Basis for In-Situ Geomechanical Testing at the Yucca Mountain Site

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ABSTRACT

This report presents an analysis of the in-situ geomechanical testing needs for the Exploratory Shaft (ES) test facility at the Yucca Mountain site in Nevada. The testing needs are derived from 10CFR60 regulations and simple thermomechanical canister- and room-scale numerical studies. The testing approach suggested is based on an "iterative" procedure of full-scale testing combined with numerical and empirical modeling. The testing suggested is based heavily on demonstration of excavation and thermal loading of full-scale repository excavations. Numerical and/or empirical models are compared to the full-scale response, allowing for adjustment of the model and evaluation of confidence in their predictive ability. Additional testing may be specified if confidence in prediction of the rock mass response is low. It is suggested that extensive drifting be conducted within the proposed repository area, including exploration of the bounding Drill Hole Wash and Imbricate fault structures, as well as the Ghost Dance fault. This approach is opposed to an a priori statistical specification of a number of "point" tests which attempt to measure a given property at a specific locations.

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1.0 INTRODUCTION

The information obtained from the in-situ testing to be conducted in the Exploratory Shaft (ES) at Yucca Mountain will ultimately be used by DOE to design the geologic repository as well as to address federal regulations, particularly 10CFR Parts 60, 960 and 20, as well as 40CFR191. A logical approach must be taken to relate the broad concerns identified in the regulations to the specific data requirements needed to specify an in-situ testing plan.

In the Consultation Draft Site Characterization Plan (CDSCP), DOE uses an issues approach to address this problem (U.S. DOE, 1988). This logic, termed an "issues hierarchy", is shown schematically in Fig. 1. The issues hierarchy begins by asking questions (Key Issues) which address the broadest scope of the program. There are four key issues: (1) post-closure performance; (2) pre-closure radiologic safety; (3) environmental quality; and (4) pre-closure performance. The key issues are then broken down in a series of steps from "issues" to "information needs". The information needs are statements of required information which may be resolved through studies, testing (laboratory or field) or an empirical data base. The information need does not specify the means by which the information is to be collected. In the CDSCP, in-situ testing needs are given to specifically address information needs (e.g., Table 8.3.1.15-1), however, the studies or logic used to develop the testing needs is not discussed. It can only be concluded that the testing needs were determined empirically—i.e., from personal judgment. It is impossible, therefore, to determine whether the testing needs described in the CDSCP are adequate for addressing the information needs.

The logic used in this document for resolving 10CFR60 regulations is given in Fig. 2. Starting with the regulations relevant to geotechnical engineering (Table 1), a set of basic thermomechanical analyses are performed to identify the data needs which must be resolved through new or existing testing or observation. Once the list of important properties and/or phenomena are identified, the existing data base (in the case of NNWSI, this is quite extensive) is examined. If the existing information is adequate to satisfy the data need, further testing is not necessary.

Fig. 1 Flow Diagram Illustrating the DOE Issues Hierarchy

Fig. 2 Logic Used in Defining In-Situ Testing Methods

Table 1

10CFR60 REGULATIONS PERTINENT TO GEOTECHNICAL CONCERNS

<u>General Heading</u>	<u>Regulation</u>	<u>Description</u>
Performance	60.111	Pre-closure radiation release limits in unrestricted areas. Waste retrievability up to 50 years after emplacement.
Performance	60.112	Overall system performance objectives. Releases of radioactive materials to the accessible environment must be within EPA limits.
Performance	60.113	Governs performance of the engineered barrier and geologic setting subsystems. Regulates waste package containment, radionuclide release rate from the engineered barrier system and pre-waste emplacement groundwater travel time.
Performance	60.122	Siting criteria.
Design	60.131	General repository design criteria. General design criteria for radiologic protection and structures, systems and components important to safety.
Design	60.132	Surface facility radiological design criteria.
Design	60.133	Underground facility design criteria general guidelines covering design and layout of underground excavation, control of water and ventilation.
Performance	60.134	Seal design for shafts and boreholes. General design criteria and materials selection guidelines for seals.
Design	60.135	Waste package design criteria. Includes guidelines on factors to be considered in package design.
Performance	60.137	Performance confirmation. Subpart F describes the purpose of confirmation testing for geotechnical parameters and waste packages.

The remaining test data needs are then separated by the probable test method. Three classifications are used here:

- (1) laboratory;
- (2) in-situ testing; and
- (3) empirical/observational.

Some personal judgment is obviously necessary in deciding whether a given rock property or phenomena associated with excavation or thermal loading requires in-situ testing, or whether laboratory data or historical data is adequate.

Once the properties to be obtained in situ have been identified, the test methods and configurations best suited to determine them can be examined. It is possible that non-standard testing techniques will be required.

The report is organized as follows:

Section 2.0 addresses the regulatory basis of the in-situ testing program and defines analyses needed to address the regulations.

Section 3.0 presents simple analyses of repository performance which are aimed at defining information needs for in-situ testing.

Section 4.0 presents a listing of the information needs.

Section 5.0 discusses an iterative approach to in-situ testing.

Section 6.0 presents an example in-situ testing program aimed at fulfilling the information needs.

2.0 REGULATORY BASIS

The 10CFR60 regulations described earlier can be divided into six main areas.

1. retrievability [10CFR60.111(b), 60.133(c)] — The rule requires that any wastes emplaced should be capable of being retrieved on a reasonable schedule for any period of up to 50 years after emplacement.
2. borehole and shaft sealing (10CFR60.134) — The rule requires that boreholes and shafts do not become pathways that compromise the performance objectives of the repository.
3. disturbance [10CFR60.133(a), (e)(2), (f) and (i)] — The rule requires that disturbances resulting from the excavation of the repository and the heating effects of the waste should not compromise the performance of the repository.
4. thermomechanical loading of the waste package [10CFR60.135(a)] — The rule requires that the integrity of the waste package should not be compromised by the environment.
5. design performance (10CFR60.131) — The rule requires that the repository be designed to keep radiological health risks within required bounds.
6. overall system performance (10CFR60.112, 60.113) — The rule governs the release limits from the engineered barrier system, limits to the accessible environment, and the pre-waste emplacement groundwater travel time.

There is considerable overlap between these areas in terms of data needs. In essence, the information needed to address each of the regulatory requirements is that information needed to perform the following analyses:

- (1) stability evaluation of the repository room openings and canister emplacement holes at ambient and post-emplacement temperatures;
- (2) mining- and thermally-induced damage evaluation of the material around the repository openings and shafts and boreholes;

- (3) thermal analysis of the waste package and the surrounding rock mass; and
- (4) hydrologic analysis of the transport of radionuclides through the rock mass. Hydrologic analysis is not discussed further in this report.

