined by transient heat transfer; heat output declines at a rate dominated by the 30-year half-life of Cs-137 while the zone of heated rock expands. In the extended-ventilation scenarios, the peak temperature appears to approach a quasi-steady-state value that reflects the very slowly declining heat output of transuranic nuclides and slowly varying rock temperatures.

One implication of the transition to temperature peaking in a quasi-steady-state regime is that aggressive approaches are not required to obtain the benefit of extended ventilation. A promising approach would be 50 years of mechanical ventilation followed by 200 to 250 years of natural ventilation (driven by buoyancy) before the ventilation drifts are sealed. Because heat removal factors for natural ventilation are not yet available, it was not possible to simulate this scenario, but the high rate of air flow for natural ventilation in this period calculated by Danko and Bahrami (2003) suggests that natural ventilation would remove a sufficient amount of heat to delay peak temperatures until the quasi-steady-state regime. A repository strategy that planned on natural ventilation in this period would be very robust, because ventilation models could be calibrated and refined during the period of mechanical ventilation, and the use of mechanical ventilation could be extended if necessary.
A second implication of the transition is that certain conservatisms in thermal models may have a greater effect on predicted temperatures than they do in the baseline repository design. As discussed in Section 4.6, the relative importance of convection compared to conduction on the mountain scale increases in extended-ventilation scenarios and analyses showing mountain-scale convection to have negligible effects on peak temperatures must be reconsidered. Additional thermal analyses that address these conservatisms are necessary to determine the amount of added capacity that could result from long-term ventilation.
The following sections identify a number of additional features and factors that could also increase the maximum amount of CSNF that could be safely disposed at Yucca Mountain. Whereas the previous sections of this EPRI analysis have adopted the constraints of using an unmodified repository configuration of the current reference repository design concept as well as existing site characterization data, the factors cited below in some cases are not similarly constrained. Where significant departures from current site characterization data, materials science data or the reference repository design are proposed, the need for additional analysis or data is identified. This listing is preliminary and should not be considered as exhaustive of the additional design options that might successfully lead to increasing the capacity for disposal of CSNF at Yucca Mountain.

7.1 Hybrid Options: Option 1 + (Option 2 or Option 3)

Both Option 2 (multi-level repository) and Option 3 (grouped emplacement drifts) evaluated in this report were constrained to the current 6.5 km² footprint of the current repository design (70,000 MTHM with 63,000 MTHM of CSNF). However, either of these Options could also be combined with the independent Option 1 of an expanded disposal area based on current site characterization.

7.1.1 Potential Benefits

By combining either Option 2 or Option 3 with Option 1 involving an expanded footprint (Section 3), the derived ‘combined expansion factors’ would be on the order of 6-9. This would suggest that between 378,000 to 567,000 MTHM of CSNF could be disposed at Yucca Mountain for this hybrid option, based on currently available site characterization and materials science data.

7.1.2 Additional Requirements

Combining design options with an expanded footprint has not been modeled in this report. However, there are no apparent reasons why blocks other than the current Upper Block and Lower Block would present geotechnical issues or properties that are significantly different than the range of properties already considered in the Section 4 thermal analyses.
7.2 Hybrid Option: Option 2 + Option 3

Theoretically it is possible to envision the combination of grouped emplacement drifts (Option 3) in each of three levels of a repository (Option 2).

7.2.1 Potential Benefits

The derived ‘combined expansion factors’ would be on the order of 4-9. This would suggest that between 252,000 to 567,000 MTHM of CSNF could be disposed at Yucca Mountain for this hybrid option, based on currently available site characterization and materials science data.

7.2.2 Additional Requirements

Both Option 2 and 3 involve adding heat-producing packages into a fixed volume rock block. Combining these two options, therefore, cannot be confidently extrapolated or derived from the thermal analyses provided in this current report. However, the conceptual model, data and assumptions for conducting an analysis of this hybrid option would be the same as the analyses described in this report.

7.3 Closer Drift Spacing (FEIS Design Concept)

As noted in Section 2.5 of this report, the previous Final Environmental Impact Statement (FEIS) design for emplacing CSNF at Yucca Mountain involved a thermal management strategy in which the proposed spacing between emplacement drifts was 29 m (e.g., CRWMS M&O, 1996; USDOE, 2002a; 2002b). This would lead to longer above-boiling temperatures and possibly higher peak temperatures within the emplacement drifts and tuff, although allowable temperature limits for tuff (Appendix A) and waste packages (Appendix B) are much higher than reached for the current 81-m drift spacing design. Sub-boiling pillars between drifts would be blocked for an indeterminate time, although the decay in radiogenic heating would eventually lead the formation of such drainage zones.

7.3.1 Potential Benefits

Closer spacing of emplacement drifts would obviously lead to more space-efficient loading of CSNF into Yucca Mountain. It would also preserve the beneficial effects of a sustained dry-out period on corrosion of waste packages and prevent any potential early release of radionuclides from failed waste packages into the host tuff. Furthermore, this option is based on thermal analyses already completed and published by YMP.

7.3.2 Additional Requirements

More extensive thermal modeling, including 3-D modeling might be useful to evaluate expected condensation and drainage of water in such a configuration. This option would mean changing back from the current ‘sub-boiling pillar for all time’ design concept to the earlier FEIS design (USDOE, 2002a) in which coalesced boiling fronts of adjacent drifts are relied upon to prevent any early contact of condensate water with waste packages.
CONCLUSIONS AND RECOMMENDATIONS

This report provides a preliminary analysis of the maximum physical capacity of a geological repository at Yucca Mountain for the disposal of commercial spent nuclear fuel (CSNF). The conclusion of this report is that the current legislative limit on Yucca Mountain disposal capacity, 70,000 MTHM of a combination of CSNF, DOE, and defense wastes (63,000 MTHM CSNF; 7000 MTHM or equivalent of DOE and defense wastes) is a small fraction of the available physical capacity of the Yucca Mountain system assuming the current high-temperature operating mode (HTOM) design. EPRI is confident that at least four times this legislative limit (~260,000 MTHM) can be emplaced in the Yucca Mountain system. It is possible that with additional site characterization, upwards of nine times the legislative limit (~570,000 MTHM) could be emplaced. The minimum factor of four and possible factor of nine increase is based on the following:

- At least a factor of two times more area is available for waste emplacement than the current Upper Block proposed for use by DOE to dispose of 70,000 MTHM of waste. A factor of 2.6 to 3.5 times as much additional disposal area is potentially available with additional site characterization studies (Table 3-1).

