191 W.B. ①

12-10-91

SANDIA REPORT

SAND89-1989 • UC-814

Unlimited Release

Printed November 1991

Yucca Mountain Site Characterization Project

Areal Power Density: A Preliminary Examination of Underground Heat Transfer in a Potential Yucca Mountain Repository and Recommendations for Thermal Design Approaches

Eugene S. Hertel, Jr., Eric E. Ryder

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

"Prepared by Yucca Mountain Site Characterization Project (YMSCP) participants as part of the Civilian Radioactive Waste Management Program (CRWM). The YMSCP is managed by the Yucca Mountain Project Office of the U.S. Department of Energy, DOE Field Office, Nevada (DOE/NV). YMSCP work is sponsored by the Office of Geologic Repositories (OGR) of the DOE Office of Civilian Radioactive Waste Management (OCRWM)."

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831

Prices available from (615) 576-8401, FTS 626-8401

Available to the public from
National Technical Information Service
US Department of Commerce
5285 Port Royal Rd
Springfield, VA 22161

NTIS price codes
Printed copy: A05
Microfiche copy: A01

SAND89-1989
Unlimited Release
Printed November 1991

SAND--89-1989
DE92 004789

AREAL POWER DENSITY:
A PRELIMINARY EXAMINATION OF UNDERGROUND HEAT TRANSFER
IN A POTENTIAL YUCCA MOUNTAIN REPOSITORY
AND RECOMMENDATIONS FOR THERMAL DESIGN APPROACHES

Eugene S. Hertel, Jr.
Computational Physics Research and Development Division 1541

and

Eric E. Ryder
Performance Assessment Applications Division 6313

Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

The design of the potential Yucca Mountain repository is subject to many thermal goals related to the compliance of the site with federal regulations. This report summarizes a series of sensitivity studies that determined the expected temperatures near the potential repository. These sensitivity studies were used to establish an efficient loading scheme for the spent fuel canisters and a maximum areal power density based strictly on thermal goals. Given the current knowledge of the site, a design-basis areal power density of 80 kW/acre can be justified based on thermal goals only. Further analyses to investigate the impacts of this design-basis APD on mechanical and operational aspects of the potential repository must be undertaken before a final decision is made.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

The SNL Quality Assurance Program Plan (including Department 6310 QAPP specific to the Yucca Mountain Site Characterization Project) was in effect during the course of this work. Criteria 1-7 and 15-18 of the QAPP applied to this work. Department Operating Procedures (DOP) 2-4, 3-2, and 3-3 were specifically used to assure quality in the conduct of these analyses. The results discussed in this report were the product of work carried out under a Yucca Mountain Site Characterization Project Problem Definition Memo (PDM). PDM 75-11, "A Parametric Study of Controlling Variables of the Areal Power Density (APD) in Support of ACD," dated October 21, 1988, was used to generate the results of Section 4. This report was reviewed in accordance with DOP 6-2; the reviews were conducted by two technical peers, line management, and the Yucca Mountain Site Characterization Project Office. The work contained in this report was done under WBS No. 1.2.1.4.3.1.

As a result of the SNL Preparedness Review of WBS No. 1.2.1.4.3.1 regarding the initiation of quality affecting work, it was determined that the procedures used during this study were not sufficient to assume compliance with the current SNL QAPP (Rev. E). Therefore, the work reported should be considered as non-quality affecting (NQ).

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1.0 INTRODUCTION	1-1
2.0 DEFINITION OF AREAL POWER DENSITY	2-1
3.0 SURVEY OF CURRENT THERMAL GOALS	3-1
3.1 Borehole Temperature Limit	3-1
3.2 One-m Rock Temperature Limit	3-3
3.3 Emplacement Drift Temperature Limit	3-5
3.4 Access Drift Temperature Limit	3-6
3.5 TSw3 Temperature Limit	3-6
3.6 Modification of Surface Temperature Limit	3-7
3.7 Recommendations for Changes in Thermal Goals	3-7
4.0 AREAL POWER DENSITY STUDY RESULTS	4-1
4.1 Analysis Approach	4-1
4.1.1 Material Properties	4-2
4.1.2 Canister Loading	4-3
4.1.3 Geometry	4-4
4.1.4 Boundary and Initial Conditions	4-6
4.2 Material Properties Sensitivity Study	4-6
4.3 Canister Loading Sensitivity Study	4-8
4.4 Canister Spacing Sensitivity Study	4-8
4.4.1 Vertical Emplacement	4-9
4.4.2 Horizontal Emplacement	4-9
4.5 Emplacement Drift Spacing Sensitivity Study	4-13
4.5.1 Vertical Emplacement	4-15
4.5.2 Horizontal Emplacement	4-20
4.6 Emplacement Drift Standoff Sensitivity Study	4-25
4.6.1 Vertical Emplacement	4-25
4.6.2 Horizontal Emplacement	4-27
4.7 Access Drift Standoff Sensitivity Study	4-28
4.7.1 Vertical Emplacement	4-30
4.7.2 Horizontal Emplacement	4-30

TABLE OF CONTENTS
(Concluded)

<u>Section</u>	<u>Page</u>
4.8 TSw3 Standoff Sensitivity Study	4-31
4.8.1 Vertical Emplacement	4-32
4.8.2 Horizontal Emplacement	4-34
4.9 Surface Temperature Modification Sensitivity Study	4-35
4.10 Alternative Underground Layout Studies	4-37
5.0 AREAL POWER DENSITY AND UNDERGROUND DESIGN RECOMMENDATIONS	5-1
6.0 SUMMARY AND CONCLUSIONS	6-1
7.0 REFERENCES	7-1
APPENDIX A PARAMETERS USED IN THIS STUDY AND CORRESPONDING YMP REFERENCE INFORMATION BASE VALUES	A-1

LIST OF TABLES

<u>Table</u>	<u>Page</u>
3-1 Principal 10 CFR 60 Sections Applicable to Underground Repository Design	3-1
3-2 Parameters Used in Mechanical Model of Very-Near-Field Region	3-4
4-1 Peak Borehole Temperatures for Single Canisters with Varying Material Properties.....	4-7
4-2 Average Emplacement Drift Temperatures for Single-Panel Horizontal Orientation	4-27
4-3 Vertically Emplaced Panel Access Temperatures 50 yr After Emplacement for a 30-m Standoff	4-30
4-4 Horizontally Emplaced Panel Access Temperatures 50 yr After Emplacement for a 30-m Standoff.....	4-31
4-5 Canister Spacings and LAPDs for Square Layouts	4-39
4-6 Canister Spacings and LAPDs for Triangular Layouts	4-39
5-1 Thermally Optimized APDs and Layouts	5-1
A-1 Summary of Material Properties.....	A-2

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2-1 Unit Cell Used in the Definition of the Local Areal Power Density	2-3
2-2 Heated Drift Length Definition	2-3
4-1 A Typical Vertical Emplacement Layout	4-5
4-2 A Typical Horizontal Emplacement Layout	4-5
4-3 Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Drift with 2.29-m Canister Spacing and 2-kW Canister Loading	4-10
4-4 Borehole and 1-M Temperature Histories for a Single Vertically Emplaced Drift with 2.40-m Canister Spacing and 2-kW Canister Loading	4-10
4-5 Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Drift with 3.70-m Canister Spacing and 3-kW Canister Loading	4-11
4-6 Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Drift with 6.10-m Canister Spacing and 4-kW Canister Loading	4-11
4-7 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Drift with 5.20-m Canister Spacing and 2-kW Canister Loading (6-kW Loading per Borehole)	4-12
4-8 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Drift with 5.60-m Canister Spacing and 2-kW Canister Loading (6-kW Loading per Borehole)	4-12
4-9 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Drift with 9.00-m Canister Spacing and 3-kW Canister Loading (9-kW Loading per Borehole)	4-14
4-10 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Drift with 16.0-m Canister Spacing and 4-kW Canister Loading (12-kW Loading per Borehole)	4-14
4-11 Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 2.40-m Canister Spacing, 60-m Drift Spacings, and 2-kW Canister Loading	4-16
4-12 Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 2.90-m Canister Spacing, 30-m Drift Spacings, and 2-kW Canister Loading	4-16

LIST OF FIGURES
(Continued)

<u>Figure</u>	<u>Page</u>
4-13 Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 3.70-m Canister Spacing, 60-m Drift Spacings, and 3-kW Canister Loading	4-17
4-14 Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 4.35-m Canister Spacing, 30-m Drift Spacings, and 3-kW Canister Loading	4-17
4-15 Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 6.10-m Canister Spacing, 50-m Drift Spacings, and 4-kW Canister Loading	4-18
4-16 Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 6.85-m Canister Spacing, 30-m Drift Spacings, and 4-kW Canister Loading	4-19
4-17 Borehole Temperature Histories for a Range of Drift Spacings	4-19
4-18 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 5.60-m Canister Spacing, 110-m Drift Spacings, and 2-kW Canister Loading (6-kW Loading per Borehole)	4-21
4-19 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 6.50-m Canister Spacing, 65-m Drift Spacings, and 2-kW Canister Loading (6-kW Loading per Borehole)	4-21
4-20 Borehole and 1-m Temperature Histories for a Single Horizontal Panel with 7.20-m Canister Spacing, 65-m Drift Spacings, and 2-kW Canister Loading (6-kW Loading per Borehole)	4-22
4-21 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 9.00-m Canister Spacing, 100-m Drift Spacings, and 3-kW Canister Loading (9-kW Loading per Borehole)	4-23
4-22 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 16.0-m Canister Spacing, 90-m Drift Spacings, and 4-kW Canister Loading (12-kW Loading per Borehole)	4-23

LIST OF FIGURES (Concluded)

<u>Figure</u>	<u>Page</u>
4-23 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 11.2-m Canister Spacing, 65-m Drift Spacings, and 3-kW Canister Loading (9-kW Loading per Borehole)	4-24
4-24 Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 18.5-m Canister Spacing, 65-m Drift Spacings, and 4-kW Canister Loading (12-kW Loading per Borehole)	4-24
4-25 Temperature Histories at the Emplacement Drift Floor for a Single Vertically Emplaced Panel with 4.35-m Canister and 30-m Drift Spacings for 3-kW Canister Loading	4-26
4-26 Emplacement Drift Floor Temperatures versus LAPD for Vertical Emplacement	4-26
4-27 Emplacement Drift Floor Temperatures versus LAPD for Horizontal Emplacement	4-28
4-28 Six-Panel Model Geometry	4-29
4-29 Contour Map of the Thickness Between the Top of the TSw3 Unit and the Repository Floor	4-32
4-30 TSw3 Temperature Response (60 m below Repository Horizon) versus LAPD for Vertical Emplacement	4-33
4-31 TSw3 Temperature Response (40 m below Repository Horizon) versus LAPD for Vertical Emplacement	4-34
4-32 TSw3 Temperature Response (60 m below Repository Horizon) versus LAPD for Horizontal Emplacement	4-36
4-33 TSw3 Temperature Response (40 m below Repository Horizon) versus LAPD for Horizontal Emplacement	4-36
4-34 Square and Triangular Emplacement Layouts	4-38

1.0 INTRODUCTION

The Yucca Mountain Site Characterization Project (YMP) is currently assessing the feasibility of locating a high-level nuclear waste repository at Yucca Mountain, Nevada. The purpose of a repository is to safely and effectively dispose of spent fuel generated by nuclear reactors and high-level radioactive waste resulting from plutonium production. It has determined that a geologic repository is the best means of accomplishing the objective of waste containment and isolation. Sandia National Laboratories, a prime contractor to the DOE, was responsible for the conceptual design of the waste repository.

The areal power density (APD) is an important characteristic of the repository¹ because it is directly related to the capacity of the site, the repository layout, and the extent to which the original characteristics of the site are thermally modified as a consequence of waste emplacement. The APD has been identified as the first product of Information Need 1.11.6 (repository thermal loading and predicted thermal and thermomechanical response of the host rock; DOE, 1988) and as such forms the basis for subsequent products of that Information Need.