The analyses performed in this report are of two types: (1) numerical parameter studies of the response of the system to variations in rock mass properties and repository geometry; and, (2) empirical determination of factors important to underground opening stability, such as ground support. Those properties or phenomena which are judged to be of importance in determination of repository performance and design are then identified. Possible methods for determination of these properties through in-situ testing can then be defined.

3.0 ANALYSIS OF TESTING NEEDS

3.1 Introduction

The simplest means for determination of the geotechnical information needs is to conduct a series of simple scoping studies which will predict the performance of the rock mass openings, boreholes and waste form to variations in the rock mass material parameters as well as the in-situ environmental conditions. In this manner, the "sensitivity" of the performance to given parameters can be determined and the key properties or phenomena which require examination in situ can be identified. Once these key parameters are identified, in-situ tests may be designed to determine their value on appropriate physical scales. It is not possible in a study of the present scope to conduct a complete statistical analysis of all parameters. Instead, a small number of studies are conducted with design values, and the importance of parameters are determined empirically.

3.2 The Problem of Scale

The repository design and performance assessment process requires recognition of the following considerations.

1. Various thermal, mechanical, hydrologic, and chemical processes occur at different physical scales.
2. The above-noted physical processes are often transient, non-linear, and/or coupled.
3. The physical structure and properties of the rock mass are poorly defined and may vary significantly over the repository area. The mechanical and hydrologic properties of the rock mass are also scale-dependent due to the presence of discontinuities.
4. There is no experience or empirical data base for repository thermal loading.
5. The performance of the system must be predicted over timeframes greater than previous engineered systems.
6. The predicted transient response of the host rock can only be verified by experiments in situ or in the laboratory for relatively short time periods.

Empirical data exist for mining operations in heavily-jointed rock. These data have been used to design optimum opening shapes and rock support systems. To examine the effects of waste loading over extended time periods, models (numerical and analytical) will necessarily be used to examine performance and establish the operational safety factors for the repository. In order that the design and performance assessment process be tractable, the overall scenario described in the previous section must be divided into a number of physical scales. Figure 3 divides the problem into four scales: canister, room, repository, and regional.

Fig. 3 Illustration of the Phenomena Which Are Important at Various Physical and Time Scales for Repository Design and Performance Assessment

The canister scale is concerned with examination of the detailed thermal, mechanical and chemical processes which occur within a few radii of the emplacement boreholes (Fig. 4). Here, the structural integrity of the waste canister, the borehole liner (if any) and the borehole geometry are important factors. The details of heat transfer from the waste form to the rock mass are examined, as well as the effects of high thermal gradients on borehole stability. These processes are of greatest concern on a "short" timeframe, when the peak temperatures are greatest. This occurs at timeframes less than 100 years and encompasses the retrievability period. However, the possible saturation of the hole and the subsequent hydrochemical processes occur on a much longer time scale.

Fig. 4 The canister-scale studies examine the detailed heat transfer and stress development mechanisms from the canister to the surrounding rock mass within a few radii of the borehole.

The room scale (Fig. 5) includes the effects of single or multiple emplacement panels and boreholes. At this scale, the primary concern is with the examination of the thermomechanical stability of the excavations and the hydrologic effects of the rooms and backfill over short and long time periods in a partially-saturated medium. Here, the details of the room shape and jointed rock mass response are required, but the details of heat transfer from the canister to the rock mass are less important, and the waste canister may be considered to act as a line or planar heat source. The effects of heat and mechanical forces on drift backfill are examined at this scale. The potential for geomechanical effects such as precipitation of minerals along joints and fractures, thus preventing free drainage of the drifts over short and long time periods, is also examined here.

Fig. 5 The room-scale studies include the emplacement drifts and the canisters. Here, the waste forms are treated as line or planar heat sources, and particular details of heat transfer from the canisters to the rock mass are ignored.

At the repository scale (Fig. 6), the details of room design and heat source are less important. Here, the interaction of the emplacement panels, the overall structural stability of the repository, and the immediate strata surrounding it, as well as the performance of shaft and borehole seals, are examined. The interaction of the thermal, mechanical, and hydrologic processes and its effect on groundwater and/or gas transport through the site is most important. At this scale, the stability calculations may be considered short term; however, the radionuclide transport is a long-term problem.

Fig. 6 At the repository scale, the details of excavations are ignored; however, the effects of excavation and heating on the surrounding strata are examined. [MacDougall et al., 1987]

Finally, the regional scale (Fig. 7) includes primarily hydrologic and geochemical processes which occur from the repository horizon to the free surface. At this scale, the mechanical effects are primarily related to the potential for induced slip on pre-existing joint and fault surfaces. The time scale can be considered long. At this scale, the primary concern is the calculation of transport mechanisms and radionuclide flux, and performance of seal components over time is an important area of investigation. Investigations at this scale must, by necessity, be geometrically simple. Non-linear and coupled processes may be of importance at the smaller problem scales, where thermal and stress gradients are highest—i.e., within the flow in which the repository is located.

Fig. 7 On the regional scale, the heating is considered in terms of gross thermal loading. The regional groundwater flow field and the effects of buoyancy forces are examined.

3.3 The Use of Models in Geomechanical Design and Performance Assessment

Models (numerical, analytical and empirical) are used to determine the performance of the rock mass to repository development and waste emplacement. Four basic processes will occur during the construction and operation of the repository: mechanical effects, heat transfer, fluid (water or gas) transport, and chemical interaction. These four processes are interdependent to a certain extent. If the degree of coupling between the processes is high, the models necessarily become more complex and, consequently, it becomes more difficult to provide data for the models and more difficult to verify them.

From the geomechanics standpoint, the interactive effects of the thermomechanical process are of greatest importance, and the studies here are restricted to this level of coupling. Figure 8 illustrates the type of procedure used to determine the geomechanical performance effects of waste loading. Through a calculation process such as the one shown in Fig. 8, the ultimate thermal load per canister and the areal thermal load can be determined. The analysis proceeds from the canister to the repository scale and, at each scale, a prediction of performance is made and the results compared to an engineering or geotechnical criterion.

The initial data needs for this process are the rock mass material model, elastic, thermal and strength properties, and environmental conditions as well as the waste form geometry and decay properties. These are reviewed in Table 2. Also required are performance criteria by which the response may be judged as acceptable or not acceptable. Performance criteria developed by DOE for repository design are given in Table 3. No judgment is made here as to the correctness or completeness of these criteria.