- Even just within the proposed Upper Block area, a revised layout of the repository drifts (Figure 4-2) could allow for two to three times the waste loading per unit area. Two examples of such a revised layout to accomplish the higher loading density are provided in Figure 4-2. For the options considered for these two layouts, peak rock temperatures were estimated to remain below 200°C, the minimum published temperature at which additional rock spallation could occur.

These physical Yucca Mountain potential disposal capacity estimates suggest that 100% of the inventory of CSNF from the existing commercial nuclear reactors in the U.S. could be disposed of at Yucca Mountain from the existing commercial nuclear reactors in the U.S., even if each of these reactors operated for 60 years. Furthermore, there would be a minimum of an additional ~140,000 MTHM of capacity beyond that needed for the existing reactor lifetimes. Potentially, the capacity at Yucca Mountain could be expanded to a significantly higher level.

3 It is estimated that if all of the present operating commercial nuclear reactors each operated for 60 years, approximately 140,000 MTHM of CSNF would be available for disposal, including the existing CSNF from reactors previously shut-down.
Thus, it is possible for Yucca Mountain to hold not only all the waste from the existing U.S. nuclear power plants, but it could hold waste produced from a significantly expanded U.S. nuclear power plant fleet for at least several decades. Even if the U.S. decides to close the nuclear fuel cycle by introducing reprocessing along with the use of advanced reactors, Yucca Mountain could, if necessary, serve as the only CSNF and high-level radioactive waste repository this country needs for at least several decades into the future, if not longer. This capability of an expanded Yucca Mountain capacity would allow the necessary time for the necessary R&D to accomplish a full-scale and economically competitive closed fuel cycle.

The advantage of the two proposed expansion designs in this report is that DOE can proceed with its current design for the first 70,000 MTHM into licensing without delay. The work to establish sufficient technical bases to allow for the magnitude of future expansion proposed in this report can be conducted over a longer period of time.
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A
THERMAL LIMITS TO NATURAL BARRIERS

A.1 Introduction

The emplacement of CSNF and high-level nuclear waste in the repository at Yucca Mountain will result in elevated temperatures for thousands of years. Assuming the average thermal properties for an emplacement drift with a 1.45 kW/m initial heat load and 50 years pre-closure ventilation (BSC, 2004e), the drifts remain below 90°C until the ventilation is turned off at 50 years following emplacement, at which time the temperature rapidly increases to a peak temperature of about 140°C at 80 years after emplacement. The temperature then decreases to below 100°C at about 1000 years, and below 40°C at about 10,000 years.

For the case of an isolated heated drift, thermal compressive stresses are generated in the surrounding rock due to the fact that the heated rock wants to expand but is restricted due to the cylindrical geometry. The highest thermally generated stress component near the boundary is the tangential or hoop component, with the highest values at the boundary of the drift opening. The radial component is zero at the boundary of the opening but increases with distance into the rock. In the case of YM, the emplacement drifts are not isolated but separated by a centerline-to-centerline distance of 81 m, resulting in near-horizontal rows of heated drifts. This results in the generation of additional horizontal stresses. Thus, the final thermally-generated stress state will have the highest stresses in the roof and lower stresses in the wall. These stresses will be the highest during the peak of the thermal pulse and will decrease as the temperature returns to ambient conditions.

The magnitude of the thermal stress state is strongly dependent on the Young’s modulus of the rock mass. This will vary between the non-lithophysal units and lithophysal rock units. The Young’s modulus of the rock mass is a function of the modulus of the intact rock plus the density and properties of voids and fractures. In the non-lith units, the Young’s modulus of the intact rock is about 33 GPa and the shear and normal stiffnesses of the fractures are about 50 GPa/m (BSC, 2004c). Depending on the density of fractures, this will result in a rock mass Young’s modulus between 20 and 30 GPa in the non-lith units. For the lithophysal units, the rock mass Young’s modulus depends on the lithophysal porosity, and varies from 1.9 to 19.7 GPa for variations in lithophysal porosity ranging from 7 to 35%.

For the current design, thermal stresses generated at the peak of the thermal pulse vary from just a few MPa in the high-porosity lithophysal rock to over 40 MPa in the low porosity lithophysal rock and the non-lithophysal rock. Even though the thermal stresses are high in some cases, this results in only a small amount of rockfall (EPRI, 2005a). This is because the extent of failure in the weakest category of lithophysal rock is limited due to the lower thermal stresses generated in this case, and the extent of failure in the stronger rock categories is limited due to the high strengths in these cases. The result is that in all cases, the failure of the rock is limited to a “skin”...
around the opening with a thickness of no more than 0.5 meters. This small amount of failure is not expected to impact repository performance.

For alternative designs that may involve additional heat, additional drifts, and possibly multiple levels, the thermal stresses generated and the rockfall due to these stresses depend on the temperature profiles as well as the particular drift designs. For alternative designs that result in drift wall temperatures between 140 and 200°C, additional rockfall is expected, even though the amount is expected to be small. For instance, for a design that results in peak drift wall temperatures of 180°C (compared with the current design of 140°C), an increase in thermal stress in the rock of about 35% is predicted. This is expected to result in no more than about 0.7 meter depth of failure around the drifts (compared with about 0.5 meters for the current design). For designs that result in drift temperatures exceeding 200°C, the large volume expansion associated with the cristobalite phase change could result in larger amounts of rockfall. This is discussed in Section A.2 below. In addition to the effect of thermal loading, other geomechanical aspects of alternative designs must be considered. For instance, for alternative designs that involve multiple levels, a seismic event that causes failure in a drift at one level could induce deformation and failure of a drift in another level directly above or below that drift. Similarly, a small pillar between parallel drifts in the same level could be impacted by the large stresses associated with a large seismic event. Another geomechanical issue involves changes in the percentage of different rock types (the current design has 15% in non-lithophysal rock and 85% in lithophysal rock) that could occur with multiple layers or an expanded footprint, including the possibility of new rock types that must be characterized.