The current design basis APD of 57 kW/acre was chosen during the Unit Evaluation Study of Johnstone et al. (1984) and is based on a waste concentration that would produce a peak emplacement drift floor temperature of 100°C. Since the time of the Johnstone study many aspects regarding the potential repository have changed, resulting in the need for a reinvestigation of the allowable repository APD. The work undertaken for this report was envisioned as a general sensitivity study of the factors that control APD; the results to be used in establishing recommendations for the maximum allowable thermal loading of the potential repository.

¹The term "repository" appears throughout this document. The use of the term "repository" to identify the facility or some portion of the facility that may be constructed and operated at Yucca Mountain is not intended to imply that such a facility will be constructed or operated at this site.

To provide a general understanding of the controlling variables, this report is organized as follows. First, a comprehensive definition of APD is presented. Then, a review of existing thermal design goals is presented, with recommendations for changes in these constraints noted where sufficient justification exists. Finally, the results from a series of sensitivity studies are presented. Specifically, the effects of material properties, canister sizes, and repository layouts on APD are evaluated with respect to applicable thermal design goals outlined in the federal regulations (10 CFR 60). Thermal analyses carried out in support of these evaluations use analytical, conduction-only solutions. Therefore, the effects of ventilation, layered stratigraphy, and temperature dependent thermal properties are not addressed in this report and should be investigated in future studies.

The analyses performed here should not be considered "reference" analyses. They have been performed as scoping studies in support of the Advanced Conceptual Design. A similar set of calculations may be performed in support of the License Application Design with (possibly) different models. The recommendations being made are preliminary and may change before the License Application Design is started. Finally, it is emphasized that the recommendations and analyses consider only thermal goals; no operational, mechanical, or other goals are addressed in this report.

2.0 DEFINITION OF AREAL POWER DENSITY

The APD can be defined in a variety of ways, depending on what area is chosen as "containing" the thermal power. For this report, two APD definitions, spanning the range of physical regimes from near-field (canister and drift scale) to very-far-field (repository scale), will be used. All definitions of the APD assume that the thermal power identified is the initial thermal power (at emplacement). The following paragraphs serve as an introduction and present definitions of the two APDs used in this report.

The project has, since its inception, used the concept of APD. The first reference to APD comes from the Unit Evaluation Study of Johnstone et al. (1984). At that time, the maximum areal loading was dependent on a temperature limitation at the emplacement drift floor. This limit (100°C) has since been deemed unnecessary because of expectations that blast cooling of emplacement drifts is feasible. During the Unit Evaluation Study, it was found that APD was not sensitive to emplacement horizon (APDs ranged from 57 to 54 kW/acre, depending on the thermomechanical unit containing the potential repository). The limiting thermal goal of emplacement drift floor temperature was affected by the emplacement geometry (floor to canister offset) more than differing material properties. For the potential repository's conceptual design, the design-basis APD was selected to be that defined by the Unit Evaluation Study. This was done even though the emplacement drift floor temperature limit had been discarded. This same design-basis APD has been used since. This report contains the first systematic reevaluation of APDs since the Unit Evaluation Study.

The simplest definition of APD is the local areal power density (LAPD). Defined to be the initial thermal power of a single canister divided by the area of a unit cell, the LAPD is useful in monitoring the near-field thermal effects of a canister that is not situated near the edge of a panel. Any effects caused by the sequential nature of the emplacement operation are ignored because the time involved in emplacement is much shorter than the evaluation time of the various thermal goals. The unit

cell area is defined to be the drift spacing times the canister spacing. Figure 2-1 shows a unit cell and layout for a typical series of emplacement drifts (vertical emplacement). For a regular layout (constant canister and drift spacings), the LAPD is given by

$$\text{LAPD} = Q/(\text{CS} \cdot \text{DS}) \quad , \quad 2-1$$

where

Q = total thermal loading within unit cell, W,
CS = canister spacing, m, and
DS = drift spacing, m.

Equation 2-1 reports results in W/m²; however, the Yucca Mountain Site Characterization Project has historically referred to APD in terms of kW/acre. To convert the units of Equation 2-1 to historical units, a factor of 4.047 (1 acre = 4047 m²) must be included as follows:

$$\text{LAPD} = (4.047 \cdot Q)/(\text{CS} \cdot \text{DS}) \quad . \quad 2-2$$

The second definition of the local APD (Equation 2-2) will be used in the remainder of this report.

The second definition of APD we utilize for this study is one that includes the effects of panel layouts. The panel areal power density (PAPD) is calculated as a reduction in the value for LAPD. This reduction is based on the PAPD's inclusion of that area not used for actual waste emplacement contained in the standoffs at the lateral edges of each panel. The unused area contained in the main drifts and perimeter drifts is not included in the definition of PAPD. Figure 2-2 displays a typical panel with the lateral standoffs (vertical emplacement). For a regular layout, the PAPD is given by

$$\text{PAPD} = \text{LAPD} \cdot (\text{HDL}/\text{DW}) \quad , \quad 2-3$$

Figure 2-1. Unit Cell Used in the Definition of the Local Areal Power Density

Figure 2-2. Heated Drift Length Definition

where

HDL = heated drift length, m, and

DW = design drift width, m.

For the Site Characterization Plan-Conceptual Design Report (SCP-CDR) design, the ratio HDL/DW is approximately 0.8 (SNL, 1987). The PAPD is primarily used for estimating the area required for the potential repository. Because it is linearly scaled to the LAPD, it can also be used to estimate near-field thermal effects. The Yucca Mountain Site Characterization Project has historically used the term APD when referring to the panel areal thermal loading. That is, the design-basis APD of 57 kW/acre from the SCP-CDR (SNL, 1987) was calculated using the definition of PAPD in Equation 2-3.

3.0 SURVEY OF CURRENT THERMAL GOALS

A series of goals has been developed by the Yucca Mountain Site Characterization Project to assist in the performance assessment process. These goals can be traced back to applicable federal regulations that govern the development of a nuclear waste repository. The bulk of the applicable federal regulations are contained in 10 CFR 60, Section 133. Table 3-1 outlines the principal sections that pertain to the thermal design of an underground repository.

TABLE 3-1

PRINCIPAL 10 CFR 60 SECTIONS APPLICABLE TO UNDERGROUND REPOSITORY DESIGN

<u>Section</u>	<u>Subject</u>
111	Waste Retrievability
133(a)(1)	Design Layout and Engineered Barriers to Contribute to Performance
133(b)	Accommodate Site-Specific Conditions
133(e)(2)	Design to Reduce Deleterious Rock Movement
133(h)	Assist Performance of Geologic Setting in Meeting the Post-closure Performance Objectives
133(i)	Predict Thermal and Thermomechanical Response

The design goals discussed in the following sections resulted from an iterative process that started with the development of the SCP-CDR (SNL, 1987) and continues today. These goals are evolutionary in nature and their modification represents an attempt to improve the ability to license a nuclear waste repository.

3.1 Borehole Temperature Limit

To aid in the Issue Resolution process for Issue 1.10 (waste package postclosure behavior; DOE, 1988), the borehole temperature limit has been

chosen so that performance (for isolation and containment) can be allocated to the spent-fuel cladding. Current spent-fuel assemblies have cladding that is designed to withstand temperatures greater than 350°C. The maximum allowable value of the centerline canister temperature for this project (350°C) has been chosen conservatively; the actual temperature at which the cladding may start to fail in long-term storage is thought to be 30 to 50°C higher. Using current canister designs, an estimate of the borehole temperatures can be made so that the maximum cladding temperatures are not exceeded. The Site Characterization Plan (SCP) lists the maximum borehole wall temperature as 275°C (DOE, 1988). The borehole temperature goal relates directly to 10 CFR 60, 133(a)(1), "Design Layout and Engineered Barriers to Contribute to Performance," where the performance is that of radionuclide containment by the fuel cladding.

The borehole temperature limit is commonly modified when linear heat conduction is used to model the energy transfer in an underground repository. Linear models ignore two competing physical effects: (1) they do not consider the effects of the boiling of pore water (that water trapped in the pores of tuff) which will absorb energy early in time and release it, possibly in a different location, later in time, and (2) they do not include the effect of variations in material properties (conductivity and heat capacity) with changes in temperatures. Comparisons have been made by Mansure (1987) between a linear heat-conduction model (Klett et al., 1981) and a nonlinear finite element model (Gartling, 1982) that modeled the temperature dependent material properties implicit in boiling phenomena. For the bulk of the time domain considered (100 to 1000 yr), the differences between linear and nonlinear models were small. However, the linear model significantly underpredicted the peak borehole temperature. Mansure (1987) has recommended that linear heat-conduction models adhere to a lower peak borehole temperature limit than noted in the SCP (DOE, 1988) to account for the near-field errors in this class of models. The modified borehole temperature limit that will be used for the analyses contained in this report is 235°C. It should be noted that this lower temperature limit was used in developing the underground layouts contained in the SCP-CDR (SNL, 1987).

3.2 One-m Rock Temperature Limit

The 1-m rock temperature limit was chosen to minimize the potential for borehole collapse. The goal of limiting borehole collapse has origins in at least three regulations: 10 CFR 60.133(e)(2), "Design to Reduce Deleterious Rock Movement;" 10 CFR 60.111, "Retrieval;" and sections of the Generic Requirements Document (DOE, 1984). The temperature limit itself has some basis in the material properties (a phase change that takes place between 200°C and 250°C) of welded tuffs, but the location of the limit (1 meter into the rock as measured radially from the borehole wall) was chosen somewhat arbitrarily. In fact, the SCP states that this goal may be replaced before license application with some other measure of the volume of rock that may exceed the temperature bounds (DOE, 1988). For this reason, it is recommended that the 1-m limit be further investigated with the goal of understanding the actual stress/strain state at the borehole surface and predicting the potential for borehole failure. In support of this recommendation, an idealized model of the thermally induced stress/strain around a borehole was examined. By modeling the borehole region as a thick-walled cylinder constrained to no displacement at the outer surface ($U(r_o) = 0$) and zero radial stress at the inner surface ($\sigma(r_i) = 0$), analytic solutions to the stress/strain equations are readily available (Eisenberg, 1980). For the case of a cylinder with elastic, non-temperature dependent properties and no residual stresses, the displacement solution reduces to the following:

$$U(r) = Ar + \frac{B}{r} + \frac{\alpha}{r} \frac{(1 + \nu)}{(1 - \nu)} \int_{r_i}^r x \Delta T(x) dx \quad 3-1$$

where

$U(r)$ = radial displacement,

r = radius,

r_i = inner radius,

r_o = outer radius,

α = coefficient of linear thermal expansion,
 ν = Poisson's ratio,
 ΔT = change in radial temperature distribution;

and from the boundary conditions listed above:

$$A = \frac{(1 - 2\nu)}{r_i^2} B \quad ; \quad 3-2$$

$$B = \frac{r_i^2 r_o}{(1 - 2\nu) r_i^2 + r_o^2} \frac{-\alpha(1 + \nu)}{r_o(1 - \nu)} \int_{r_i}^{r_o} x \Delta T(x) dx \quad . \quad 3-3$$

If the cylinder is assumed to have the initial geometric description and constant mechanical property values listed in Table 3-2, and the final temperature distribution in the cylinder ($\Delta T(r)$) is taken to range from 275°C at the borehole to 200°C at the outer surface, a 5-mm (0.2-in.) radial displacement (reduction in radius) is predicted at the borehole wall. Considering that the current limitation on borehole wall movement is 50 mm (2 in.) (DOE, 1988), the above displacement indicates that the 1-m rock temperature limit may be increased without jeopardizing the current mechanical limit on rock movement in the borehole region. It should be recognized that this model takes an extremely idealized approach to the problem; however, the results indicate that a more detailed investigation would prove invaluable in clarifying the 1-m thermal goal and its relationship to other goals.

TABLE 3-2

PARAMETERS USED IN MECHANICAL MODEL OF
VERY-NEAR-FIELD REGION

$$\begin{aligned}
 r_i &= 0.37 \text{ m} \\
 r_o &= 1.37 \text{ m} \\
 \nu &= 0.3 \\
 \Delta T(r) &= -75^\circ\text{C/m } (r - r_i) + 250^\circ\text{C}
 \end{aligned}$$

For the purposes of this report, the 1-m rock temperature limit will be imposed as currently stated with no modification of that limit made because of the use of linear heat-conduction models. If this limit is the constraining thermal goal for any of the sensitivity studies described here, that fact will be noted for future reinvestigation.