The performance calculation approach used by NNWSI to date has been based on analytical, numerical and empirical models. The three-dimensional temperature distributions in the rock mass have been determined by analytical (superposition) and finite element methods [St. John (1985) and Mansure (1985)]. These analyses have resulted in an allowable overall gross thermal load (GTL) of 57 kw/acre in either vertical or horizontal emplacement schemes. Analysis of the stability of emplacement rooms in pre-closure time has been determined using finite element and boundary element methods [Johnstone et al. (1984) and St. John (1987)]. In these runs, opening stability has been judged assuming a Mohr-Coulomb failure criteria for the rock mass with a range of cohesion and friction values for the intact rock and joints. Input properties for the models have been obtained from the Reference Information Base (Zuech and Eatough, 1986), which is a compilation of average properties obtained from laboratory and in-situ values of intact rock and discontinuities.

Fig. 8 Flow Chart Illustrating the Sequence in Analyses Necessary for Design and Performance Assessment in Geomechanics

Table 2

BASIC INFORMATION NEEDS REQUIRED TO CONDUCT PRELIMINARY
REPOSITORY GEOMECHANICAL PERFORMANCE ANALYSIS

<u>INFORMATION NEED</u>		<u>COMMENT</u>
1. Rock Properties, Intact*		
i. Thermal		
a. Thermal Conductivity		for all units, dry and saturated, as a function of porosity and temperature
b. Heat Capacity		for all units, dry and saturated, as a function of porosity and temperature
c. Thermal Expansion Coefficient		for all units, as function of temperature.
ii. Elastic		
a. Young's Modulus		for all units, as function of temperature, stress
b. Poisson's Ratio		

*Anisotropy in properties needs to be determined.

Table 2 (continued)

<u>INFORMATION NEED</u>		<u>COMMENT</u>
iii.	Strength	
	a. Cohesion	define intact failure envelope
	b. Internal Angle of Friction	define intact failure envelope
	c. Uniaxial (Compressive) Strength	define intact failure envelope
iv.	d. Tensile Strength	define intact failure envelope
	Physical	
	a. Bulk Density	
2.	Rock Properties, Jointed	
	i. Thermal	testing at G-Tunnel in Grouse Canyon (welded) unit has shown thermal properties of jointed rock are reasonably well approximated by intact values (Zimmerman et al., 1986)
	ii. Elastic	
	a. Deformation Modulus	for Topopah Springs; other units
iii.	Strength	
	a. Cohesion	of fractures
	b. Friction Angle	
	c. Roughness	
	d. Stiffness Dilation	

Table 2 (concluded)

<u>INFORMATION NEED</u>	<u>COMMENT</u>
3. Rock Mass Structure	
i. Geology	stratigraphy
ii. Hydrology	depth of water table
iii. Jointing	
a. Spacing b. Continuity c. Orientation d. Aperture	characteristics of jointing
iv. Lateral and Vertical Variation of Intraflow Structure	
v. Faults	
4. Repository Geometry	waste layout, room geometry, depth, shaft and ramp location, seal configuration
5. Waste Form	
i. Age, Decay Characteristics	
ii. Geometry of Canister	
iii. Emplacement Scheme	
6. Environmental	
i. In-Situ Stress State	
ii. Initial Temperature	
iii. Dynamic Events	location, waveform, etc.

Table 3

DESIGN CRITERIA FROM NNWSI CDSCP*
[Chapter 6, pp. 33-35]

I. Retrievability-Related Design Criteria

A. General Design Criteria

1. The design of the repository at Yucca Mountain will incorporate the option to retrieve the emplaced waste as a planned contingency operation. Therefore, the equipment and facilities necessary to carry out full repository retrieval need not be constructed at the time of repository construction.
2. The inclusion of the retrieval option will not compromise the safety of the repository, nor will it compromise the ability of the repository to isolate the emplaced waste.
3. The method of retrieval will anticipate off-normal conditions and will be designed to operate under expected off-normal conditions. (The term off-normal is used to identify conditions expected to occur infrequently. In future documents, the term off-normal will be replaced with the term abnormal).
4. The design of facilities and equipment for retrieval will be based upon technology that is reasonably available at the time of license application. In addition, the design of retrieval methods and proof-of-principle demonstrations must be completed at the time of license application.

*These criteria have been developed by DOE as a basis for repository design and are given here for reference purposes only. No analysis has been made as to their completeness or correctness.

Table 3 (continued)

B. Detailed Criteria

1. The access and drifts will remain usable for at least 84 years.
2. The borehole liner lifetime will be at least 84 years.
3. The design basis for the actual retrieval period is 34 years.
4. The time required for the removal of a waste package will not exceed twice the amount of time required for emplacement of the waste package.
5. For the vertical emplacement concept, the temperature in the access drifts will not exceed 50°C for 50 years after waste emplacement.
6. For the horizontal emplacement concept, the temperature in the emplacement drifts will not exceed 50°C for 50 years after waste emplacement.
7. The time required to modify the environment in closed drifts for unprotected workers will not exceed 8 weeks.
8. The worker dose rate during removal operations will not exceed the allowable limit for emplacement operations.
9. For operations areas, all applicable air quality standards will be met.
10. The ability to remove the waste under normal and selected off-normal conditions will be demonstrated.
11. The maximum liner deflection is 5 cm for the vertical emplacement concept and 8 cm for the horizontal concept.
12. For the horizontal emplacement concept, the minimum radius of curvature for the liner is 34 m (110 ft) over the length of a waste package.
13. The ability to perform the retrieval operations using reasonably available technology is required.

Table 3 (continued)

II. Post Closure Waste Isolation and Containment

A. General Design Criteria

1. Provide orientation, geometry, layout, and depth of the underground facility such that the facility contributes to containment and isolation taking into account flexibility to accommodate site-specific conditions [10CFR60.133(a)(1) and 10CFR60.133(b)].
2. Limit water usage and potential chemical effects, thereby contributing to containment and isolation of radionuclides and assisting engineered barriers in meeting performance objectives [10CFR60.133(a)(1) and 10CFR60.133(h)].
3. Limit potential for excavation-induced changes in rock mass permeability [10CFR60.133(f)].
4. Provide thermal loading taking into account performance objectives and thermomechanical response of the host rock [10CFR60.133(i), 10CFR60.133(e)(2), and 10CFR60.133(h)].
5. Ensure the usable area for the repository will have greater than 200 m overburden, be within the TSw2 portion of the Topopah Spring Member; be more than 70 m above the water level, and be in the primary area.
6. Design accesses, drifts, and boreholes so that drainage is away from containers.
7. Limit quantity of cement, shotcrete, and grout used in borehole and drift construction.
8. Limit quantity of organics introduced during underground construction.
9. Limit underground water usage during underground development to that required for dust control and proper equipment function; remove all excess water.