A.2 Cristobalite Phase Change Between 225 and 300°C

Data from Brodsky et al. (1997) show that the mean coefficient of thermal expansion (MCTE) for TSw2 tuff is a strong function of temperature. A plot of MCTE for TSw2 tuff as a function of temperature is shown in Figure A-1 (data from Brodsky et al., 1997). At room temperature the MCTE for the TSw2 tuff is 6.7 x 10^-6 °C. It shows a strong increase starting at around 225°C, with a value of about 35 x 10^-6 °C at 300°C. The temperature dependence of the thermal expansion coefficient is due to phase changes that take place in cristobalite and tridymite. Cristobalite comprises about 30% of the TSw2 tuff (Blair, 1998). The phase change between low tridymite and high tridymite takes place at a transition temperature of about 163 °C. This phase change results in only a modest thermal expansion, and does not appear to be associated with micro-cracking and permanent rock damage. The phase change between low cristobalite and high cristobalite takes place at a transition temperature range of between 225 and 282 °C (some references such as Hurlbut (1971) put the transition temperature as low as 200 °C). The cristobalite phase change results in a significant volume expansion and is responsible for the large MCTE values from 225 to 300 °C. Even though the cristobalite phase change is reversible, micro-cracking that is associated with the large cristobalite volume expansions is not reversible, resulting in some permanent damage to the rock.

Alternative designs that result in drift wall temperatures above 225 °C may result in increased rockfall for two reasons. First of all, near the boundary of the drifts where the radial stresses are low, the cristobalite phase transformation could result in micro-cracking, rock damage and potential rockfall. As a conservative assumption, the depth of failure can be assumed to be equal
to the depth into the rock where temperatures exceed 225 °C. Secondly, the high thermal expansion coefficients will result in higher stresses in the rock mass due to thermal loading. These stresses could result in additional rockfall due to sliding along discontinuities and intact rock failure. For instance, for a design that has drift wall temperatures as high as 250 °C, some parts of the rock mass will have thermal expansion coefficients more than twice the value for the current design. This could potentially double the thermal stresses for this case (for instance 80 MPa instead of 40 MPa in the drift roof for the case of low-porosity lithophysal rock).

![Figure A-1](image)

**Figure A-1**  
Mean Coefficient of Thermal Expansion (MCTE) vs. Temperature for Rock Samples from TSw2 Tuff  
(source: Brodsky et al., 1997)
A.3 Geomechanical Issues Associated with Alternative Designs

In this section, the geomechanical issues associated with alternative designs are discussed.

A.3.1 Multi-Level Repository

In this section, a three level repository with the same map-view footprint as shown in Figure 4-2a is considered. The emplacement drifts on each level will be separated by 81-meters centerline-to-centerline, and the levels will be separated by either 30 meters or 50 meters centerline-to-centerline separation. The drifts on each level are assumed to be aligned directly on top of one another.

Issue 1: Rockfall due to thermal stresses. The temperature profile for the multilevel repository depends on the heat load in the drifts, the ventilation, and the vertical drift spacing. In this report, 6 multilevel cases were considered, as shown in Table 4-3 (cases 1 though 6). As shown in Table 4-4, Case 1 resulted in the highest drift wall temperatures, with a maximum drift wall temperature of 197°C 94 years after emplacement. This case considered 30 meter vertical spacing of drifts, 1450 W/m loading in all drifts, and 50 years of ventilation with 86.3% efficiency. This case results in a maximum drift temperature increase about 50% greater than the current design (25 – 197°C compared with 25 – 140°C). Also, Figure A-1 indicates that the thermal coefficient of expansion at 200°C is about 30% greater than the expansion coefficient at 150°C. Both the increased temperature and the increased thermal expansion coefficient will result in higher thermal stresses and increased rockfall during the thermal pulse. Modeling will need to be conducted to determine the exact amount of rockfall expected in the six rock types (non-lithophysal rock plus five categories of lithophysal rock). However, as a conservative estimate, the depth of failure is not expected to be more than twice that predicted for the current design (maximum 1 meter rockfall depth compared with maximum 0.5 meters for the current design). This is based, first of all, on the fact that the maximum drift wall temperature of 197°C is less than the transition temperature for cristobalite, and therefore the permanent damage associated with the cristobalite phase change will not occur. Secondly, the increase in rockfall should be proportional to the increase in thermal stresses, which is expected to be less than twice the thermal stresses for the current design based on the discussion given above. Rockfall with a depth into the rock of 1 meter or less should have little effect of repository performance. This represents a rockfall volume of less than 6 m³/m, and therefore there should be no permanent static load on the DS/ WP (i.e., the small amount of rockfall should accumulate at the sides of the waste packages, see EPRI, 2005a). Also, in the non-lithophysal rock where the dynamic impact of large blocks must be considered, this represents a maximum equi-dimensional block size less than 2 m³, which should not cause damage to the DS/ WP due to dynamic impact (according to the finite element modeling given in EPRI, 2005a).

The remaining 5 cases all have maximum drift wall temperatures less than Case 1 described above. Of these, the only case with drift wall temperatures significantly higher than the current design is Case 4, with a maximum drift wall temperature of 172°C at 121 years after emplacement. This case considered 50 meter vertical spacing of drifts, 1450 W/m loading in all drifts, and 50 years of ventilation with 86.3% efficiency. This case results in a maximum drift temperature increase about 30% greater than the current design, and a thermal expansion at the
peak temperature about 10% greater than the current design. As a conservative assumption, the depth of failure is not expected to be more than 50% more than the current design (0.75 meters compared with 0.5 meters). Case 2 is expected to result in about the same rockfall as the current design, and cases 4, 5, and 6 are expected to result in less rockfall than the current design (see Tables 4-3 and 4-4 for details on these cases and the resulting temperatures).