3.3 Emplacement Drift Temperature Limit

An emplacement drift temperature limit of 100°C was established as the limiting thermal goal in the Unit Evaluation Study of Johnstone et al. (1984). The controlling parameter for this limit is the standoff from the emplacement drift floor to the waste canister for vertical emplacement, and from the canister to the emplacement drift wall for horizontal emplacement. In the SCP-CDR design, there were different emplacement drift temperature limits for the vertical and horizontal emplacement (SNL, 1987). The issue resolution process of the SCP did not, however, recognize the need for an emplacement drift temperature limit, but did (for retrieval purposes) recognize the need for the access drift temperature limit. Potentially, any given emplacement drift could be cooled by the potential repository's ventilation system, thereby allowing retrieval and inspection activities to proceed at appropriate temperatures. A set of analyses to assess the feasibility for the blast cooling of an emplacement drift is in progress and should be available before the Advanced Conceptual Design process begins. The access drift temperature limit and expected blast cooling capabilities make it reasonable to eliminate the need for an emplacement drift temperature limit.

Even though the emplacement drift temperature limit is not included in the current list of thermal goals, a sensitivity study of the effects of the standoff on emplacement drift temperatures is presented in Section 4.6 of this report.

3.4 Access Drift Temperature Limit

The Repository Design Requirements (RDR) of the Yucca Mountain Mined Geologic Disposal System states that the temperatures in the panel access drifts in both vertical and horizontal emplacement configurations shall not

exceed temperatures that impede inspection, maintenance, or retrieval operations. The design goal is to limit the wall temperature of the access drifts to 50°C for the first 50 yr following the initiation of waste emplacement. The RDR assumes that the access drifts will be partially cooled by controlled ventilation at low flow rates. For this report, no credit will be taken for the heat removed by ventilation. The rock temperature at the access drift will be reported as if there were no ventilation. The connection of the access drift temperature limit to regulations lies in the area of retrievability, 10 CFR 60.111, and the Generic Requirements Document (DOE, 1984).

3.5 TSw3 Temperature Limit

One of the more credible paths that radionuclides could take to the accessible environment would be as a contaminant in the groundwater. Because the repository may be constructed in partially saturated material, that material between the repository and the water table is important to total system performance. In addition, some of the thermal/mechanical units below the repository horizon are subject to mineralogic changes when they dehydrate. Such dehydration has the potential to cause chemical and physical changes that could be detrimental to waste isolation. The SCP has set a performance goal of limiting the amount of temperature modification that the underlying units may experience (DOE, 1988). This goal, which is intended to minimize the extent of potentially adverse thermal effects, is dictated by performance assessment considerations like the groundwater travel time.

The TSw3 temperature limit is a constraint imposed at the interface between the second Topopah Springs unit (TSw2) and the third (TSw3), and is currently set at 115°C. In the event that the thermal goal changes, the results discussed in this report are presented as a sensitivity study of the predicted interface temperatures over a range of times and depths. The results of the sensitivity study are general in that they are applicable for a different temperature limit should the thermal goal be modified in the future. Regulations that can be applied to this thermal goal are 10 CFR 60.133(b) and 10 CFR 60.133(i).

3.6 Modification of Surface Temperature Limit

Temperature modification at the surface is a plausible long-term effect of the potential repository's heat-generating capabilities. A limit on the temperature change at the surface of 6°C has been selected. This limit was chosen by inspection of long-term temperature records for the Yucca Mountain site and by measuring the average temperature fluctuations caused by climatic variability. The 6-degree limit is similar to the average temperature change caused by normal climatic variability. This report does not attempt to predict the surface temperature changes, but results from other reports will be cited to assure that this thermal goal will be met for all APDs recommended in this report. The regulation that applies to this goal is 10 CFR 60.133(e)(2).

3.7 Recommendations for Changes in Thermal Goals

Of the thermal goals discussed above, the 1-m rock temperature limit and the TSw3 temperature limit are candidates for possible modification. In addition, the modification of the borehole temperature limit for linear heat-conduction models needs further analysis to assure that the spent fuel cladding thermal goal (350°C) is met. This analysis is necessary to set a value that is sensibly conservative and appropriate for use in underground repository design when linear heat-conduction models are used.

As noted in the SCP, the 1-m temperature limit may be replaced with some other measure of performance (DOE, 1988). Further investigation will be required; however, before any specific recommendations can be made.

Based on the model results presented here, the 1-m rock temperature limit appears significantly more restrictive than the thermomechanical goals set for the borehole wall. The model developed here is strongly idealized and its intent is only to identify a need for additional analyses; not to drive project-level decisions. Given the uncertainty as to the 1-m temperature limit and the actual stress/strain produced under that limit, it is our position that a temperature limit (1-m rock

temperature) may not be the appropriate performance measure for borehole stability and should be investigated further.

Because one of the stated intents of the TSw3 temperature goal is to limit the potential for mineralogic changes caused by dehydration, a reasonable and conservative temperature limit may be the unconfined boiling point of water at the appropriate elevation. That value is approximately 97°C. Therefore, if the temperatures in the TSw3 unit does not exceed 97°C, no dehydration will occur because pore-water boiling is not possible. This lower limit may be overly conservative because the water contained in the rock is trapped in small pores and pressure effects will elevate the actual boiling point of the water. These pressure effects are not well understood in the in situ environment, so it is not currently possible to accurately assess the "overly conservative" nature of a lower TSw3 temperature limit. The predictions presented in this report are given in terms of a sensitivity study and are applicable to a lower limit, if required.

4.0 AREAL POWER DENSITY STUDY RESULTS

The results of a series of sensitivity studies that establish acceptable canister and drift spacing combinations for various initial canister power outputs are presented in this chapter. The bases for determining the acceptability of any configuration are the thermal goals outlined in Chapter 3. Results for vertical and short-horizontal (three-canister) emplacement schemes are included. The studies were carried out in a systematic fashion that used a progressively greater number of thermal goals to establish final combinations of acceptable canister and drift spacings. The first study uses a single drift model to determine the minimum canister-to-canister spacing that satisfies both the borehole and 1-m temperature goals. The results from this study are applied to a multi-drift single-panel model to establish appropriate drift spacings, again subject to the borehole and 1-m goals. Once acceptable canister and drift spacing combinations are determined based on the borehole and 1-m goals, they are tested for compliance with the emplacement drift, panel access, and TSw3 temperature goals. Presentation of the canister/drift spacing studies is preceded by a discussion of two sensitivity studies that (1) examine a single canister model's response to variations in the rock's thermal properties, and (2) establish the maximum acceptable loading for an isolated vertically emplaced canister.

4.1 Analysis Approach

The thermal modeling of the potential nuclear waste repository at Yucca Mountain is complicated by the existence of open air spaces (drifts) and complex layered stratigraphy in and around the site. In order to match the scoping nature of the proposed analyses with an appropriate model, simplifying assumptions were made.

For this study, the potential repository site was assumed to be composed of a single homogeneous, isotropic material with constant material properties. In addition, no open air spaces or variations in surface topography were considered, and the waste canisters were assumed to be

adequately represented by heat-generating right-circular cylinders in contact with the emplacement medium. Using these simplifications, analytical solutions to the heat-conduction equation can be derived.

Based on closed-form analytical solutions to the heat-conduction equation, the NARY 1.0 code (Hertel, E. S., Jr., Description, Verification, and User's Manual for NARY 1.0: A Three-Dimensional Linear Superposition Heat-Conduction Program, SAND88-2216, Draft) employs the ideas of point/cylindrical heat sources, superposition, and the method of images to obtain temperature histories at discrete points in three dimensions. NARY 1.0 was, therefore, chosen for use in this investigation. The following sections describe the material properties, canister loading, geometry, and boundary conditions used in the modeling.

4.1.1 Material Properties

All models assumed the waste to be isolated in an infinite mass of TSw2. For the time frames of the thermal analyses carried out (0 to 1000 yr), the heat pulse does not have sufficient time to reach the surface region. Because of the long travel time for the heat pulse, the assumption of an infinite mass is not unreasonable. For those thermal goals very near the waste canister (borehole and 1-m temperature limits), the heat pulse that controls the temperatures at these locations is not influenced by the adjacent strata. It is noted, however, that as the physical scale of the thermal goals increases, the use of homogeneous material properties becomes less appropriate.

As indicated above, TSw2 was chosen to represent the host rock of the potential repository. Item 1.2.2 of Version 4.0 of the Reference Information Base (RIB) lists the rock mass thermal conductivity of TSw2 to be 1.839 ± 0.064 W/m K for a dry state. RIB item 1.2.4 reports the rock mass thermal capacitance of TSw2 to range from 2.0065 to 2.3410 J/cm³ K for temperatures of 115°C to 275°C. For the analyses presented, a thermal conductivity of 1.84 W/m K and a thermal capacitance of 2.16 J/cm³ K were selected from the ranges noted above. Parameters representing dry rock

were selected for this study because these values model a slower-moving thermal pulse, yielding higher temperatures that can be considered conservative. Furthermore, the region near the waste canisters is expected to experience temperatures in excess of 100°C for the first 300 to 1000 yr. These temperatures should cause some fraction of the trapped pore water to boil and leave the region surrounding the waste canister. This will reduce the saturation level of the rock in the region near the waste canister, again supporting the choice of dry material properties for the modeling.

4.1.2 Canister Loading

Spent fuel with a mixture of 60% pressurized water reactor (PWR) and 40% boiling water reactor (BWR) was used to represent the waste. As referenced in the RIB, Appendix B of "Generic Requirements for a Mined Geologic Disposal System" (DOE, 1984) documents the heat generation of such waste with respect to time. An exponential fit to this data was performed by Mansure and Petney (1991), and is valid for times of up to 1000 yr out of the reactor. The thermal power as a function of time is given by

$$P(t) = P_o \sum_{i=1}^n a_i e^{-b_i t}, \quad 4-1$$

where P_o represents the initial thermal power and t is the time from removal from the reactor.

The normalized coefficients for the power decay function above are as follows:

i	a_i	b_i
1	2.4988E-2	1.108E-3
2	7.0672E-2	1.467E-2
3	9.1560E-2	3.259E-2
4	8.1278E-1	4.674E-1

The effects of aging the waste out of the reactor is accounted for by including a term of the following form:

$$e^{-b_i t_{age}},$$

4-2

where t_{age} is the intervening time, in years, between the waste's removal from a reactor and its emplacement at a repository.

For the results presented in this report, all waste was assumed to have a time delay of 10 yr prior to emplacement.

In terms of initial canister loading, the SCP-CDR design basis is 3 kW/canister for consolidated spent fuel rods (SNL, 1987). Current project plans do not include consolidation, but instead assume that the canister will contain intact fuel assemblies. The hybrid canister currently under consideration can contain up to four PWR assemblies, up to ten BWR assemblies, or three PWRs and four BWRs simultaneously. Given the storage capacity of the hybrid canister, the initial thermal output of a canister could range from 0.54 to 4.79 kW. The low end of this range represents old, low-burnup fuel and the high end represents young, high-burnup fuel. The bulk of the currently expected inventory will allow canisters to be loaded in the 2- to 4-kW range. Thus, the canister loadings of 2, 3, and 4 kW were chosen as representative, and used in the models presented below.

4.1.3 Geometry

For vertical emplacement, the canister is assumed to be a 4.76-m (187.5-in.) long right-circular cylinder of 0.74-m (29-in.) diameter. Figure 4-1 shows a generalized representation of a panel for the vertical emplacement of nuclear waste.

For short-horizontal emplacement (three-canister), the waste assembly is modeled as a single equivalent right-circular cylinder having a length of 15.28 m (601.5 in.) a diameter of 0.94 m (37 in.). Figure 4-2 shows

Figure 4-1. A Typical Vertical Emplacement Layout

Figure 4-2. A Typical Horizontal Emplacement Layout

a generalized representation of a panel for the short-horizontal emplacement scheme.