Table 3 (concluded)

10. Limit repository extraction ratio to less than 30 percent for vertical emplacement (<10 percent for horizontal) and limit drift spans to less than 10 m (35 ft).
11. Limit potential for subsidence by backfilling underground openings during decommissioning.
12. Limit impact on surface environment by limiting surface temperature rise to less than 6 Celsius degrees.
13. Establish borehole spacing to ensure that areal power density of 57 Kw/acre is not exceeded, borehole wall temperature remains below 275°C, and rock mass temperature at 1 m into rock is below 200°C. This spacing must consider the 50°C at 50-year criteria identified in retrieval-related criteria.

3.4 Parametric Analyses of Repository Thermomechanical Performance

A series of thermomechanical parametric studies are conducted here to provide some insight into the rock properties or phenomena which have the greatest impact on repository performance. Once these properties and/or phenomena are identified, those requiring in-situ testing can be determined. The parametric studies are conducted at three scales: the canister, room, and regional scales as described earlier. The conceptual design of the repository, as given in the Site Characterization Plan Conceptual Design Report (SCPCDR) (MacDougall et al., 1987) is reviewed first as the basis for the calculations.

3.4.1 Repository Conceptual Design

The conceptual design of the repository is reviewed in Chapter 6 of the CDSCP (U.S. DOE, 1988) and is described in detail in the SCPCDR (MacDougall et al., 1987).

Yucca Mountain is the proposed site for the nation's first mined geologic repository. The facility is to be constructed on federal land adjacent to and within the Nevada Test Site in southern Nevada (Fig. 9). Yucca Mountain is composed of a layered sequence of welded, non-welded and bedded tuffs. The repository horizon is to be located within the welded portion of the Topopah Springs ash flow tuff at a depth of roughly 300 meters below the ground surface. The rock mass at this horizon is unsaturated and is 200 to 400 meters above the water table. Access to the repository horizon is to be gained primarily by ramps, although four shafts are planned for access and ventilation. The facility is designed to accept 400 MTU (metric tons of uranium) for the first three years of operation, 900 MTU in the fourth year, 1800 MTU in the fifth year, and 3,400 MTU in each succeeding year until the full 70,000 MTU have been emplaced at Year 25. The waste is to be placed at a gross thermal loading (GTL) density of 57 kW/acre.

Two basic emplacement configurations of fuel are described in the SCPCDR: vertical emplacement of single waste packages in short boreholes drilled in the floor of emplacement rooms and horizontal emplacement of multiple waste packages in long, lined horizontal holes drilled in the walls of the emplacement rooms. In both cases, defense high level waste and spent reactor fuel are commingled in separate boreholes.

Figures 10 and 11 show plan and cross-section views of the vertical and horizontal emplacement schemes. Relevant geometrical and waste form details are given in Table 4.

Fig. 9 Yucca Mountain Repository Site Location
[U.S. DOE, 1988, Chapter 6]

Fig. 10 Plan and Cross-Sectional Views of the Vertical,
Commingled Emplacement Configuration [U.S. DOE,
1988, Chapter 6]

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Fig. 11 Plan and Cross-Section Views of the Horizontal,
Commingled Emplacement Configuration [U.S. DOE,
1988, Chapter 6]

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Table 4

GEOMETRICAL DATA FOR VERTICAL EMPLACEMENT CONFIGURATION

— COMMINGLED WASTE FORMS

[U. S. DOE (1988) and O'Brien (1985)]

Power at Emplacement

Spent Fuel approximately 3 to 3.4 kW/canister

DHLW approximately 0.42 kW/canister

Canister Pitch 4.57 m (15 ft) center to center for spent
fuel or DHLW

2.29 m (7.5 ft) borehole spacing, due to
commingling

Canister Spacing 38.4 m (126 ft) center to center between
emplacement drifts

Canister Length

Spent Fuel 4.57 m (15 ft)

DHLW 3.05 m (10 ft)

Waste Form Characteristics

The decay characteristics of spent fuel and DHLW are given
by Peters (1983) for ten-year waste:

Spent Fuel $P(t) = 0.54 \exp(\ln(0.5)t/89.3) +$
 $0.44 \exp(\ln(0.5)t/12.8)$

DHLW $P(t) = 0.86 \exp(\ln(0.5)t/34.2) +$
 $0.14 \exp(\ln(0.5)t/15.2)$

where $P(t)$ = normalized power, and t = time in years.

The normalized power as a function of time, as derived from the above equations as well as that given by Mansure (1985) are shown in Fig. 12. As seen, the approximations for spent fuel are more-or-less equivalent. The initial power for spent fuel was reviewed by O'Brien (1985) and may range from a high limit of 3.4 kW to 2.3 kW. Previous studies (Mansure, 1985) examined variations over this range but assumed average conditions of 3.0 kW/can. In this study, we have chosen a conservative assumption of 3.2 kW/can. The initial power for DHLW was chosen to be 0.42 kW/can., after Peters (1983).

Fig. 12 Waste Form Normalized Power Decay/Spent Fuel and Defense High-Level Waste

3.3.2 Thermal Analysis

The thermal analysis of the vertical and horizontal emplacement configurations is a truly three-dimensional problem due to the commingling of waste forms. The model used to perform the calculations is the three-dimensional superposition program STRES3D (St. John and Christianson, 1980). Canisters are represented as a number of point heat sources with previously specified decay characteristics in an infinite or semi-infinite continuous medium (i.e., joints are considered to have no effect on thermal properties). The thermal affects of the point sources are superimposed at desired locations to provide the solution at any particular time. Heat transfer within the rock mass is assumed to be by conduction only. This assumption has been shown to be quite good in past field experiments (e.g., Zimmerman, 1983). Openings (with the exception of a free surface) are not modelled explicitly in this approach, but it has been shown (St. John, 1985) that the solution provides an upper bound to the case with openings present.

The details of the calculations are presented in the Appendix, and only the conclusions are discussed here. Two base sets of average rock thermal properties were used in the analyses: dry and saturated. These rock properties were obtained from the reference data base presented in Chapter 2 of the CDSCP (Table 2-9) and are given in Table II in the Appendix. Figures 13 and 14 show the near field temperature distributions around representative spent fuel canisters for the vertical and horizontal emplacement schemes.

It is seen that the peak borewall temperature for both cases is roughly 240°C, occurring at about 15 years time after emplacement for dry conditions. This temperature is well below the 275°C criteria established by NNWSI and given in Table 3. Figure 15 shows the temperature distribution across a typical panel of vertically-emplaced canisters. As described in greater detail in the Appendix, the temperature peaks correspond to canister locations, but are not equidistant from the canister centerline for all cases. Therefore, the temperature of the peaks should not be confused with the borewall temperatures shown earlier.