**Issue 2: Rockfall due to a large seismic event.** For the current design, a large seismic event with a peak ground velocity (PGV) of 2 m/s is expected to result in minor rockfall in some areas (non-lithophysal units and lithophysal units with low lithophysal porosity) and complete collapse of the drifts in other areas (lithophysal units with high lithophysal porosity). A summary of rockfall predicted from a single seismic event with a PGV of 2 m/s/ is shown in Figure A-2 (EPRI, 2005a). In particular, due to a seismic event with a PGV of 2 m/s, 4% of the drifts in lithophysal rock and none of the drifts in non-lithophysal rock are expected to experience complete collapse. For those drifts where complete collapse is predicted, the depth of failure in the roof is expected to be 8 to 22 meters (EPRI, 2005a). This is based on an estimate of the bulking factor for the broken rock. The smaller the bulking factor the higher the depth of failure in the roof. EPRI’s best estimate for the bulking factor, based on values given in the literature, is about 1.4 (EPRI, 2005a). This results in a maximum depth of failure in the roof of 8 meters. However, the value given in BSC (2004c) is conservatively estimated at 1.2 based on the results of UDEC modeling. This gives a maximum depth of failure in the roof of 22 meters.

The issue is whether the total or partial collapse of a drift on one level could impact the stability of a drift directly above it. This could then create a channel of broken rocks between levels. Of the six multilevel cases considered in this report, four of them considered a vertical drift spacing of 30 meters, and two of them considered a drift spacing of 50 meters. If EPRI’s best estimate for the bulking factor of 1.4 is used, then a total collapse of a drift on one level will leave a pillar thickness of about 17 meters for the 30 meter vertical spacing case and about 37 meters for the 50 meter vertical spacing case. These are both probably stable pillars, although additional modeling will be necessary to further confirm this conclusion. If the conservative value for the bulking factor of 1.2 is used, then a total collapse of a drift on one level will leave a vertical pillar thickness of only 3 meters for the 30 meter vertical spacing case and 23 meters for the 50 meter vertical spacing case. Thus using the conservative value of 1.2 as given in BSC (2004c), a channel of broken rock between levels is likely to occur for the case of 30 meter spacing between levels (cases 1, 2, 5 and 6).

For the drifts that do not experience complete collapse when subjected to a PGV of 2 m/s (rockfall types 1 and 2 in Figure A-2), the 30 or 50 meter vertical spacing of drifts should be sufficient to prevent a breech of the vertical pillar separating the drifts.

**Issue 3: Site characterization.** Rock mass characterization has been extensive for the current repository horizon, but the characterization of the rock for potential levels 30 to 50 meters above and below the current repository horizon has not been equally extensive. Six basic rock types have been characterized for the current design, the non-lithophysal rock and 5 categories of lithophysal rock. For the multi-level repository, additional site characterization may be necessary, and this may result in a different mix of rock types compared with the current design.
**Issue 4: Modeling.** The multi-level repository represents a major change from the current design, and much of the extensive geomechanical modeling that is contained in the Drift Degradation AMR (BSC, 2004c) would have to be revised (the Drift Degradation AMR REV 03 is 976 pages). The revised modeling would take into account the interaction of drifts on different levels under thermal loading, seismic loading and time-dependent drift degradation. It would also take into account the increased drift wall temperatures and the increased thermal expansion coefficient, and any changes in the rock mass material properties due to the expanded rock mass characterization.

![Diagram](image)

**Figure A-2**
Probability of Seeing Different Types of Rockfall in the Yucca Mountain Emplacement Drifts Due to a Single Seismic Event with a PGV of 2 m/s (for current repository design, source: EPRI, 2005a)

**A.3.2 Single-Level Repository with Triad-Grouped Drifts**

In this section, a single-level repository with the same map-view footprint as shown in Figure 4-2 is considered. The emplacement drifts are assumed to consist of groups of three drifts separated by 20 meter pillars, and the groups are separated by the same 81 meter centerline to centerline distance between central drifts as is included in the current DOE design.

**Issue 1: Rockfall due to thermal stresses.** The temperature profile for the single-level triad-grouped repository depends on the heat load in the drifts, the ventilation, and the size of the pillar separating the triad drifts. In this report, 6 single-level triad-grouped cases were considered, as shown in Table 4-3 (cases 7 through 12). As shown in Table 4-4, Case 10 resulted in the highest drift wall temperatures, with a maximum drift wall temperature of 198°C 227 years after emplacement. This case considered 20-meter pillars separating the triad drifts, 1450 W/m loading in all drifts, and ventilation with 86.3% efficiency for 50 years following emplacement. This case results in a maximum drift temperature increase about 50% greater than the current design (25 –198°C compared with 25 –140°C). Also, Figure A-1 indicates that the thermal coefficient of expansion at 200°C is about 30% greater than the expansion coefficient at 150°C.
Both the increased temperature and the increased thermal expansion coefficient will result in higher thermal stresses and increased rockfall during the thermal pulse. Modeling will need to be conducted to determine the exact amount of rockfall expected in the six rock types (non-lithophysal rock plus five categories of lithophysal rock). However, as a conservative estimate, the depth of failure is not expected to be more than twice that predicted for the current design (maximum 1 meter rockfall depth compared with maximum 0.5 meters for the current design). This is based, first of all, on the fact that the maximum drift wall temperature of 198°C is less than the transition temperature for cristobalite, and therefore the permanent damage associated with the cristobalite phase change will not occur. Secondly, the increase in rockfall should be proportional to the increase in thermal stresses, which is expected to be less than twice the thermal stresses for the current design based on the discussion given above. Rockfall with a maximum depth into the rock of 1 meter should have little effect of repository performance. This represents a rockfall volume of less than 6 m³/m, and therefore there should be no permanent static load on the DS/WP (i.e., the rockfall should accumulate at the sides of the waste packages, see EPRI, 2005a). Also, in the non-lithophysal rock where the dynamic impact of large blocks must be considered, this represents a maximum equi-dimensional block size less than 2 m³, which should not cause damage to the DS/WP due to dynamic impact (according to the finite element modeling given in EPRI, 2005a).