For all models, the nominal drift length available for waste emplacement was assumed to be 426.7 m (1400 ft).

Based on the work of St. John (1985), an exponentially decaying point source has a radius of influence defined by

$$R_e = 4\sqrt{\alpha' t} \quad , \quad 4-3$$

where

$$\begin{aligned} \alpha' &= \text{thermal diffusivity} = K/\rho C_p, \\ K &= \text{thermal conductivity, and} \\ \rho C_p &= \text{heat capacitance.} \end{aligned} \quad 4-4$$

Using the thermal properties from Section 4.1.1, the diffusivity (α) is 26.9 m²/yr. To assure accurate solutions for the first 50 yr, therefore, all sources within 150 m should be explicitly included. For all single-panel models, the inclusion of nine emplacement drifts was deemed adequate to satisfy this requirement.

4.1.4 Boundary and Initial Conditions

As discussed in Section 4.1.1, the heat-generating canisters were assumed to be contained in an infinite mass of TSw2. The initial temperature of the rock was taken as a uniform 24.7°C and is representative of temperatures at the repository horizon.

4.2 Material Properties Sensitivity Study

To assess the effects of uncertainties associated with the thermal properties of TSw2, a sensitivity study was carried out examining the rock's thermal response subject to variations in its thermal properties. A single isolated vertical canister of waste initially loaded at 3 kW was taken as the baseline model. The model's response to variations around the mean dry TSw2 thermal property values were examined. Table 4-1 shows the peak borehole wall temperatures as predicted by the model for the indicated

TABLE 4-1

PEAK BOREHOLE TEMPERATURES (°C) FOR SINGLE CANISTERS
WITH VARYING MATERIAL PROPERTIES

ρC_p (MJ/m ³ K)	Peak Temperature (°C)							
	1950.0	2050.0	2100.0	2150.0	2160.0	2200.0	2250.0	2300.0
K (MW/m K)								
0.00170	156.7				156.2			155.9
0.00175					152.6			
0.00180					149.2			
0.00184	147.0	146.8	146.7	146.6	146.5	146.5	146.4	146.3
0.00190					142.8			
0.00195					139.9			
0.00200	137.5				137.1			136.9

thermal conductivities and thermal capacitances. In all cases, the peaks were found to occur approximately 2 yr after emplacement. It is apparent from Table 4-1 that the temperature field surrounding a canister is primarily dependent upon values for thermal conductivity, with variations in thermal capacitance showing much less influence. For the range in thermal conductivity defined by the standard deviation for dry TSw2 (± 0.064 W/m K), the peak borhole wall temperature varies on the order of 4°C from that calculated for the mean, decreasing with increasing conductivity.

It is apparent, therefore, that for a wide range of thermal properties the peak temperatures are relatively insensitive to changes given the assumptions of linear heat conduction. Effects such as two-phase flow, layered geologic strata, ventilated air spaces, and spatially dependent properties may be more important than uncertainties in constant material

properties. Some of the above concerns are the subject of investigations currently underway for the Yucca Mountain Site Characterization Project, and these effects will be addressed in future reports.

4.3 Canister Loading Sensitivity Study

To determine the maximum possible canister loading subject to the borehole and 1-m thermal goals, a sensitivity study was carried out on a single, isolated vertical canister of waste. It was determined that for initial loadings less than 5.2 kW, the indicated temperature limits were not violated. This upper limit does not take into account the canister-to-canister overlap of temperatures fields that would exist in a repository, and is valid only for 10-yr-old waste. This result is presented strictly to demonstrate the absolute upper limit that exists as a result of the thermal properties of the surrounding rock. As noted in Section 4.1.2, a credible upper limit for canister heat output based on the hybrid design is less than 5.2 kW. Therefore, the initial canister loadings selected for investigation in this study were considered appropriate.

4.4 Canister Spacing Sensitivity Study

For this study, a single drift of equally spaced, simultaneously emplaced canisters was modeled to establish the minimum acceptable canister spacings subject to the borehole and 1-m temperature limits. The temperatures reported here are those evaluated for a centrally located canister only. Specifically, for vertical emplacement, the temperatures discussed apply to the canister located at the model origin. Similarly, for short horizontal emplacement, the temperatures are those obtained for a canister located a minimum distance from the model origin. This distinction is made because temperatures at locations near the ends of a drift will be lower due to the reduced number of heat sources that would contribute strongly to the superposition effects.

4.4.1 Vertical Emplacement

For a single drift of canisters initially loaded at 2 kW, the borehole temperature limit was satisfied for a canister spacing of 2.29 m; however, the 1-m limit was violated (Figure 4-3). To satisfy both limits, a canister spacing of 2.40 m was required (Figure 4-4).

For initial canister loadings of 3 and 4 kW, the controlling temperature limit proved to be that for the borehole. As shown in Figure 4-5, a 3.70-m spacing was found to be the minimum for canisters initially loaded at 3 kW, and 6.10 m was established as the minimum for a 4-kW initial loading (Figure 4-6).

It is interesting to note that the canister spacing values reported above are all equal to or greater than the minimum allowable spacing of 7.5 feet (2.29 m). In addition, the tendency of the 2-kW canisters to be controlled by the 1-m temperature limit, and the higher loadings to be controlled by the borehole temperature limit, will emerge as a noticeable pattern in later sections of this report.

4.4.2 Horizontal Emplacement

Unlike the case of vertical emplacement, a single drift of horizontally emplaced waste is composed of two rows of waste canisters. It is noted that for the case of horizontal emplacement, canister spacings are defined as that spacing between adjacent emplacement boreholes within a drift and do not refer to the canister-to-canister spacing within a given three-can assembly. As with the case of a single drift of 2-kW waste in a vertical configuration, the defining constraint on a single drift of 6-kW (2 kW per canister) horizontally emplaced waste is the 1-m temperature goal. Specifically, for canister spacings of 5.20 m (Figure 4-7), the borehole wall limit is satisfied; however, the 1-m limit is violated. Increasing the canister spacing to 5.60 m allows both the borehole and 1-m goals to be met (Figure 4-8).

Figure 4-3. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Drift with 2.29-m Canister Spacing and 2-kW Canister Loading

Figure 4-4. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Drift with 2.40-m Canister Spacing and 2-kW Canister Loading

Figure 4-5. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Drift with 3.70-m Canister Spacing and 3-kW Canister Loading

Figure 4-6. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Drift with 6.10-m Canister Spacing and 4-kW Canister Loading

Figure 4-7. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Drift with 5.20-m Canister Spacing and 2-kW Canister Loading (6-kW Loading per Borehole)

Figure 4-8. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Drift with 5.60-m Canister Spacing and 2-kW Canister Loading (6-kW Loading per Borehole)

For initial total loadings of 9 and 12 kW, the deciding constraint is the borehole temperature limit. For waste initially loaded at 9 kW (3 kW per canister), a canister spacing of 9.00 m proved sufficient to satisfy the indicated thermal goals (Figure 4-9). Similarly, as shown in Figure 4-10, a canister spacing of 16.0 m is required for a single drift of 12-kW (4 kW per canister) waste.

As expected from the vertical results, models using canisters loaded at 6 kW (the horizontal emplacement scheme's counterpart to 2-kW canisters emplaced vertically) is controlled by the 1-m temperature goal. This trend as well as the borehole temperature limit's primary influence on models at higher loadings will continue to be encountered in later studies.

4.5 Emplacement Drift Spacing Sensitivity Study

Expanding the results of Section 4.4, nine-drift single-panel models were created to establish combinations of canister and drift spacings that would maximize the LAPD. In these analyses, the thermal constraints applied were the borehole and 1-m goals. As with the previous study, the temperatures discussed in this section apply only to a centrally located canister, and all canisters in a panel are assumed to have been emplaced simultaneously. Because a "typical" panel should be filled within a couple of years following the start of emplacement within that panel, this approximation should not be a significant source of error.

It was expected before the actual calculations were started that the minimum spacings as determined by the previous study would be the cornerstone of future sensitivity studies. However, it was determined that the drift spacings corresponding to the previously calculated canister spacings yielded substantially lower values for APD than anticipated. Consequently, the approach of reducing the interaction between nearby heat sources (those in the same drift) was adopted in order to increase the APD. That is, to maximize the APD it was necessary to increase the canister spacings and decrease the drift spacings from those determined by the original intent of this study. These trends will be discussed in the following sections.

Figure 4-9. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Drift with 9.00-m Canister Spacing and 3-kW Canister Loading (9-kW Loading per Borehole)

Figure 4-10. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Drift with 16.0-m Canister Spacing and 4-kW Canister Loading (12-kW Loading per Borehole)

4.5.1 Vertical Emplacement

As with the single-drift models examined in Section 4.4, the 1-m temperature constraint is the defining goal for a panel of vertically emplaced waste initially loaded at 2 kW. Using the 2.40-m minimum canister spacing established above, a drift spacing of 60 m is required to satisfy the borehole and 1-m temperature goals (Figure 4-11). The combination of 2.40-m canister and 60-m drift spacings yields an LAPD of 56 kW/acre.

A canister's peak borehole and 1-m temperatures are primarily controlled by the heat generation within that canister. The contributions of the "few" nearest neighbors are also important, but canisters in the nearby drifts do not have a strong impact on the very-near-field temperature profile. Thus, it is reasonable to expect that for relatively small increases in a panel's canister spacings, substantial increases in LAPD could be realized from the correspondingly greater decreases in acceptable drift spacings. Imposing a hypothetical limit on the minimum drift spacing of 30 m based on construction considerations, it was found that an LAPD of 93 kW/acre is attained for a combination of 2.90-m canister spacing and 30-m drift spacing for canisters initially loaded at 2 kW (Figure 4-12). From the success of this example in dramatically raising the value of LAPD (56 to 93 kW/acre), the approach of increasing canister spacings in order to decrease drift spacings was adopted for all subsequent studies.

For vertically emplaced waste initially loaded at 3 kW, the drift spacing that satisfies the borehole and 1-m temperature constraints, in combination with the 3.70-m minimum canister spacing established in Section 4.4, is approximately 60 m (see Figure 4-13). Yielding an LAPD of 55 kW/acre, these spacings were adjusted as with the 2-kW single panel models in an attempt to maximize LAPD. If the canister spacing is increased to 4.35 m, the borehole and 1-m thermal goals are satisfied for the imposed minimum drift spacing of 30 m (Figure 4-14). Thus, the LAPD is increased to 93 kW/acre.

In the case of waste with an initial power output of 4 kW, the minimum acceptable drift spacing corresponding to a 6.10-m canister spacing was

Figure 4-11. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 2.40-m Canister Spacing, 60-m Drift Spacings, and 2-kW Canister Loading

Figure 4-12. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 2.90-m Canister Spacing, 30-m Drift Spacings, and 2-kW Canister Loading

Figure 4-13. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 3.70-m Canister Spacing, 60-m Drift Spacings, and 3-kW Canister Loading

Figure 4-14. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 4.35-m Canister Spacing, 30-m Drift Spacings, and 3-kW Canister Loading

determined to be 50 m (Figure 4-15), resulting in an LAPD of 53 kW/acre. When the canister and drift spacings are modified to maximize LAPD, a 6.85-m canister and a 30-m drift spacing combine to yield an LAPD of 79 kW/acre (Figure 4-16).

In summary, the peak temperatures near a canister depend on the initial thermal loading of that canister, the thermal decay profile (an aspect that is not addressed in this report), and the superposition of temperature increases because of nearby canisters. To increase the APD, it is most effective to increase the canister spacing and decrease the drift spacing. A logical limit for the upper value of APD would be to set the canister and drift spacings that provide the optimal value. This aspect of layouts will be discussed in a later section.