Fig. 13 Borewall Temperature as a Function of Time for Vertical Emplacement Scheme (Results are given for dry and saturated conditions at a representative spent fuel and DHLW Canister).

Fig. 14 Borewall Temperature as a Function of Time for Horizontal Emplacement Scheme (Results are given for dry and saturated conditions at a representative spent fuel and DHLW canister.)

Fig. 15 Temperature Distribution Across Panel for Vertical Emplacement (Note that temperature peaks are indicative of canister locations, but not peak canister temperature since the location does not coincide with the borehole wall.)

Figure 16 illustrates the approximate temperature of a typical closed emplacement drift for the horizontal emplacement scheme. The purpose of the diagrams is to determine the temperature at the location of unventilated service or access drifts which are subject to the 50°C at 50 years criterion given by NNWSI. It should be noted that this criterion is not necessarily driven by regulatory concerns, but is a result of operational concerns. It is included here, however, to illustrate the effects rock properties and waste characteristics and geometry on meeting design and performance criteria which are given in the CDSCP. These figures show that a standoff distance to surface drifts from the vertical emplacement panel of roughly 42 meters is necessary for the assumed dry conditions. This is opposed to a 35 m standoff given in the SCPDR (MacDougall et al., 1987) in which calculations were based on a non-commingled waste array with lower floor thermal loading (Mansure, 1985). The horizontal simulation shows an average emplacement drift temperature of 65°C at 50 years; significantly above the NNWSI-imposed constraint.

TEMPERATURE
AT 50 YEARS

Fig. 16 Temperature Distribution Along Emplacement Drift as a Function of Time for the Case of Horizontal Emplacement

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3.3.3 Thermomechanical Analysis

A room-scale thermomechanical analysis of the emplacement rooms for vertical and horizontal emplacement was conducted for a panel thermal loading of 20 W/m^2 (81 kw/acre) using the FLAC computer code (Itasca, 1988). The details of the study are presented in Brandshaug (1989). The following discussion is taken primarily from that report.

A plane strain model was used, and the rock is characterized as an elastic perfectly plastic material with ubiquitous vertical joints (planes of weakness). A Mohr-Coulomb failure criterion is used to determine if new fractures are created in the rock matrix (e.g., Brady and Brown, 1985). Figure 17 illustrates the Mohr-Coulomb failure criterion for the rock matrix for an arbitrary state of stress.

Fig. 17 Mohr-Coulomb Failure Criterion for a Rock Matrix

Slip or opening along the vertical planes of weakness is determined by a Mohr-Coulomb criterion for joints [e.g., Goodman (1980)]. Figure 18 illustrates the Mohr-Coulomb criterion for the ubiquitous vertical joints. By allowing inelastic rock behavior to occur, the potential and extent of room instability may be evaluated.

Fig. 18 Mohr-Coulomb Failure Criterion for a Rock Joint

The simultaneous mass and heat transfer (coupled convection/diffusion process) which occurs in forced ventilation of a waste disposal room is not included in FLAC. However, FLAC allows the use of convective boundaries by applying Newton's law of cooling (e.g., Pitts and Sissom, 1977). This requires the specification of a convective heat transfer coefficient and a temperature of the cooling "fluid", which in this case is air. Svalstad and Brandshaug (1981) compared the thermal response of a waste disposal room during forced ventilation, using separately, coupled convection/diffusion heat transfer and Newton's law of cooling. They found the thermal response to be similar when properly specifying the heat transfer coefficient and the temperature of the ventilating air.

Rock mass and room heating is assumed to take place for 50 years, followed by a 120-day period of forced ventilation with air at 1 m/sec velocity at 10°C or 20°C. Temperature histories for locations at the floor, roof and wall of an emplacement room prior to and for 120°C after ventilation is shown in Fig. 19 for vertical emplacement, and Fig. 20 for horizontal emplacement. The maximum floor temperature prior to ventilation is 126°C for vertical emplacement and roughly 65°C for horizontal emplacement. Note the substantial rapid cooling upon ventilation.

The mechanical properties of the rock mass used in these simulations are:

deformation modulus	15.2 GPa
Poisson's ratio	0.22
cohesion	17.8 MPa (intact) 0.1 MPa (joints)
friction angle	23.5° (intact) 28.0° (joints)

In Fig. 21, the predicted slip along the pre-existing vertical joints is shown after 50 years of vertical emplacement, and also after an additional 120 days of forced ventilation. There is very little additional joint slip induced as a result of the thermomechanical response of the rock for 50 years after room excavation and 120 days of forced ventilation beyond the 50 years. Using air of 10°C or 20°C during ventilation has the same effect on the predicted joint slip.

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Fig. 19 Predicted Temperature Histories in the Floor, Wall and Roof of the Waste Disposal Room for Vertical Emplacement.

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Fig. 20 Predicted Temperature Histories in the Floor, Wall and Roof of the Waste Disposal Room for Horizontal Emplacement

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Fig. 21 Predicted Slip Along Vertical Joints Around the Waste Disposal Room for Vertical Emplacement at the Time of Waste Retrieval and After Waste Retrieval

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The predicted 50 year history of roof to floor closure, and wall to wall closure are shown in Fig. 22. Both the roof/floor and wall/wall close as a result of excavation. The deformations predicted are very small, and far below the maximum amount of 0.152 m currently listed as a criterion in the SCPCDR, Chapter 2.

Fig. 22 Predicted History of the Roof to Floor Closure and Wall to Wall Closure of the Waste Disposal Room for Vertical Emplacement

As forced ventilation is initiated, the temperatures of the room surface rock decrease, resulting in thermal contraction of the rock. Depending on the system of rock fractures around the room, this effect may cause individual blocks of rock to become unstable. The kinematics of individual blocks of rock is not included in the mechanical model; thus, this phenomenon is not predicted in this study.

Joint movement may not result in room instability, however, it does result in the potential of such an event. Because most of the joint slip results from the effect of excavation, the chart in Fig. 23 (after Hoek, 1979) can be used to approximate the required ground support for the disposal rooms. When applied to the vertical emplacement rooms, assuming that the quality of the rock can be classified as "fair to good" according to the Geomechanics Classification system (Bieniawski, 1974), only light ground support such as rockbolts, wire mesh, or shotcrete is estimated to be required to maintain room stability. Similar results are obtained for horizontal emplacement where maximum room closures of 5 mm are predicted.

Fig. 23 Suggested Ground Support As a Function of Induced Stresses and Rock Mass Quality [after Hoek, 1979]

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4.0 DEFINITION OF INFORMATION NEEDS

The numerical modeling has shown the following broad conclusions.