The remaining 5 cases all have maximum drift wall temperatures less than Case 10 described above. Of these, the only case with drift wall temperatures significantly higher than the current design is Case 9, with a maximum drift wall temperature of 171°C at 115 years after emplacement. This case considered 20-meter pillars separating the triad drifts, 1450 W/m loading in the center triad-drifts and 725 W/m loading in the outer triad-drifts, and 50 years of ventilation with 86.3% efficiency. This case results in a maximum drift temperature increase about 30% greater than the current design, and a thermal expansion at the peak temperature about 10% greater than the current design. As a conservative assumption, the depth of failure is not expected to be more than 50% more than the current design (0.75 meters compared with 0.5 meters). Cases 7 and 11 are expected to show about the same rockfall as the current design, and cases 8 and 12 are expected to show less rockfall than the current design (see Tables 4-3 and 4-4 for details on these cases and the resulting temperatures).

Issue 2: Rockfall due to a large seismic event. Some additional rockfall may occur due to a large seismic event (PGV of 2 m/s) compared with the current design. This is because the 20-meter pillars separating the grouped drifts may experience partial failure due to the large stresses associated with the large seismic event. Additional modeling may be required to evaluate this topic in greater detail. This may change the percentages in the different rockfall categories as shown in Figure A-2. This is not expected to change the maximum height of the failed zone above the roof of the drifts (predicted to be 8 to 22 meters) or the maximum block size that can impact the DS/WP because the drift sizes will remain the same as the current design. Thus the conclusions regarding the impact of a large earthquake on repository performance as described in EPRI (2005a) remain the same.

Issue 3: Site characterization. Site characterization is not expected to be an issue for the modified single-level designs, since all drifts will be in the same horizon and footprint as the current design.
Issue 4: Modeling. The single-level triad-grouped repository represents a significant change from the current design, and some of the extensive geomechanical modeling that is contained in the Drift Degradation AMR (BSC, 2004) would have to be revised. The revised modeling would take into account the interaction of the triad drifts under thermal loading, seismic loading and time-dependent drift degradation. It would also take into account the increased drift wall temperatures and the increased thermal expansion coefficient. Since no additional site characterization would be required (Issue 3 above), no changes in the rock mass material properties would be needed for the modeling.

A.4 Summary

This section of the report considers the geomechanical implications of the 12 revised designs given in Table 4-3. Cases 1 though 6 considered a three level repository, and Cases 7 through 12 considered a single-level repository with triad-grouped drifts. Four of these designs (multilevel Cases 1 and 4 and single-level grouped Cases 9 and 10) resulted in significantly higher maximum drift wall temperatures than the 140°C maximum for the current design. In Cases 1 and 10 maximum drift wall temperatures of about 200°C are predicted, and in Cases 4 and 9 maximum drift wall temperatures of about 170°C are predicted. In all cases, the maximum drift wall temperature is less than the phase-change transition temperature for cristobalite, and therefore the rock damage associated with this transition is avoided. The four cases with drift wall temperatures higher than the current design are expected to see additional rockfall, but the rockfall is still expected to be minor and not impact repository performance. An important issue with the 3-level design is the possibility that drift collapse due to a large earthquake on one level could breach the pillar separating a drift directly above the collapsed drift. This could then create a channel of broken rock between levels. Using the conservative estimate for the bulking factor of 1.2 as given in BSC (2004c), this is a possibility, but using EPRI’s best estimate for the bulking factor of 1.4 (EPRI, 2005a), it is unlikely to occur. Additional modeling may be required to evaluate this topic in greater detail. An additional issue with the 3-level repository is the additional site characterization that would be required, and the possibility that new material properties for areas above and below the current repository horizon would need to be determined. Both the 3-level repository and the single-level triad-grouped repository are different enough from the current design that some of the geomechanical modeling that is contained in the Drift Degradation AMR (BSC, 2004c) would have to be revised to determine the behavior of the new designs under thermal loading, seismic loading and time-dependent drift-degradation.
A.5 References


THERMAL LIMITS FOR ENGINEERED BARRIERS

B.1 Background

The EBS materials (Alloy 22 for the waste package (WP) and Ti Grade-7 for the drip shields (DS)) were specifically selected because of their excellent corrosion resistance in high-temperature aqueous environments. The evolution of the corrosion behavior of the EBS is linked to the evolution of the repository environment and is typically divided into three time periods or phases: (i) the initial dry-out period during which the surfaces of the EBS are too hot for the formation of an aqueous solution, (ii) a transition period during which corrosion (including localized corrosion of the WP underneath a failed DS) is possible in the presence of seepage or deliquescent water, and (iii) a long-term cool period during which corrosion (except for localized corrosion of the WP) is possible but proceeds slowly because of the low temperatures.

Given this description of the evolution of the in-drift environment, higher repository temperatures resulting from the disposal of a greater amount of radioactive waste could have a number of effects on the corrosion performance and lifetimes of the DS and WP, including:

1. delaying the onset of aqueous corrosion processes by extending the dry-out phase and delaying the formation of aqueous solutions on the EBS surface,
2. increasing the duration of the transition period during which the WP could be susceptible to localized corrosion,
3. increasing the rates of general corrosion of the DS and WP and localized corrosion of the WP,
4. increasing the susceptibility of the WP to localized corrosion through thermal ageing of the Alloy 22,
5. increasing the susceptibility of the WP outer closure weld to stress corrosion cracking (SCC) by decreasing the threshold stress (expressed as a fraction of the temperature-dependent yield stress),
6. delaying the onset of microbiologically influenced corrosion by extending the period during which the relative humidity at the WP surface is below the threshold value for microbial activity.

Previous EPRI analyses (EPRI 2005b, King and Kolar 2006) have shown that localized corrosion and SCC are not significant failure mechanisms for the WP.