A further understanding of the concept of thermal overlaps is evident in Figure 4-17. When the minimum canister spacing is selected, the drift spacing must be set at a distance that corresponds to no effective thermal overlap between drifts at the time of peak borehole temperature (~20 yr). Figure 4-17 shows an overlay of borehole temperature profiles for drift spacings of 30, 50, 60, 70 m and ∞ , a canister spacing of 3.70 m, and an

Figure 4-15. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 6.10-m Canister Spacing, 50-m Drift Spacings, and 4-kW Canister Loading

Figure 4-16. Borehole and 1-m Temperature Histories for a Single Vertically Emplaced Panel with 6.85-m Canister Spacing, 30-m Drift Spacings, and 4-kW Canister Loading

Figure 4-17. Borehole Wall Temperature Histories for a Range of Drift Spacings

initial loading of 3 kW. At drift spacings greater than 50 m, there is no increase in the predicted temperatures for times less than 20 yr. As time increases, the effect of those drifts farther away from the central canister becomes more important. This is evident in the tail of the temperature profiles. The critical feature of layout design is to pick canister and drift spacings such that thermal overlap is minimized and APD is maximized.

4.5.2 Horizontal Emplacement

Using the knowledge gained from the calculations of the vertical emplacement scheme, the approach taken in this study was (1) to establish the appropriate drift spacings corresponding to the canister spacings developed in Section 4.4, and (2) to maximize the LAPD of a nine-drift single-panel repository layout based on the short-horizontal emplacement of waste canisters with a borehole loading of 6, 9, and 12 kW. The only thermal goals of interest to this study are those for the borehole and 1-m locations. As with the vertical case, a minimum value for drift spacing can be calculated for the horizontal emplacement scheme. In the case of horizontal emplacement, however, the minimum drift spacing is not imposed arbitrarily, but instead is set to eliminate any physical overlap of canister boreholes in adjacent drifts. By combining the canister-to-drift offsets with the three-canister assembly length, a minimum drift spacing of 50 m can be established. At this distance, the backs of the three-canister assemblies in adjacent drifts nearly touch. Thus, drift spacings closely approaching the 50-m limit should be avoided.

Beginning with the 6-kW (2 kW per canister) case, the combination of a 110-m drift spacing with the minimum canister spacing of 5.60 m established for a single drift of waste was required to satisfy the borehole and 1-m goals (Figure 4-18). This combination yields an LAPD of 79 kW/acre. When the canister spacing was increased in an attempt to maximize LAPD, it was found that a 6.50-m canister and 65-m drift spacing satisfied the borehole temperature goal, but the 1-m limit was violated (Figure 4-19). Increasing the canister spacing to 7.20 m and maintaining the 65-m drift spacing allows both thermal goals to be met (Figure 4-20), resulting in an LAPD of 104 kW/acre.

Figure 4-18. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 5.60-m Canister Spacing, 110-m Drift Spacing, and 2-kW Canister Loading (6-kW Loading per Borehole)

Figure 4-19. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 6.50-m Canister Spacing, 65-m Drift Spacing, and 2-kW Canister Loading (6-kW Loading per Borehole)

Figure 4-20. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 7.20-m Canister Spacing, 65-m Drift Spacings, and 2-kW Canister Loading (6-kW Loading per Borehole)

For 9- and 12-kW initial borehole loadings, the borehole temperature limit proved to be the limiting constraint. Using the single-drift results of Section 4.4, an LAPD of 81 kW/acre is realized for 9-kW (3 kW per canister) waste emplaced in the configuration of 9.00-m canister and 100-m drift spacings (Figure 4-21). For the 12-kW (4 kW per canister) case, the combination of a 16.0-m canister and a 90-m drift spacing yielded an LAPD of 67 kW/acre (Figure 4-22).

By decreasing "nearest neighbor" interactions (increasing emplacement hole spacing), substantial increases in LAPD were realized for the short-horizontal emplacement of 9- and 12-kW waste. For the 9-kW case, an LAPD of 100 kW/acre was calculated for the combination of an 11.2-m emplacement hole and a 65-m drift spacing (Figure 4-23). Similarly, for the 12-kW case, a borehole spacing of 18.5 m was required in conjunction with a 65-m drift spacing to satisfy the indicated temperature goals (Figure 4-24), yielding an LAPD of 81 kW/acre.

Figure 4-21. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 9.00-m Canister Spacing, 100-m Drift Spacings, and 3-kW Canister Loading (9-kW Loading per Borehole)

Figure 4-22. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 16.0-m Canister Spacing, 90-m Drift Spacings, and 4-kW Canister Loading (12-kW Loading per Borehole)

Figure 4-23. Borehole and 1-m Temperature Histories for a Single Horizontally Emplaced Panel with 11.2-m Canister Spacing, 65-m Drift Spacings, and 3-kW Canister Loading (9-kW Loading per Borehole)

Figure 4-24. Borehole and 1-m Temperature Histories for a Single Panel with 18.5-m Canister Spacing, 65-m Drift Spacings, and 4-kW Canister Loading (12-kW Loading per Borehole)

4.6 Emplacement Drift Standoff Sensitivity Study

As discussed in Chapter 3, the emplacement drift temperature limit is not currently considered a critical factor, and lack of compliance with the old goal does not, by itself, dictate an alteration in the canister and drift spacing combinations established in Section 4.5. However, if it is determined that blast cooling of an emplacement drift is not possible, the results presented here may be useful in directing future studies. The specific limit examined in this study is the maintenance of a temperature less than 50°C in the emplacement drift for the first 50 yr following waste emplacement.

4.6.1 Vertical Emplacement

In the vertical emplacement scheme, alteration of the emplacement drift standoff (distance from the top of the waste canister to the drift floor) only involves the vertical translation of the horizontal plane defined by the centerpoints of the waste canisters. Thus, the configuration of the canisters remains constant for all emplacement drift standoffs. If the 3-kW case of 4.35-m canister and 30-m drift spacing is considered to be representative, the variation in temperature of the emplacement drift floor as a function of standoff is shown in Figure 4-25 (ceiling temperature will be lower than the floor temperatures). It is apparent from Figure 4-25 that the emplacement drift temperature goal can not be achieved for any reasonable offset at LAPDs near 100 kW/acre. These results are typical of all vertical configurations tested.

Figure 4-26 displays the drift floor temperature at 50 yr after emplacement as a function of LAPD for a range of values. For the material properties chosen for this study, the maximum LAPD that corresponds to the temperature limit of 100°C used in the Unit Evaluation Study (Johnstone et al., 1984) is approximately 60 kW/acre. Given the difference in material properties, the difference in APDs is reasonable. It is interesting to note that the temperature varies linearly with APD. This is expected because the temperature change should vary directly with heat load for linear solutions to the heat-conduction equation.

Figure 4-25. Temperature Histories at the Emplacement Drift Floor for a Single Vertically Emplaced Panel with 4.35-m Canister and 30-m Drift Spacings for 3-kW Canister Loading

Figure 4-26. Emplacement Drift Floor Temperatures versus LAPD for Vertical Emplacement

4.6.2 Horizontal Emplacement

Unlike the case of vertical emplacement, any alteration in the standoff between the canisters and the emplacement drift for horizontal emplacement would change the canister-to-canister geometry of the system. Thus, a sensitivity study of emplacement standoff from the repository floor like that presented for vertical emplacement is not possible for the horizontal case without changing the basic layout. The models investigated in Section 4.4 use a standoff of 6.10 m between the end of a canister and the emplacement drift wall (SNL, 1987). The average drift temperatures 50 yr following emplacement are included in Table 4-2 for each of the optimized horizontal configurations presented in Section 4.4.

TABLE 4-2
AVERAGE EMPLACEMENT DRIFT TEMPERATURES FOR
SINGLE-PANEL HORIZONTAL ORIENTATION

Total Borehole Loading (kW)	Canister Spacing (m)	Drift Spacing (m)	Average Emplacement Drift Temperature 50 yr after Emplacement (°C)
6	7.20	65	161.9
9	11.2	65	157.1
12	18.5	65	132.2

Figure 4-27 displays the drift floor temperature at 50 yr after emplacement as a function of LAPD for a range of values. For the material properties chosen for this study, the maximum LAPD that corresponds to the emplacement drift floor temperature limit of 100°C used in the Unit Evaluation Study (Johnstone et al., 1984) is approximately 55 kW/acre. Given the difference in material properties and emplacement orientation, the difference in APDs is reasonable. Again, one should note that the temperature varies linearly with APD. In addition, Figures 4-26 and 4-27 show almost identical slopes, as should be expected because both orientations use the same linear solution to the heat-conduction equation.

Figure 4-27. Emplacement Drift Floor Temperatures versus LAPD for Horizontal Emplacement

4.7 Access Drift Standoff Sensitivity Study

As discussed in Chapter 3, maintenance and retrieval considerations have dictated a temperature limit of 50°C in the panel access drifts for the first 50 yr following waste emplacement. The panel access drift standoff is defined to be the distance from the centerline of the last waste canister to the plane formed by the intersection of the emplacement drift and the panel access drift. Using the canister and drift spacing combinations established above for vertical and horizontal emplacement, sensitivity studies were carried out to determine acceptable standoffs between the last canisters in an emplacement drift and the intersection of the emplacement and panel access drifts. To achieve an accurate approximation of minimum acceptable standoffs, the single-panel layouts examined in the previous studies had to be expanded. Specifically, because the panel access drifts typically lie between two panels, the effect of the interaction between waste in adjacent panels had to be accounted for by expanding

the single-panel layout to an idealized six-panel repository layout (Figure 4-28). In the expanded layout, the sizes of the panel access and main drifts, the panel access barrier pillar widths, and the offset between the outer emplacement drifts and the main access drift were taken from the potential repository's conceptual design published in the SCP-CDR (SNL, 1987). In addition, the multi-panel models were generated assuming eleven drifts of waste per panel as opposed to the nine drifts used in the single-panel models.

The panel access drift's temperature was sampled at three points along the drift. Specifically, those points lying on the panel access drift's floor defined by the intersection of the vertical planes passing through the centerlines of the first, central, and last emplacement drifts and the vertical plane that includes the centerline of the panel access drift were sampled. An acceptable standoff distance was assumed to be that distance at which the panel access temperature at the central location was approximately 50°C at 50 yr, and the average of the three points was below the 50°C point.

Figure 4-28. Six-Panel Model Geometry

4.7.1 Vertical Emplacement

For all vertical emplacement configurations established in the previous sections based on the borehole and 1-m temperature limits, a 30-m panel access standoff proved sufficient to satisfy the panel access temperature goal (Table 4-3). Although the 30-m value could be refined, such refinement would result in negligible changes (on the order of 2 to 3 m). Thus, the 30-m standoff is presented here as a reasonable approximation of the required standoff for the vertical emplacement configurations examined. The panel access drift standoff required for the higher LAPDs of this study (~90 kW/acre) compares favorably with the equivalent distance taken from the SCP-CDR of 28.2 m (92.5 ft) for the lower LAPDs (~70 kW/acre) of the SCP-CDR design.

TABLE 4-3

VERTICALLY EMPLACED PANEL ACCESS TEMPERATURES
50 YR AFTER EMPLACEMENT FOR A 30-m STANDOFF

Initial Canister Loading (kW)	Canister Spacing (m)	Drift Spacing (m)	Panel Access Temperature (°C)	
			<u>Central</u>	<u>Average</u>
2	2.90	30	50.0	44.2
3	4.35	30	51.6	45.4
4	6.85	30	48.6	43.2

The results quoted here do not include any effects of the ventilation system or the existence of an opening filled with air. The actual temperatures should be lower because of the heat removed by the ventilation system. This lowering may be significant and would allow the standoff to be controlled by the transporter length and not the thermal considerations. A decreased standoff would allow for less wasted space and could increase the ratio of LAPD to PAPD.

4.7.2 Horizontal Emplacement

A panel access standoff of approximately 35 m was found to be sufficient to satisfy the 50°C for 50-yr temperature goal for all horizontal

emplacement configurations discussed above (Table 4-4). As with the vertical emplacement results, minor refinements of the 35-m value appear possible; however, the changes realized would be negligible. The APDs attainable using the horizontal orientation (~105 kW/acre) are greater than those for the vertical option and require a slightly greater standoff because of the higher thermal loading.