1. Using the laboratory-based (CDSCP) design values for rock thermal properties, it would appear that temperature criteria for canister boreholes can be met for non-lithophysal welded tuff. The present analyses indicate that emplacement drift temperatures will exceed the design criteria set by the NNWSI program for retrieval at 50 years. These predictions are based on a knowledge of the thermal diffusivity which is inversely linearly related to the peak temperature, as well as the in-situ temperature, waste emplacement power, and emplacement geometry. In-situ measurements of the thermal diffusivity and its variability is needed to verify the correctness of thermal design calculations.
2. The mechanical calculations indicate that yield of the rock mass surrounding the emplacement drifts is likely to be confined to within a diameter of the opening. This yield will likely be characterized by slip and separation of existing joint surfaces and not fracturing of the intact rock. The primary mechanical effects appear to be a result of excavation with little additional yield resulting from thermally-induced stresses. It would appear that bolting and wire mesh will be sufficient rock support with light shotcrete as needed. The results additionally show that curvature of the emplacement boreholes due to heating is less than the design criteria given in Table 3. The results given here do not address potential fracturing of the borewall.

These studies are based on average rock properties given in the CDSCP (U.S. DOE, 1988, Chapter 2). The sensitive mechanical properties include the deformation modulus (stress related linearly to deformation modulus), joint orientation and cohesion/ friction angles, and in-situ stress state. It is noted that the prediction of failure using ubiquitous or compliant joint models is very sensitive to the frequency and orientation of fracturing as well as the in-situ stress magnitude and direction. This points out the need to determine: (a) a proper mechanical constitutive model for the rock; (b) appropriate deformation modulus of the rock and strength properties of the joints; (c) variability in geologic

structure, particularly the frequency and orientation of fracturing; and (d) the in-situ state of stress. These studies did not consider dynamic stresses from seismicity.

3. The thermomechanical studies did not consider the stability of seals (backfill, concrete) or the effects of heat and displacement on drainage characteristics of the Topopah Springs. These are vital questions which appear to be best determined via in-situ testing.

The conclusions from the parameter study may be summarized in five broad geotechnical or mining issues:

- (1) the need for a detailed geotechnical description of the Topopah Springs and overlying horizons;
- (2) the need to verify the predictability of the thermal and mechanical response of the rock mass;
- (3) the need to demonstrate the stability of excavations and their conformance to design criteria—particularly under mining, but also seismic and thermally-induced stresses (These excavations include shafts, drifts and emplacement boreholes.);
- (4) the need to assess the properties and extent of rock mass disturbance to mining and heating; and
- (5) the need to define the effectiveness of sealing and drainage in the welded tuff.

These five issues are broken down into information needs in Table 5. These information needs are also related to the corresponding 10CFR60 regulations and suggested in-situ testing methods. The testing methods are described later.

TABLE 5
INFORMATION NEEDS AND THEIR RELATION TO THE REGULATIONS AND IN-SITU TESTING

BROAD ISSUE	INFORMATION NEED	10 CFR 60 REG.	STUDIES TO DATE	IN-SITU TEST
1. A Detailed Geotechnical Characterization of the Topopah Springs formation and surrounding structure	1. Examine lateral variability of the Topopah Springs	General-base input applying to all regs below	Extensive laboratory study-see Chap. 2 of CDSCP	a,b,c,d,e
	2. Determine in situ stress state			
	3. Determine fault locations and geological/geotechnical/hydrological characteristics			
	4. Define a thermomechanical constitutive model for tuff		G Tunnel heated block, heater, flatjack, mine-by tests	
	5. Determine a range of in-situ properties for tuff, including:			
	a. thermal diffusivity			
	b. deformation modulus			
	c. strength properties of joints			
	-cohesion			
	-friction			
	d. strength properties of intact rock		Examination of constitutive laws, equivalent elastic, continuum joint	
2. Determination of the Predictability of the In Situ Thermal and Mechanical Response	1. Determine suitable numerical models to be used in design and performance assessment	60.135 (a) 60.131 60.112	Extensive numerical model examination and constitutive model representation-see Chap. 6 CDSCP	a,e,f,g,h,i
	2. Determine the confidence level with which the code can be used for prediction of pre-closure thermomechanical response	60.113 60.111 (b) 60.133 (c)		
	a. Geotechnical mapping, geophysical surveys			
	b. In situ stress measurement			
	c. Microseismic monitoring			
	d. Permeability measurement (gas)			
	e. Controlled in situ compression test (e.g. heated block)			
	f. Single heading exploration test/measurement of displacement response			
	g. Multiple excavation test (non-thermal)			
	h. Multiple excavation test (thermal)			
	i. Full scale heater tests (vertical/horizontal orientation)			
	j. Seal/drainage testing			

TABLE 5 (CONCLUDED)

BROAD ISSUE	INFORMATION NEED	10 CFR 60 REG.	STUDIES TO DATE	IN-SITU TEST
3. Demonstration of the Stability of Excavations and Rock Mass Structure to Thermal/Mining/Seismic-Induced Stresses	1. Determine the rock support requirements under realistic repository conditions (thermal and excavation-induced) 2. Examine stability of emplacement boreholes and liners under representative peak repository temperature and stress conditions 3. Determine the ability of numerical or empirical models for prediction of failure response of the rock under mechanical and thermal loading 4. Determine the stability of faults and underground openings under seismic loading	60.111 (b) 60.133 (c) 60.131 60.112 60.113	Empirical support calculations using Q system Numerical calculations using Mohr-Coulomb model Field experience in various tunnels in Ranier Mesa, NTS	a,c,f,g,h,i
4. Assessment of the Extent and Properties of Rock Mass Disturbance to Mining and Thermally-Induced Stresses	1. Determine the extent and properties of the disturbed zone 2. Determine disturbance of bounding faults as a result of excavation and seismicity	60.133 (a) (e) (2) (f) (i)	Seismic analysis of faults	a,c,d,f,g,h
5. Examination of the Characteristics of Sealing and Drainage	1. Determine the drainage characteristics of the Topopah Springs 2. Determine thermomechanical response of seal materials and bulkheads in laboratory and in situ under repository conditions	60.134		j
a. Geotechnical mapping, geophysical surveys b. In situ stress measurement c. Microseismic monitoring d. Permeability measurement (gas) e. Controlled in situ compression test (e.g. heated block) f. Single heading exploration test/measurement of displacement response g. Multiple excavation test (non-thermal) h. Multiple excavation test (thermal) i. Full scale heater tests (vertical/horizontal orientation) j. Seal/drainage testing				

5.0 TESTING METHODOLOGY — AN ITERATIVE APPROACH FOR ANALYSIS AND IN-SITU TESTING

The approach used by NNWSI in specification of in-situ testing as given in the CDSCP (Chapter 8) involves identification of all rock properties required for calculation of thermomechanical response and estimation of the present confidence to which they are known (low, medium, high). Judgment is then used to define a tentative goal and needed confidence interval for each parameter. A statistical analysis is then used to determine the number of tests required, in situ, to obtain that required confidence.