B.2 Analyses of EBS Performance at Higher Temperatures

A number of analyses have been performed using the EBSCOM code, EPRI's model for predicting the lifetimes of the DS and WP under a range of in-drift environmental conditions
EBSCOM is a probabilistic code that uses probability distributions for different input parameters to account for various sources of conceptual model uncertainty and variability in the system. For example, a different water chemistry is selected for each of the one million realizations in a typical EBSCOM run to represent the variability in seepage water and deliquescent solution composition.

The EBSCOM code also accounts for the spatial variation in the EBS temperature in the repository by selecting a different temperature-time profile for each realization. (In EBSCOM, the temperature of the DS and WP are assumed to be the same). In addition, the time at which aqueous corrosion becomes possible in the repository can be varied by selecting a value for the threshold temperature for moisture film formation \((T_{aq})\) from a range of values representing uncertainty in the nature of the deliquescent salt that will lead to first wetting of the surface.

Lifetimes for the DS and WP have been estimated by EPRI using the EBSCOM code for hypothetical temperature profiles based on thermal analyses for the multi-level and grouped-drift repository designs as described in Section 4 (see Figures 4-3, 4-5 and 4-7). In order to examine possible thermal limits on waste package performance, four different temperature-time profiles are considered in the EBSCOM analyses reported here (Table B-1); Cases A, B and D include higher peak temperature than calculated for the specific multi-level and grouped-drift designs presented in Section 4 in order to confidently bound possible thermal limits.

The variability of the EBS temperatures in the repository is simulated by selecting a temperature coefficient value for each realization from a triangular distribution representing the spread in temperatures. This temperature coefficient is then used to increment the temperature-time \((T-t)\) profile for the average-temperature EBS for the nominal scenario for the reference HTOM repository design to arrive at the \(T-t\) profile for the elevated temperature. The peak value of the triangular temperature coefficient distribution is defined so that the peak EBS temperature corresponds to the peak temperature in each of the four sets of analyses (e.g., Figure B-1). The peak temperatures and corresponding values for the maximum temperature coefficient for the four cases considered are given in Table B-1. For all four simulations, the minimum value of the EBSCOM temperature coefficient is taken as one, corresponding to a peak EBS temperature of 153°C.

<table>
<thead>
<tr>
<th>Case</th>
<th>Peak Temperature (°C)</th>
<th>Maximum EBSCOM Temperature Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>309</td>
<td>2.02</td>
</tr>
<tr>
<td>B</td>
<td>205</td>
<td>1.34</td>
</tr>
<tr>
<td>C</td>
<td>168</td>
<td>1.10</td>
</tr>
<tr>
<td>D</td>
<td>253</td>
<td>1.65</td>
</tr>
</tbody>
</table>

In each EBSCOM simulation, therefore, a range of EBS \(T-t\) profiles was used to account for the spatial variability in temperature within the multi-tier or grouped-drift repository designs. For example, for Case A the peak EBS temperature (which occurs after ~100 years following
The emplacement of the WP (Figure B-1) ranges from 153°C to 309°C. This range of temperatures is used to represent the distribution in EBS peak temperatures for the alternative repository design options (see Sections 4 to 6). Figure B-2 shows the distribution of peak temperatures for the EBSCOM simulation for Case A, expressed as a fraction of EBS for various ranges of peak temperature.

![Temperature Profiles Used to Represent the Hottest and Coolest EBS for the EBSCOM Simulation of the Case A Optional Repository Design](image)

**Figure B-1**  
Temperature Profiles Used to Represent the Hottest and Coolest EBS for the EBSCOM Simulation of the Case A Optional Repository Design
For the EBSCOM simulations of the alternative repository design options, the threshold temperature for aqueous corrosion (TAQ) was selected for each realization from a uniform distribution between 120°C and 140°C.

A separate set of EBSCOM analyses was performed to determine the effect of the value of T_{AQ} on the predicted EBS lifetimes. In these analyses, a second triangular distribution of EBSCOM temperature coefficients was used, with minimum and maximum values of 0.67 and 1.68 and a peak value of 1.0, corresponding to peak EBS temperatures of 103°C, 258°C, and 153°C, respectively. Two analyses were performed; one using the uniform distribution for T_{AQ} of 120-140°C; the other using a fixed value for T_{AQ} of 400°C. This latter value of T_{AQ} results in aqueous corrosion at all temperatures and represents the possible formation of deliquescent solutions at elevated temperatures (Bryan 2005). Bryan (2005) reported the possible formation of mixed-salt deliquescent solutions forming at temperatures up to 300°C, although the composition of such salts would not support localized corrosion of the WP.
B.3 Results of EBSCOM Analyses and Discussion of the Thermal Limits for the EBS Components

Figure B-3 shows the predicted distribution of EBS failure times for Case A assuming a peak EBS temperature of 309°C. The predicted failure times are similar to those for the nominal scenario (EPRI 2005b, King and Kolar 2006). Table B-2 gives the predicted time dependence of the cumulative fraction failed (CFF) for WP for the four cases considered for the alternative repository designs. The results suggest there is little impact of the elevated temperatures in an expanded-capacity repository with, if anything, slightly longer WP lifetimes for the hotter repository designs. Similar results are obtained for the DS and the combined DS/WP.

(Note: the CFF of 0.0001 corresponds to approximately one WP failure and includes the fraction of initially defective WPs (selected randomly in each realization from a distribution with a mean value of 10⁻⁴). For the nominal scenario and Case A, the fraction of initially defective WP exceeds 10⁻⁴ and is assumed to occur at 50 years after WP emplacement, the period of ventilation. For Cases B-D, the CFF only exceeds a value of 0.0001 following the first corrosion failure).