TABLE 4-4

HORIZONTALLY EMPLACED PANEL ACCESS TEMPERATURES
50 YR AFTER EMPLACEMENT FOR A 30-m STANDOFF

Total Borehole Loading (kW)	Canister Spacing (m)	Drift Spacing (m)	Panel Access Temperature (°C)	
			<u>Central</u>	<u>Average</u>
6	7.20	65	50.2	46.7
9	11.2	65	51.2	47.6
12	18.5	65	50.1	46.3

As for the vertical case, the results quoted here do not include any effects of the ventilation system or the existence of an opening filled with air. The actual temperatures should be lower because of the heat removed by the ventilation system. This lowering could be significant and allow a standoff that would be controlled by the transporter length and not thermal considerations. As for the vertical orientation, a decreased standoff would allow for less unused space and could increase the ratio of LAPD to PAPD.

4.8 TSw3 Standoff Sensitivity Study

As shown in Figure 4-29, the distance between the repository floor and the top of the TSw3 unit ranges from approximately 37 to 122 m, with a 60-m separation being representative. At this distance from the repository horizon, interaction between heat sources in adjacent panels is important. Therefore, as with the studies of panel access temperature, six-panel layouts were again used.

Figure 4-29. Contour Map of the Thickness Between the Top of the TSw3 Unit and the Repository Floor

In this section, the temperature responses at a variety of depths from the repository floor for the vertical and horizontal emplacement configurations established in Section 4.5 are presented. If the results at a distance 60 m below the repository floor are taken as representative of the majority of the repository area, an evaluation of the canister and drift spacings previously discussed can be carried out with respect to the 115°C temperature limit imposed on the TSw2/TSw3 interface.

4.8.1 Vertical Emplacement

In all vertical emplacement cases tested, the temperatures calculated at a depth of 60 m from the repository floor were less than 115°C. For the 2-kW case defined by a 2.90-m canister and a 30-m drift spacing, the temperature at 60 m peaks at 99.3°C. Similarly, for the 4.35-m canister and 30-m drift spacings established for an initial loading of 3 kW, the maximum temperature calculated at the chosen depth is 99.4°C. For 4-kW

initial loading and spacings of 6.85-m canister and 30-m drift, the peak temperature at 60 m below the repository floor is 88.0°C. Because a large percentage of the TSw2/TSw3 interface lies in excess of 60 m from the repository floor, the results presented here indicate that the TSw3 temperature limit can be easily met for the vertical configurations examined.

Figure 4-30 displays the peak temperature at 60 m below the repository floor for all of the six-panel vertical layouts examined. The peak temperatures are plotted versus the LAPDs for the various layouts. The linearity of the relationship between LAPD and peak temperature should allow a designer, keeping in mind the limitations of the models used, to choose an appropriate LAPD for any given peak temperature requirement. For example, if the peak temperature at the TSw2/TSw3 interface were restricted to 85°C, the maximum LAPD that would satisfy this thermal goal would be approximately 80 kW/acre.

Figure 4-30. TSw3 Temperature Response (60 m below Repository Horizon) versus LAPD for Vertical Emplacement

Figure 4-31 displays the peak temperature at 40 m below the repository floor for the vertical layouts. The 40-m separation approximates the closest approach of the TSw3 unit to the potential repository. Note that the temperature limit may be violated at this distance for LAPDs above 90 kW/acre. However, since only a small section at the edge of the potential repository block is represented by the 40-m approach, this apparent violation of the temperature goals is not considered significant.

Figure 4-31. TSw3 Temperature Response (40 m below Repository Horizon) versus LAPD for Vertical Emplacement

4.8.2 Horizontal Emplacement

For the horizontal emplacement of waste initially loaded at 6 kW in an array defined by a 7.20-m canister and a 65-m drift spacing, the peak temperature at a distance 60 m below the repository floor is 114.6°C. In the case of horizontal emplacement initially loaded at 9 kW, the 60-m peak temperature is equal to 112.5°C. Similarly, for the short-horizontal emplacement of 12-kW waste canisters in a configuration defined by 18.5-m

canister and 65-m drift spacings, the peak temperature at the indicated depth from the repository floor is 95.9°C. Thus, as with the vertical case, the TSw3 temperature limit dictates no alteration of the canister and drift spacing combinations established in Section 4.5.

Figure 4-32 displays the peak temperature at 60 m below the repository floor for all of the horizontal layouts. Similarly, Figure 4-33 shows the same peak temperature information at a depth 40 m below the repository floor. As for the vertical emplacement option, the peak temperatures are plotted versus the LAPDs for the various layouts. The linearity of the relationship between LAPD and peak temperature for the horizontal orientation is similar to that of the vertical. Again, this relationship would allow a designer to choose an appropriate LAPD for any given peak temperature requirement. For example, if the peak temperature at the TSw2/TSw3 interface were restricted to 85°C, an LAPD that would satisfy this thermal goal would be approximately 80 kW/acre.

The differences between the temperature predictions for the vertical and horizontal models is expected because the horizontal emplacement configurations have higher APDs than do the vertical. As a point of interest, the results noted above are taken 60 m from the floor of the repository, ~55.5 m from the heat source for the vertical emplacement orientation, and ~62 m from the heat source for the horizontal emplacement orientation. At these distances, the form of the heat source is relatively insignificant. Either of these models could have been replaced with a plate heat source at identical distances, and peak temperatures should be equivalent to those shown in this report. In fact, comparison calculations show that for comparable APDs, the vertical and horizontal emplacement orientation predictions at a distance of 60 m are identical.

4.9 Surface Temperature Modification Sensitivity Study

The possible modifications of the surface temperature caused by an underground repository depend on the gross heat transfer through the geologic strata and the efficiency of convective and radiative heat transfer at the surface. The treatment of convection requires a nonlinear solution to the energy equation and is outside the scope of the current

Figure 4-32. TSw3 Temperature Response (60 m below Repository Horizon) versus LAPD for Horizontal Emplacement

Figure 4-33. TSw3 Temperature Response (40 m below Repository Horizon) versus LAPD for Horizontal Emplacement

modeling effort. Brandshaug (1991) has developed a two-dimensional model of Yucca Mountain with a potential repository. His model consisted of a vertical slice through Yucca Mountain (lengthwise) and included layered stratigraphy, surface topography, and convective heat transfer at the surface. He considered two APDs: 57 and 80 kW/acre. The APDs used for the Brandshaug report were defined as panel-wide averages (PAPD), as in Section 2 of this report. An inspection of his results shows that the predicted temperature increases at the surface were 0.8 and 1.1°C for the 57- and 80-kW/acre cases, respectively. A further inspection of other sensitivity study results from his work would indicate that the surface temperature predictions should not exceed the current thermal goal of 6°C peak change. Further nonlinear modeling should and will be conducted before License Application to verify the potential surface temperature modifications. Our current knowledge about the potential repository indicates that the surface temperature increase should not exceed the thermal goal for the current design basis APD (57 kW/acre) or the new recommended design basis APD.

4.10 Alternative Underground Layout Studies

Two alternative layouts were considered as limiting cases for underground vertical emplacement. Neither of the layouts described here is being considered for use in the potential repository, but they do give insight into the processes that control temperatures near the emplacement boreholes.

The two layouts considered are shown in Figure 4-34 and can be described as a regular square and a triangular pattern. The triangular pattern represents a hexagonal close-packed planar system that provides an efficient (from the standpoint of minimizing area) mechanism of emplacing canisters. Again, it is important to note that these layouts, if constructed using room and pillar arrangements, would violate the extraction ratio limits (DOE, 1988) and possibly other thermomechanical performance goals. These layouts are not being considered or proposed for use; the results are presented as limiting cases only.

Figure 4-34. Square and Triangular Emplacement Layouts

For the square layout, Table 4-5 lists the canister spacings and maximum LAPDs for the three canister loadings considered in this report. For the triangular layout, Table 4-6 lists the canister spacings and maximum LAPDs for the three canister loadings considered in this report.

TABLE 4-5

CANISTER SPACINGS AND LAPDs FOR SQUARE LAYOUTS

Canister Loadings	2 kW	3 kW	4 kW
Canister Spacings	7.50 m	10.0 m	13.1 m
LAPD (kW/acre)	144	121	94

TABLE 4-6

CANISTER SPACINGS AND LAPDs FOR TRIANGULAR LAYOUTS

Canister Loadings	2 kW	3 kW	4 kW
Canister Spacings	8.00 m	10.6 m	14.0 m
LAPD (kW/acre)	146	125	95

The LAPDs for both alternative layouts are significantly higher than those described in the previous sections. The relief of canister-to-canister interactions coupled with the decrease in effective drift spacing allows for this increase. For both layouts, the 2-kW canisters are constrained by the 1-m rock temperature limit, not the peak borehole temperature--a result consistent with the previous sections. These results graphically illustrate the effectiveness of increasing the canister spacing as a means of increasing the LAPD.

The temperatures for the alternative layouts were checked at locations appropriate to the TSw2/TSw3 interface. The higher LAPDs that can be supported by the alternative layouts produce higher average temperatures at the interface. However, the temperatures predicted for the TSw3 unit do not exceed the appropriate thermal goal for these layouts. Access drift temperature modifications were not calculated for these layouts.

5.0 AREAL POWER DENSITY AND UNDERGROUND DESIGN RECOMMENDATIONS

The purpose of this report is to provide a general understanding of the thermal constraints to APD. The discussion contained in this section does not consider any other possible constraints on the APD. The authors understand that operational and/or mechanical concerns may further restrict the possible upper limit of the APD. However, the potential limiting effects of these areas will be addressed in separate analyses. Furthermore, all analyses and model results contained in this report are not to be considered "reference" analyses and will be performed again in support of the License Application Design with (possibly) different models.

If a definition consistent with the current design basis APD is used (that is, the panel areal power density of Equation 2-3) a recommendation can be made for a new design basis APD from a strictly thermal standpoint. Table 5-1 lists the thermally optimized layouts for the initial canister loadings and orientations used in this report.

TABLE 5-1

THERMALLY OPTIMIZED APDs AND LAYOUTS

<u>Orientation</u>	<u>Canister Loading (kW)</u>	<u>Canister Spacing (m)</u>	<u>Drift Spacing (m)</u>	<u>LAPD (kW/acre)</u>
Vertical	2	2.90	30	93
Vertical	3	4.35	30	93
Vertical	4	6.85	30	79
Horizontal	2	7.20	65	104
Horizontal	3	11.2	65	100
Horizontal	4	18.2	65	82

Based on the results from Table 5-1, all thermal goals are met for an LAPD of approximately 93 kW/acre for low initial loadings and vertical emplacement. If horizontal emplacement were selected, an LAPD of 100 kW/acre would meet all thermal goals for low initial loadings. Canister

loadings of 4 kW or greater would comprise a small percentage of the total waste stream under the oldest-fuel-first scenario. In addition, any selection criterion that attempted to produce "average" waste characteristics would not produce waste canisters with initial loadings above 3 kW. So the recommendation of LAPDs near 100 kW/acre for reasonable initial canister loadings should be appropriate for current waste stream expectations. This limit potentially could be higher if the average canister loading is lower than 2 kW and the 1-m rock temperature limit is modified as recommended in a previous section of this report. The controlling variable for the 2-kW canisters was not the peak borehole temperature limit. The 1-m rock temperature limit formed the basis for the maximum LAPD for both the vertical and horizontal emplacement orientations. However, further analysis will be necessary before changes are recommended based on any relaxation of the 1-m rock temperature limit.

If a reasonable upper limit of the LAPD is approximately 100 kW/acre and the current panel design is assumed, then a design basis APD (panel average) should be approximately 80 kW/acre. All panel layouts considered for this report would support a design basis APD of 80 kW/acre, and still meet all currently imposed thermal goals. No significant modifications of the SCP-CDR panel design and standoffs would be required to justify the higher APDs suggested here.

The questions surrounding underground repository design are complex and span many technical areas. The information presented here is limited to the thermal aspects of underground repository design, and the models used limited by the analytic solution method chosen. Because of these other areas of concern, the recommendations for repository design should be considered preliminary and subject to further development.

The results presented in Sections 4.5 and 4.10 graphically demonstrate the effectiveness of increasing canister spacing as a means of relieving the thermal interactions of nearby canisters. The increase in canister spacing coupled with the decrease in drift spacing allows for significant increases in LAPD. Utilizing this general idea, the process for underground thermal design should proceed as follows.