This approach may be invalid for several reasons. First, it is not obvious why a tentative goal for a property should be established a priori. The point of the testing is to determine the in-situ properties, not to prove or disprove an estimate made prior to testing. The use of statistics to define test numbers in the case of in-situ testing in an inhomogeneous rock mass needs to be approached with caution. The NNWSI approach appears to be centered on determination of "average" rock mass properties, and by "confidence levels", it means the precision of the estimated average values. This ignores the fact that one can obtain a good knowledge of the average or mean, and a poor knowledge of variability. The program defined by NNWSI appears aimed at obtaining "average" values, without potentially exploring the "best" and "worst" conditions. Other potential problems with the statistically based approach are:

- (1) rock properties are not evenly distributed throughout the rock mass, and the importance of various properties to repository response is not equal;
- (2) the measured property may be a function of size and possibly direction;
- (3) a population of parameters may not be normally distributed; and
- (4) with little information presently available on in-situ properties, it would seem impossible, a priori, to determine a sample population size necessary to obtain a given "confidence level".

In spite of these questions, geostatistics may prove to be valuable in helping to define the representativeness of a given testing or sampling approach.

In practice, rock mechanics applications to underground construction have been primarily empirical in nature due to the inherent inhomogeneity of the rock mass. In recent years, models (primarily numerical, but also empirical) have been used in an iterative process with observation and instrumentation to build models

which can be used confidently in design and performance assessment. In this program, numerical models will be relied upon, due to lack of empirical data for thermally-loaded caverns. The procedure is illustrated in Fig. 24. Here, existing laboratory or empirical data or field observation is used to choose a constitutive model for the rock mass (e.g., equivalent elastic continuum, Mohr-Coulomb plasticity, ubiquitous joint, etc.). Models are "exercised" against in-situ tests in which the loading and thermal conditions for a representative sample of the rock mass can be controlled. A test such as the heated block test can be used for this purpose. The model can then be used for initial predictions of full scale excavation performance. These performance predictions are compared to observations and measurements of opening response. These are generally measurements of rock displacements, but could also be rock or support stress change. The comparisons are, at first, quite simplistic (e.g., a single tunnel under isothermal conditions), but the detail of comparison increases with increasing model confidence to large scale, coupled thermomechanical problems. If a "reasonable" agreement can be achieved for the simpler, well defined problems, the model can be exercised on the increasingly more difficult problems which involve large scale coupled effects. At any point in the iterative process, if the comparison is poor, several options are available:

- (1) re-examine rock mass properties through lab or in-situ testing;
- (2) re-examine the constitutive model in use, (this may require additional lab or in-situ testing, or may be determined from physical observation);
- (3) re-examine the model itself to assure proper operation; or
- (4) perform additional underground measurement for further comparison.

*The term "reasonable" can be interpreted in many ways, but must be related to the confidence in prediction of rock response. As more data are obtained, the error in the prediction of response should not increase, and probably should decrease, thus bounding the ability for prediction.

Fig. 24 Flow Chart Illustrating an Interactive Approach to Determination of Constitutive Models and In-Situ Properties

The process suggested here is to build confidence in the understanding of the range of tuff response as well as its predictability by extensive comparison of the behavioral models to the rock mass response to excavation under a wide range of conditions. This type of approach requires flexibility in the testing plan as opposed to a rigidly defined set of tests developed prior to any excavation.

Figure 24 illustrates the approach for the in-situ testing suggested here. This figure illustrates an iterative procedure aimed at resolving the information needs through five basic components.

1. Monitoring of the mechanical response of shafts and lateral excavations in lithophysae-poor (TSW₂) and lithophysae-rich (TSW₁) tuff. Establish the ground support requirements under non-thermal conditions.
2. Instrumented exploration drifts to the boundary faults to determine variability of rock mass response as well as fault stability under seismic load.
3. Development of full scale repository openings which may be used to study the pre-closure thermomechanical response of the rock mass at expected repository conditions, and to verify ability to meet design criteria.
4. In-situ determination of sensitive thermal and mechanical properties.
5. Testing and verification of a constitutive model for welded tuff; establishment of the conservatism in the modeling approach.

The present in-situ testing at G-Tunnel as well as laboratory information has provided thermomechanical properties for welded tuff. The results have lead to the choice of two preliminary constitutive models for the Topopah Springs formation:

*Design calculations have used a Mohr-Coulomb continuum model for determination of opening stability.

- (a) an elastic continuum with "equivalent" rock mass elastic properties; and
- (b) a "ubiquitous" or "compliant" joint model—both are continuum representations of a jointed rock mass. These two forms of continuum joint representation are distinctly different, as the compliant joint model attempts to account for joint spacing and stiffness through a constitutive law.

These preliminary models of the behavior of welded tuff can be initially examined in detail through comparison against a controlled thermomechanical field test such as the heated block test (Zimmerman et al., 1986). Assuming the model(s) can be verified from this controlled test, it can then be used for comparison to room-scale response of the excavations in the ES facility. Initially, the model can be compared to the many measurements of displacement which will be obtained during normal monitoring of the construction of the ES facility drifts. These excavations are single drifts of simple cross-section, and will supply a good initial test case. Since these drifts will pass through a variety of rock conditions (particularly those that will explore the boundary fault structures), the comparison of the models will provide a simple means of documenting the range of in-situ properties required to describe the Topopah Springs response. It is fully expected that adjustments in properties and/or constitutive models will be necessary during this comparative stage, and additional testing of the heated block variety or, perhaps, new testing will be required. However, as the interactive approach of comparison of the models to single excavation behavior continues, increased confidence in the ability to predict the response should be obtained.

To fully test the predictive ability of the models and the understanding of rock mass behavior, the test configuration needs to subject larger volumes of rock to conditions similar to those which will be found in the repository. This can be accomplished by conducting a multiple excavation test with full-scale emplacement drifts. Initially, this test is aimed at monitoring isothermal excavation interactions; however, the facility can also be used as a laboratory for simulating full-scale repository response. Heater experiments in varying configurations can be used, and the entire facility can be heated to simulated repository conditions. This will allow examination of important pre-closure response of rock reinforcement as well as the extent and character of excavations and thermal disturbance. The facility can further be used for confirmation testing during repository development when heating effects are examined for time spans on the order of the retrieval period.