![Figure B-3](image)

Figure B-3
Predicted Time Dependence of the Cumulative Fraction of Failed EBS Components for the Case A Alternative Repository Design Simulation. Failure Times are Shown for the Drip shield (DS), Waste Package (WP), and for the Combined EBS Comprising a WP and the Corresponding DS (EBS)
Table B-2
Predicted Time Dependence of the Cumulative Fraction of Failed Waste Packages for the Simulations of the Four Alternative Repository Designs

<table>
<thead>
<tr>
<th>CFF</th>
<th>Nominal</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
<th>Case D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td></td>
<td>50*</td>
<td>50</td>
<td>272,000</td>
<td>282,000</td>
</tr>
<tr>
<td>0.001</td>
<td>408,000</td>
<td>418,000</td>
<td>411,000</td>
<td>411,000</td>
<td>417,000</td>
</tr>
<tr>
<td>0.01</td>
<td>546,000</td>
<td>557,000</td>
<td>548,000</td>
<td>549,000</td>
<td>554,000</td>
</tr>
<tr>
<td>0.1</td>
<td>886,000</td>
<td>893,000</td>
<td>886,000</td>
<td>882,000</td>
<td>889,000</td>
</tr>
<tr>
<td>1</td>
<td>&gt;2 x 10^7</td>
<td>&gt;2 x 10^7</td>
<td>&gt;2 x 10^7</td>
<td>&gt;2 x 10^7</td>
<td>&gt;2 x 10^7</td>
</tr>
</tbody>
</table>

* times in years following emplacement

There are a number of reasons that the higher repository temperature does not result in significantly shorter EBS lifetimes. First, the higher temperatures delay the onset of aqueous corrosion processes during the near term and of microbiologically influenced corrosion in the long term. Although the period of time that the WP temperature is above the critical temperature for localized corrosion and the period of higher SCC susceptibility are generally longer than for the nominal scenario, the relatively low probability of these processes means that there is no increase in the number of such failures. Secondly, the activation energies for general corrosion for Alloy 22 and Ti-7 are small (26 kJ/mol and 0 kJ/mol, respectively), so that the rates of these processes (and of H pick up by the DS) are not appreciably enhanced by the higher temperatures.

Additional EBSCOM simulations were performed to determine the impact of potential high-temperature deliquescent salts (Bryan 2005). Table B-3 lists the CFF for the WP for the two EBSCOM simulations, along with the equivalent results for the nominal scenario (peak EBS temperatures 103 – 193°C). As with the higher temperatures associated with the alternative repository designs discussed in this report, the possibility of high-temperature deliquescent salts (T_{AQ} = 400°C) has a minimal impact on the WP lifetimes (or those of the DS or complete EBS (not shown)). This lack of temperature sensitivity is again primarily due to the modest temperature dependence of the rates of general corrosion and, in the case of the Alloy 22 WP, a delay in the onset of microbiologically influenced corrosion.

Table B-3
Predicted Time Dependence of the Cumulative Fraction of Failed Waste Packages for the Nominal Scenario and Two Elevated Temperatures with Different Assumed Threshold Temperatures for Aqueous Corrosion

<table>
<thead>
<tr>
<th>CFF</th>
<th>Nominal Scenario</th>
<th>Peak EBS Temp. 103 – 258°C T_{AQ} 120-140°C Randomly Sampled</th>
<th>Peak EBS Temp. 103 – 258°C T_{AQ} Constant Value of 400°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>50*</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>0.001</td>
<td>408,000</td>
<td>408,000</td>
<td>413,000</td>
</tr>
<tr>
<td>0.01</td>
<td>546,000</td>
<td>546,000</td>
<td>553,000</td>
</tr>
<tr>
<td>0.1</td>
<td>886,000</td>
<td>886,000</td>
<td>886,000</td>
</tr>
<tr>
<td>1</td>
<td>&gt;2 x 10^7</td>
<td>&gt;2 x 10^7</td>
<td>&gt;2 x 10^7</td>
</tr>
</tbody>
</table>

* times in years following emplacement
Exposure to elevated temperatures can lead to thermal aging of Alloy 22 and enhanced corrosion susceptibility and a decrease in mechanical properties (Rebak et al., 2000). At temperatures in excess of 600°C, precipitation of tetrahedrally close-packed (TCP) phases (Mo-rich $\mu$ and $\Phi$ phases) occurs (Summers et al., 2002). At temperatures below 600°C, long-range ordering can occur due to the formation of Ni$_2$(Cr, Mo) intermetallics, which may lead to enhanced susceptibility to SCC. In addition, thermally aged material has been shown to be more susceptible to localized corrosion (LC), exhibiting less-noble re-passivation potentials and a lower threshold temperature for LC at a given [Cl$^-$] (Cragnolino et al., 2004). However, preliminary calculations suggest that the relatively low temperatures considered here compared with those required to form TCP phases or long-range ordering (even for the hottest EBS in the alternative repository designs) are insufficient to introduce thermal aging of the WP material.

**B.4 Summary**

Calculations using modified temperature-time profiles and the EBSCOM code suggest that there is little effect of temperature on the lifetimes of the various EBS components. The hottest alternative repository design considered is equivalent to a peak EBS temperature range of 153 – 309°C. Given that these elevated temperatures do not result in shorter EBS lifetimes, the upper thermal limit for the WP and DS is in excess of 300°C.

The insensitivity of the EBS lifetimes to elevated temperatures is a result of:

- The delay in the onset of EBS corrosion due to an extended period of dry out.
- The delay in the onset of microbiologically influence corrosion due to corresponding lower relative humidity.
- The low (or zero) activation energies for general corrosion of the DS and WP, the major corrosion failure modes.
B.5 References


C
VENTILATION HEAT REMOVAL EFFICIENCY

C.1 Modeling Ventilation Heat Removal

The Ventilation AMR (BSC, 2004d) presents USDOE's model calculations of ventilation heat removal. The fraction of the decay heat generated during the period of ventilation that is removed by the ventilation air is referred to as the ventilation efficiency. The DOE distinguishes between the instantaneous ventilation efficiency, which is a function of time and of position along a drift, and the integrated ventilation efficiency, which represents the total amount of heat removed in an entire drift during the entire period of ventilation.

The instantaneous ventilation efficiency is highest at the air inlet and declines along the length of the drift; as the ventilation air absorbs heat, it warms and there is a smaller temperature difference between the air and the solid surfaces it contacts. Instantaneous ventilation efficiencies increase over time because the heat output of the spent fuel declines faster than the solid surface temperatures. Because the integrated ventilation efficiency is an integral over the instantaneous efficiency, it also increases with time and decreases with greater drift length, although both trends are less pronounced than with the instantaneous efficiency.