We assume that the characteristics of the spent fuel inventory for any given year are known before the design of an emplacement panel would begin. Determination of an underground layout starts with the selection of average fuel characteristics (as given by the total inventory) for a panel or section of a panel, followed by selection of a design-basis APD. This design-basis APD could be selected using analyses similar to those presented here, coupled with appropriate analyses of mechanical and operational concerns. The design-basis APD is modified using methodology similar to that developed by Mansure and Petney (1991). This modification takes into account the waste age and burnup and how these variables effect the peak borehole temperatures. Minimum emplacement drift spacing must be selected with mechanical and operational constraints taken into account. As has been demonstrated in this report, the most efficient use of underground area (by a higher APD) requires the canister spacing to be increased and the drift spacing to be decreased. With the average fuel characteristics, an age and burnup modified design-basis APD, and an emplacement drift spacing, Equation 2-1 can be manipulated to estimate the required canister spacing. This canister spacing should be considered an estimate and used as input to a series of design verification calculations that will validate a particular underground layout.

The design verification calculations can be used to fine tune the underground layout until all performance goals are met. It is assumed that standoffs would be selected during the design verification step. Initial estimates for these variables could be taken from this report or similar future reports.

6.0 SUMMARY AND CONCLUSIONS

This report has provided a general understanding of the variables that control APD. Specifically, the effects of material properties, canister sizes, and repository layouts have been presented. The effects of these variables on APD were presented in the form of sensitivity studies. The results of these sensitivity studies were used to determine APDs that meet all current thermal goals, while efficiently utilizing the available area. The efficient use of area requires that APD be maximized with respect to the thermal goals. In addition to developing maximum APDs, a simple methodology was defined. This methodology considers only thermal goals and could form the basis for a more complete underground layout methodology in the future.

A survey of the current thermal goals was presented and discussed. Several key issues were evident from these discussions. Because the borehole temperature limit is the controlling feature for most layouts, the modification of the SCP limit of 275°C caused by the use of linear approximations needs further study. Linear modeling currently uses a lower borehole temperature limit (235°C) to account for the underprediction of peak temperatures by these models. If this modification is in error, either too low or too high, the maximum APDs as discussed in this report would require modification. However, the results have been presented in terms of sensitivity studies and could be adapted to other temperature limits. Analyses are currently underway to assess the modifications necessary to account for the linear models' underprediction of peak temperature and will be reported separately.

As discussed in Section 3.2, the 1-m rock temperature should be modified. This temperature limit controls the maximum APDs for low initial canister loadings. This goal attempts to limit the "deleterious rock movement" as noted in 10 CFR 60.133(e)(2). Section 3.2 makes a strong argument for replacing the temperature limit with some thermomechanical measure/limit that takes into account the potential borehole deformations caused by the heat source of a waste canister. The uncertainties reinforce

the idea that the material presented here is preliminary and these effects should be investigated further before any official changes are recommended.

Several aspects of the sensitivity studies presented in Section 4 are worthy of further note. For linear heat-conduction models, peak borehole temperatures are insensitive to changes in the heat capacity but very dependent on changes in the conductivity. The results show that decreasing the conductivity increases the peak temperature.

Information from the canister and drift spacing studies form the basis for the bulk of the APD evaluations and the underground layout design concepts. Results from Sections 4.4, 4.5, and 4.10 demonstrate how important the relief of canister-to-canister interactions are in reducing the peak borehole temperatures. It is obvious from the results of these sections that APDs can be increased by increasing the canister spacing and decreasing the drift spacing. The minimum drift spacing for mechanical and operational concerns can be considered to be the "best" drift spacing for maximizing the APDs. The relief of canister-to-canister interactions also explains the tendency of horizontal emplacement to produce higher APDs than equivalent vertical emplacement. Because the horizontal canisters must be farther apart to meet the peak temperature goals, the basic layout approaches the nearly ideal square arrangement more closely than the vertical orientation.

The access drift standoffs were investigated and design values from the SCP-CDR were slightly smaller than the requirements presented here. The SCP-CDR access drift standoffs were 28.2 m where the required standoffs for the thermally optimized layouts of this report were approximately 30 m. The 30-m value may be further refined, but it was not considered important for the level of model complexity reported here.

The TSw3 standoff was investigated and found not to be a concern for more than three-quarters of the potential repository. The extreme southern and northeastern edges of the potential repository are approximately 40 m from the waste canisters. At this standoff, the predicted temperatures at the TSw2/TSw3 interface exceed 115°C. However, the models used do not consider thermal edge effects, and as such it is expected that a further,

more detailed, investigation would result in lower temperatures than currently predicted. The simple technique of reducing the APD above those regions of closest approach is one possible approach toward affecting a reduction in interface temperatures. In addition, a higher design-basis APD could alleviate the need for development of the areas of closest approach in the primary block of the potential repository.

Finally, drawing on the results from this report, a recommendation for a design-basis APD can be made. Without considering mechanical and operational concerns, an LAPD of 100 kW/acre and a PAPD of 80 kW/acre appear feasible. Layouts that meet all thermal goals and attain the noted APDs can be designed for the proposed repository given our current state of knowledge of the site. After site characterization has been completed, a similar set of analyses will be undertaken in support of License Application. These future calculations will form the basis for the final underground design.

The increase in APD recommended has major impacts in two aspects of the potential underground repository. An increase in the design-basis APD will allow a significant reduction in the area allocated to waste emplacement in the repository. A decrease in the total area required will increase the probability of having sufficient area in the central block to contain the waste. The smaller area requirements will also increase the flexibility of being able to fit the required amounts of waste into the available area. In addition to effecting the area requirements, a higher APD will increase the temperatures at later times in the waste emplacement panels. This long-term increase in temperatures will increase the number of canisters that do not contact liquid water (temperatures will remain above boiling) during the 300-yr time period after closure. One of the performance goals of Issue 1.10 (waste package postclosure behavior) requires that 95% of the canisters must not contact liquid water for the 300-yr period after closure. Maintaining temperatures above the boiling temperature of water will add assurance that this goal is met.

7.0 REFERENCES

- Brandshaug, T., 1991. A Sensitivity Study of the Thermomechanical Far-Field Model of Yucca Mountain, SAND87-7079, Sandia National Laboratories, Albuquerque, NM, April. (NNA.900111.0001)
- DOE (Department of Energy), 1986. Generic Requirements for a Mined Geologic Disposal System, DOE/RW-0090, Washington, DC, September. (NNA.870605.0001)
- DOE (Department of Energy), 1988. Site Characterization Plan, DOE/RW-0199, Washington, DC, December. (HQO.881201.0002)
- Eisenberg, M. A., 1980. Introduction to the Mechanics of Solids, Addison-Wesley Publishing Company, Menlo Park, California. (NNA.891222.0007)
- Gartling, D. K., 1982. COYOTE - A Finite Element Computer Program for Nonlinear Heat Conduction Problems, SAND77-1332, Sandia National Laboratories, Albuquerque, NM, December. (HQS.880517.2294)
- Johnstone, J. K., R. R. Peters, and P. F. Gnirk, 1984. Unit Evaluation at Yucca Mountain Nevada Test Site: Summary Report and Recommendation, SAND83-0372, Sandia National Laboratories, Albuquerque, NM, June. (NNA.870519.0052)
- Klett, R. D., E. S. Hertel, Jr., and M. A. Ellis, 1981. Systems Engineering Programs for Geologic Nuclear Waste Disposal, SAND80-0440, Sandia National Laboratories, Albuquerque, NM, June. (HQS.880517.2736)
- Mansure, A. J., 1987. "COVE III Temperature Calculations Using ARRAYF, Revision 1," Appendix K, SCP-CDR, SAND84-2641, Sandia National Laboratories, Albuquerque, NM, September. (NN1.880902.0019)
- Mansure, A. J., and S. V. Petney, 1991. Determination of Equivalent Thermal Loadings as Function of Waste Age and Burnup, SAND87-2909, Sandia National Laboratories, Albuquerque, NM, December. (NNA.901128.0001)
- SNL (Sandia National Laboratories), 1987. Site Characterization Plan - Conceptual Design Report, SAND84-2641, compiled by H. R. MacDougall, L. W. Scully, and J. R. Tillerson, 6 volumes, Albuquerque, NM, September. (NN1.880902.0014-NN1.880902.0019)
- St. John, C. M., 1985. Thermal Analysis of Spent Fuel Disposal in Vertical Emplacement Boreholes in a Welded Tuff Repository, SAND84-7207, Sandia National Laboratories, Albuquerque, NM, November. (HQS.880517.2542)

APPENDIX A

PARAMETERS USED IN THIS STUDY AND CORRESPONDING YMP REFERENCE INFORMATION BASE VALUES

This report contains no data taken from or that should be included in the SEPDB and DRMS.

A complete discussion of the analysis approach for this report is contained in Section 4.1 and should be consulted for detailed information.

Parameters for the Problem Definition Memo (PDM75-11) that controlled this work and are reported in this SAND document were taken from the SCP-CDR and the RIB, Draft Version 2.002 and Version 4.00. When the PDM was being prepared, Draft Version 2.002 was applicable; in the intervening period of time Version 4.00 has been issued. The material parameters used in this report are compared to Version 4.00. The definition of the waste emplacement canister and emplacement rooms for vertical orientation was taken from the SCP-CDR. For horizontal orientation, the waste emplacement canister and emplacement room information was taken from the results of Design Investigation Memo (DIM) 102. The reader should be aware that most of the parameters surrounding the layouts were part of the sensitivity studies that comprise the bulk of this report and cannot be expected to compare exactly with previously published information. The material properties are summarized in Table A-1.

TABLE A-1

SUMMARY OF MATERIAL PROPERTIES

<u>Parameter</u>	<u>Value Used</u>	<u>RIB Value</u>	<u>RIB Section</u>
Initial Temperature	24.7°C	24.7°C	1.2.7.3
Initial Canister Loading	2, 3, or 4 kW	None	NA
Decay Form	4 term exp.	4 term exp.	3.1.1.5
Waste Age	10 yr	None	NA
Thermal Conductivity TSw2	1.84 W/mK	1.839±0.064 W/mK	1.2.2.4
Thermal Capacity TSw2	2.16 J/cm ³ K	2.0065 to 2.3410 J/cm ³ K	1.2.4.3
Poisson's Ratio TSw2	0.30	0.30±0.05	1.2.5.3
Linear Thermal Expansion Coefficient TSw2	35.6x10 ⁻⁶ /K	35.6±10.8x10 ⁻⁶ /K	1.2.3.3

DISTRIBUTION LIST

1 J. W. Bartlett, Director (RW-1)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585	1 S. J. Brocoum (RW-22)
Analysis and Verification Division
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585
1 F. G. Peters, Deputy Director (RW-2)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585	1 D. D. Shelor (RW-30)
Office of Systems and Compliance
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585
1 T. H. Isaacs (RW-4)
Office of Strategic Planning
and International Programs
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585	1 J. Roberts (RW-33)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585
1 J. D. Saltzman (RW-5)
Office of External Relations
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585	1 G. J. Parker (RW-332)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585
1 Samuel Rousso (RW-10)
Office of Program and Resources
Management
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585	1 Associate Director (RW-40)
Office of Storage and Transportation
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585
1 J. C. Bresee (RW-10)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585	1 Associate Director (RW-50)
Office of Contract Business
Management
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585
1 C. P. Gertz (RW-20)
Office of Geologic Disposal
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585	1 C. G. Russomanno (RW-52)
Office of Civilian Radioactive
Waste Management
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585

- 1 D. U. Deere, Chairman
Nuclear Waste Technical
Review Board
1100 Wilson Blvd. #910
Arlington, VA 22209-2297
- 1 Dr. Clarence R. Allen
Nuclear Waste Technical Review Board
1000 E. California Blvd.
Pasadena, CA 91106
- 1 Dr. John E. Cantlon
Nuclear Waste Technical Review Board
1795 Bramble Dr.
East Lansing, MI 48823
- 1 Dr. Melvin W. Carter
Nuclear Waste Technical Review Board
4621 Ellisbury Dr., N.E.
Atlanta, GA 30332
- 1 Dr. Donald Langmuir
Nuclear Waste Technical Review Board
109 So. Lookout Mountain Cr.
Golden, CO 80401
- 1 Dr. D. Warner North
Nuclear Waste Technical Review Board
Decision Focus, Inc.
4984 El Camino Real
Los Altos, CA 94062
- 1 Dr. Dennis L. Price
Nuclear Waste Technical Review Board
1011 Evergreen Way
Blacksburg, VA 24060
- 1 Dr. Ellis D. Verink
Nuclear Waste Technical Review Board
4401 N.W. 18th Place
Gainesville, FL 32605
- 5 C. P. Gertz, Project Manager
Yucca Mountain Project Office
U.S. Department of Energy
P.O. Box 98608--MS 523
Las Vegas, NV 89193-8608
- 1 C. L. West, Director
Office of External Affairs
DOE Field Office, Nevada
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-85180
- 12 Technical Information Officer
DOE Field Office, Nevada
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518
- 1 P. K. Fitzsimmons, Director
Health Physics & Environmental
Division
DOE Field Office, Nevada
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518
- 1 D. R. Elle, Director
Environmental Protection Division
DOE Field Office, Nevada
U.S. Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518
- 1 Repository Licensing & Quality
Assurance Project Directorate
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
- 1 Senior Project Manager for Yucca
Mountain Repository Project Branch
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
- 1 NRC Document Control Desk
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
- 1 P. T. Prestholt
NRC Site Representative
301 E. Stewart Ave.
Las Vegas, NV 89101
- 1 E. P. Binnall
Field Systems Group Leader
Building 50B/4235
Lawrence Berkeley Laboratory
Berkeley, CA 94720
- 1 Center for Nuclear Waste
Regulatory Analyses
6220 Culebra Road
Drawer 28510
San Antonio, TX 78284

- 3 L. J. Jardine
Technical Project Officer for YMP
Mail Stop L-204
Lawrence Livermore National
Laboratory
P.O. Box 808
Livermore, CA 94550
- 4 R. J. Herbst
Technical Project Officer for YMP
N-5, Mail Stop J521
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
- 1 H. N. Kalia
Exploratory Shaft Test Manager
Los Alamos National Laboratory
Mail Stop 527
101 Convention Center Dr.
Suite 820
Las Vegas, NV 89109
- 1 J. F. Divine
Assistant Director for
Engineering Geology
U.S. Geological Survey
106 National Center
12201 Sunrise Valley Dr.
Reston, VA 22092
- 6 L. R. Hayes
Technical Project Officer
Yucca Mountain Project Branch--MS 425
U.S. Geological Survey
P.O. Box 25046
Denver, CO 80225
- 1 V. R. Schneider
Asst. Chief Hydrologist--MS 414
Office of Program Coordination
& Technical Support
U.S. Geological Survey
12201 Sunrise Valley Drive
Reston, VA 22092
- 1 R. B. Raup, Jr.
Geological Division Coordinator
MS 913
Yucca Mountain Project
U.S. Geological Survey
P.O. Box 25046
Denver, CO 80225
- 1 D. H. Appel, Chief
Hydrologic Investigations Program
MS 421
U.S. Geological Survey
P.O. Box 25046
Denver, CO 80225
- 1 E. J. Helley
Branch of Western Regional Geology
MS 427
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025
- 1 Chief
Nevada Operations Office
U.S. Geological Survey
101 Convention Center Drive
Suite 860, MS 509
Las Vegas, NV 89109
- 1 D. Zesiger
U.S. Geological Survey
101 Convention Center Dr.
Suite 860 - MS509
Las Vegas, NV 89109
- 1 R. V. Watkins, Chief
Project Planning and Management
U.S. Geological Survey
P.O. Box 25046
421 Federal Center
Denver, CO 80225
- 1 A. L. Flint
U.S. Geological Survey
MS 721
P.O. Box 327
Mercury, NV 89023
- 1 D. A. Beck
U.S. Geological Survey
1500 E. Tropicana, Suite 201
Las Vegas, NV 89119
- 1 P. A. Glancy
U.S. Geological Survey
Federal Building, Room 224
Carson City, NV 89701
- 1 Sherman S. C. Wu
Branch of Astrogeology
U.S. Geological Survey
2255 N. Gemini Dr.
Flagstaff, AZ 86001

- 1 J. H. Sass
Branch of Tectonophysics
U.S. Geological Survey
2255 N. Gemini Dr.
Flagstaff, AZ 86001
- 1 DeWayne A. Campbell
Technical Project Officer for YMP
Bureau of Reclamation
Code D-3790
P.O. Box 25007
Denver, CO 80225
- 1 S. M. Dash
Science Applications International
Corp.
14062 Denver West Parkway, Suite 255
Golden, CO 80401
- 1 K. W. Causseaux
NHP Reports Chief
U.S. Geological Survey
421 Federal Center
P.O. Box 25046
Denver, CO 80225
- 1 V. M. Glanzman
U.S. Geological Survey
913 Federal Center
P.O. Box 25046
Denver, CO 80225
- 1 J. H. Nelson
Technical Project Officer for YMP
Science Applications International
Corp.
101 Convention Center Dr.
Suite 407
Las Vegas, NV 89109
- 2 SAIC-T&MSS Library
Science Applications International
Corp.
101 Convention Center Dr.
Suite 407
Las Vegas, NV 89109
- 1 Elaine Ezra
YMP GIS Project Manager
EG&G Energy Measurements, Inc.
Mail Stop D-12
P.O. Box 1912
Las Vegas, NV 89125
- 1 R. E. Jackson, Program Manager
Roy F. Weston, Inc.
955 L'Enfant Plaza, Southwest
Washington, D.C. 20024
- 1 Technical Information Center
Roy F. Weston, Inc.
955 L'Enfant Plaza, Southwest
Washington, D.C. 20024
- 1 D. Hedges, Vice President,
Quality Assurance
Roy F. Weston, Inc.
4425 Spring Mountain Road, Suite 300
Las Vegas, Nevada 89102
- 1 D. L. Fraser, General Manager
Reynolds Electrical & Engineering Co
Mail Stop 555
P.O. Box 98521
Las Vegas, NV 89193-8521
- 1 R. F. Pritchett
Technical Project Officer for YMP
Reynolds Electrical & Engineering Co
MS 408
P.O. Box 98521
Las Vegas, NV 89193-8521
- 1 B. W. Colston
General Manager & President
Las Vegas Branch
Raytheon Services Nevada
Mail Stop 416
P.O. Box 95487
Las Vegas, NV 89193-5487
- 1 R. L. Bullock
Technical Project Officer for YMP
Raytheon Services Nevada
Suite P250, MS 403
101 Convention Center Dr.
Las Vegas, NV 89109
- 1 R. E. Lowder
Technical Project Officer for YMP
MAC Technical Services
101 Convention Center Drive
Suite 1100
Las Vegas, NV 89109

- 1 C. K. Hastings, Manager
PASS Program
Pacific Northwest Laboratories
P.O. Box 999
Richland, WA 99352
- 1 A. T. Tamura
Science and Technology Division
Office of Scientific and Technical
Information
U.S. Department of Energy
P.O. Box 62
Oak Ridge, TN 37831
- 1 Carlos G. Bell, Jr.
Professor of Civil Engineering
Civil and Mechanical Engineering
Department
University of Nevada, Las Vegas
4505 South Maryland Parkway
Las Vegas, NV 89154
- 1 C. F. Costa, Director
Nuclear Radiation Assessment
Division
U.S. Environmental Protection
Agency
Environmental Monitoring Systems
Laboratory
P.O. Box 93478
Las Vegas, NV 89193-3478
- 1 ONWI Library
Battelle Columbus Laboratory
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201
- 1 T. Hay, Executive Assistant
Office of the Governor
State of Nevada
Capitol Complex
Carson City, NV 89710
- 3 R. R. Loux, Jr.
Executive Director
Nuclear Waste Project Office
State of Nevada
Evergreen Center, Suite 252
1802 North Carson Street
Carson City, NV 89710

- 1 C. H. Johnson
Technical Program Manager
Nuclear Waste Project Office
State of Nevada
Evergreen Center, Suite 252
1802 North Carson Street
Carson City, NV 89710
- 1 John Fordham
Water Resources Center
Desert Research Institute
P.O. Box 60220
Reno, NV 89506
- 1 Dr. Martin Mifflin
Water Resources Center
Desert Research Institute
2505 Chandler Avenue
Suite 1
Las Vegas, NV 89120
- 1 Eric Anderson
Mountain West Research-Southwest
Inc.
2901 N. Central Ave. #1000
Phoenix, AZ 85012-2730
- 1 Department of Comprehensive Planning
Clark County
225 Bridger Avenue, 7th Floor
Las Vegas, NV 89155
- 1 Planning Department
Nye County
P.O. Box 153
Tonopah, NV 89049
- 1 Lincoln County Commission
Lincoln County
P.O. Box 90
Pioche, NV 89043
- 5 Judy Foremaster
City of Caliente
P.O. Box 158
Caliente, NV 89008
- 1 Economic Development Department
City of Las Vegas
400 East Stewart Avenue
Las Vegas, NV 89101

<p>1 Community Planning & Development City of North Las Vegas P.O. Box 4086 North Las Vegas, NV 89030</p> <p>1 Director of Community Planning City of Boulder City P.O. Box 367 Boulder City, NV 89005</p> <p>1 Commission of the European Communities 200 Rue de la Loi B-1049 Brussels BELGIUM</p> <p>2 M. J. Dorsey, Librarian YMP Research and Study Center Reynolds Electrical & Engineering Co., Inc. MS 407 P.O. Box 98521 Las Vegas, NV 89193-8521</p> <p>1 Amy Anderson Argonne National Laboratory Building 362 9700 So. Cass Ave. Argonne, IL 60439</p> <p>1 Edgar Petrie Yucca Mountain Site Characterization Project Office U.S. Department of Energy Nevada Operations Office P.O. Box 98608 Las Vegas, NV 89193-8608</p> <p>1 Michael Cloninger Yucca Mountain Site Characterization Project Office U.S. Department of Energy Nevada Operations Office P.O. Box 98608 Las Vegas, NV 89193-8608</p> <p>1 Robert Waters Yucca Mountain Site Characterization Project Office U.S. Department of Energy Nevada Operations Office P.O. Box 98608 Las Vegas, NV 89193-8608</p>	<p>1 Jon White Yucca Mountain Site Characterization Project Office U.S. Department of Energy Nevada Operations Office P.O. Box 98608 Las Vegas, NV 89193-8608</p> <p>1 James Replogle Raytheon Services of Nevada 101 Convention Center Drive Suite P-250 Las Vegas, NV 89109</p> <p>1 Steve Smith Science Applications International Corporation 101 Convention Center Drive Suite 407 Las Vegas, NV 89109</p> <p>1 D. A. Labreche RE/SPEC 4775 Indian School Road, NE Suite 300 Albuquerque, NM 87110</p> <p>1 M. P. Hardy J.F.T. Agapito & Associates, Inc. 715 Horizon Drive, Suite 340 Grand Junction, CO 81506</p> <p>1 6300 T. O. Hunter</p> <p>1 6310 T. E. Blejwas, Actg.</p> <p>1 6310A L. E. Shephard</p> <p>1 6312 F. W. Bingham</p> <p>1 6313 L. S. Costin</p> <p>1 6313 E. E. Ryder</p> <p>1 6315 F. B. Nimick, Actg.</p> <p>1 6316 R. P. Sandoval</p> <p>2 6318 R. J. Macer for 100/121431/SAND89-1989/QA</p> <p>1 6319 R. R. Richards</p> <p>1 1541 E. S. Hertel</p> <p>5 3141 S. A. Landenberger</p> <p>8 3145 Document Processing for DOE/OSTI</p> <p>3 3151 G. C. Claycomb</p> <p>20 6341 WMT Library</p> <p>1 6410 D. J. McCloskey, Actg.</p> <p>1 8523-2 Central Technical Files</p>
---	---

The number in the lower right-hand corner is an accession number used for Office of Civilian Radioactive Waste Management purposes only. It should not be used when ordering this publication.

NNA.911106.0013

END

DATE
FILMED
2/07/92

I