According to Table 6-7 of the Ventilation AMR, the integrated ventilation efficiency for a drift with a length of 600 m (the average length) and a ventilation time of 50 yr is calculated by the preferred ANSYS LA-coarse model as 88.3%. However, this value is calculated with an air pressure of 1 atm; the lesser air pressure at Yucca Mountain reduces the efficiency by 1% (p. 6-54). Consequently, the calculations presented in this report use a ventilation efficiency of 87.3% for ventilation during the first 50 years. In these calculations, as in the USDOE's mountain-scale and drift-scale thermal calculations, a single average value of instantaneous ventilation efficiency is applied along the entire length of an emplacement drift.4

The calculations in the Ventilation AMR address only 50 years of ventilation. Figure 6-8(b) shows that the instantaneous efficiency for the presently anticipated ventilation system design after 50 years of mechanical ventilation, averaged over 600 m of drift length, is approximately 94%. Calculations in this report use (after subtracting the 1% pressure correction) an instantaneous ventilation efficiency of 93% for times after 50 years. This is conservative, if forced ventilation continues at the assumed air flow rate of 15 m³/s, because it ignores the additional increases in ventilation efficiency that occur after 50 years. Alternatively, natural

4Section 6.10 of the Ventilation AMR shows that this approach is a good approximation for host rock temperatures. This method may underestimate waste package temperatures, but as discussed above, waste package temperature is unlikely to constrain waste loading for repository designs with long-term ventilation.
ventilation could be used for the post-50-year period, taking advantage of the buoyancy effect due to the heat within the mountain to reduce the system's dependence on human support activities. Danko and Bahrami (2003) have shown that buoyancy will drive an air flow of more than half the 15 m$^3$/s forced ventilation rate throughout the remaining 250-year period during which decay heat is dominated by fission products.

For a repository design with ventilation flowing from both ends of the drifts toward the center, ventilation efficiencies are estimated at 91% for the first 50 yr and 96% thereafter. These values are estimated from Figure 6-8 of the Ventilation AMR.

In Section 6.11 of the Ventilation AMR, the DOE estimates the 2-$\sigma$ standard error of ventilation efficiency as ±5%. Repository temperature is seen to be much more sensitive to ventilation efficiency when ventilation times are extended. This uncertainty therefore has greater significance for repository designs that involve extended ventilation.

The reason that temperature becomes more sensitive to ventilation efficiency in extended-ventilation scenarios has been discussed in a previous EPRI report (EPRI, 2002). Briefly, the temperature depends not on how much heat is removed from the repository, but on the amount of heat that is not removed. The bulk of the heat delivered to the repository during the first 300 years after waste emplacement is generated by decay of $^{137}$Cs. During the 50 yr ventilation period assumed in the baseline repository design, only 68.3% of the $^{137}$Cs will decay. The remaining 31.7% of the decay, and thus 31.7% of the heat generation, would occur after ventilation ceases. Forced ventilation with 87.3% efficiency for the first 50 years removes only 59.6% of the total $^{137}$Cs heat generation. As a result, 40.4% of the heat remains within the mountain. If the true ventilation efficiency is 82.3% or 92.3% (87.3% ± 5%), the fraction of the heat that remains within the mountain becomes 43.8% or 37% respectively, a relatively small sensitivity.

On the other hand, if forced ventilation continues for an additional 250 yr and removes 93% of the decay heat generated in the period from 50 to 300 years, the fraction of $^{137}$Cs decay heat that remains within the mountain is only 11.0%. Reducing the ventilation efficiency by 5% increases this fraction to 16.0%; increasing the efficiency by 5% reduces the fraction of heat remaining within the mountain to 6.0%. This is a large sensitivity.

### C.2 Conservatism in Ventilation Analyses

The high sensitivity of temperature to ventilation efficiency also means that the conservatisms existing in the USDOE ventilation analysis become much more important in extended-ventilation scenarios. One such conservatism is the neglect of latent heat in USDOE's ventilation model. USDOE justifies this exclusion on the basis of two calculations of potential latent heat removal.
These two calculations do not demonstrate that latent heat is negligible in the context of 300-yr ventilation:

- One argument calculates the amount of liquid water that can flow toward the drift wall. The calculated rate of water flow is unrealistic because it ignores the dual-porosity nature of the host rock in which mass flow of gas, which will be enhanced by ventilation-related gas pressure changes, can carry water vapor through fractures (Danko and Baharami, 2003).

- The second argument shows that evaporating the entire percolation flux over 50 years will remove only 1.4% of the heat generated in that period. However, if the ventilation period is increased to 300 years, the same rate of heat removal results in a removal of 6% of the heat generated. This is far from negligible when compared with the 11% of the generated heat that is predicted above to remain within the mountain.

A second DOE conservatism that may be significant is that dry-out of the host rock is ignored (Ventilation AMR, Section 6.5.2). The USDOE’s sensitivity analysis indicates that if the host rock dries out, the resulting decrease in thermal conductivity increases the integrated ventilation efficiency by 3%. As discussed above, if extended ventilation scenarios where only 11% of the \(^{137}\text{Cs}\) decay heat remains within the mountain are considered, a 3% increase in ventilation efficiency substantially reduces the amount of heat flowing to the surrounding rock.

Because of the complexity of the physical processes involved, reducing these uncertainties through modeling will be difficult. But the performance of the ventilation system can be monitored during the first 50 years following emplacement as part of the Performance Confirmation Program, facilitating the determination of more accurate model parameters. Because mechanical ventilation has a planned end-point of 50 to 300 years, performance will be measured on the same time scale as is needed for performance assessment. Model recalibration against Performance Confirmation Program data will provide a very substantial reduction in uncertainty and enhancement of confidence. The repository loading strategy discussed here, based on a model calibrated against actual performance of the repository, and thus offers the potential for gaining substantial advantages in reliability and avoidance of unnecessary conservatism.
C.3 References


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