In conclusion, this methodology is based on the idea that the rock response is best determined through extensive excavation, monitoring and full-scale testing as opposed to an approach based strictly on statistical definition of a test plan. Ultimately, the purpose of the in-situ testing is to demonstrate predictability of response by quantifying the confidence in the predictive capability, and to define the range in the expected response. This would appear to be practical only with an iterative-type approach. This is not unlike the present NNWSI program given in the CDSCP (U.S. DOE, 1988), but emphasis there is placed on the ability to define the numbers and types of tests necessary to support the modeling effort prior to any excavation.

6.0 IN-SITU TESTING PLAN

6.1 The ES Facility

The planned ES facility is located at the Yucca Mountain site and consists of (U.S. DOE, 1988): (1) two 3.66 m finished diameter concrete-lined exploratory shafts; (2) approximately 1220 m (4,000 ft) of drifting within the main test level at 320 m; (3) an upper demonstration breakout room at 183 m; and (4) three exploratory drifts from the main test level totaling about 1700 m of drifting to explore the surrounding fault structures.

A plan view of the proposed ES facility is shown in Fig. 25. Important features are the drifts to the Ghost Dance, Drill Hole Wash and Imbricate fault structures. At the time this report was written, detailed plans for the type and location of in-situ tests were not available; therefore, comments on the sufficiency of the space provided for testing is not possible. Our primary comment on the design is that significantly more exploration of the repository area would be useful. In particular, drifting to the southern extent of the repository block would provide practical data on a region of the proposed site for which little data have been obtained at present. Intersection of the Ghost Dance fault at more than one location would also be advantageous.

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Fig. 25 Plan View of the ES Facility and Exploration Drifts
[MacDougall et al., 1987]

6.2 Construction Monitoring

Construction monitoring is a basic requirement in most civil-oriented underground excavation. This monitoring is used to verify the effects of construction on the rock mass as well as document the performance of the shafts and lateral excavations. The monitoring suggested here involves:

- (1) geologic and geotechnical mapping/classification of the excavations;
- (2) blast monitoring;
- (3) support testing/observation of rock instability;
- (4) displacement monitoring;
- (5) disturbed zone determination and characterization;
- (6) in-situ stress measurement;
- (7) wet and dry bulb air temperature and rock temperature; and
- (8) determination of water balance (i.e., water in the Exploratory Shaft versus water outside it).

The model validation studies described previously make extensive use of the data gathered here during preliminary studies.

6.3 Geological Mapping and Geotechnical Characterization

6.3.1 Geotechnical Characterization

A detailed geotechnical characterization of the rock mass (in addition to a geologic mapping of the rock mass) is performed as the ES excavations proceed. The techniques employed include: (1) engineering classification; (2) geological characterization; and (3) in-situ stress measurement.

6.3.1.1 Engineering Classification — Two engineering classification schemes which have found widespread use in civil construction and mining are the "Q" system developed at the Norwegian Geotechnical Institute (Barton et al., 1977) and the RMR system developed by Bieniawski (1974). Both methods provide a framework for an empirical description of the properties of the joints and

intact rock and an estimation of the effects of external conditions such as in-situ stress on the support methods required to maintain stable openings.

These methods have been applied to design in welded tuff (CDSCP-CDR); but we are aware of no other actual underground applications in welded tuff at NTS or elsewhere. In addition, there is no precedent for estimation of thermal loading effects on support. It is therefore necessary to begin with the present form of these classification systems but adjust them empirically as excavation continues to meet the particular needs of the welded tuff. The goal of these classifications within the ES is to develop a methodology by which rock support can be prescribed confidently under varying intraflow structures prior to excavation within the repository.

Either classification scheme can be used for this work. Detailed geotechnical line surveys (Call et al., 1976) can be used to follow the excavation as it is advanced. Maps (e.g., plan sections) are constructed which plot the Q or RMR values as a function of the geologic structure. The classification should be done shortly after excavation before support obscures the view of the rock.

The excavation dimensions, rock mass classification, internal structure (e.g., lithophysae), type of support, and success of support should be recorded in a data base which can allow updating of the classification as necessary.

6.3.1.2 Geologic Characterization — As a standard procedure, geologic mapping, photography, and sample collection will be performed in addition to the engineering classification.

6.3.1.3 In-Situ Stress Measurement — Measurements of the in-situ stress state are required for any design or performance calculations. A number of techniques are available, but overcoring is probably the best suited here since hydraulic fracturing involves injection of water into the unsaturated rock mass. Stress measurements are notorious for their poor ratio of success and it is therefore not possible to explicitly state the number of measurements necessary. In the ES facility, it would seem best to conduct measurements covering as large an areal dimension as possible to explore the lateral variability of the stress field. Several measurements are made at the same location using a single or a set of boreholes (depending on technique). The accuracy of the measurements at any location can be judged by their repeatability.

6.3.1.4 Geophysical Logging — Some simple geophysical tests should be conducted to provide a baseline on the rock mass characteristics at a number of locations within the ES facility. Several borehole logging techniques and survey methods provide useful background data, including cross-hole ultrasonics and the neutron log.

The general quality of the rock mass can be established by measurement of the speed of propagation of sound (Stacy, 1976). Although the elastic properties can be calculated from these data, we have found its use to be of greater qualitative—rather than quantitative—value due to the difficulties in relating the wave speed or frequency spectrum to specific geologic structure (e.g., Zimmerman et al., 1986). The cross-hole method involves recording an ultrasonic waveform as it passes through the rock mass between two boreholes. Probes containing piezoelectric crystals of user-variable frequency output are mechanically seated in the boreholes (Bellman and Wilson, 1985). The transmitter crystal is excited by high voltage pulses (of the order of 5kV) which create the desired waveform through coupling of the probe to the rock wall. The resulting waveform is picked up at the receiver, amplified, and stored on disk for analysis. The primary use of these data is to provide a background for qualitative comparison of wavespeed and, possibly, frequency content, to the geologic conditions encountered. The variability of dynamic elastic constants may also prove useful as a means of quantifying geologic effects on rock properties. The neutron probe can be used in diamond drill probe holes to document water content of the formation and possibly identify proximity to aquifers.

6.4 Examination of Shaft Response

The shaft provides the primary access to the ES and a secondary access to the repository for personnel, materials, and ventilation. As a result of the importance of these openings, they must be stable over the operational period of the repository.

In addition, the shaft and its surrounding disturbed zone provides one of the shortest pathways for groundwater or gas transport to the accessible environment. The exploratory shaft provides a case example for studying the properties of the damaged zone and the effectiveness of methods for sealing it. The geomechanical purposes for performing testing within the exploratory shafts are:

- (1) determination of the effects of shaft construction on the surrounding rock mass;
- (2) determination of the stability of the shaft liner under the action of mechanical loading;
- (3) determination of the effectiveness of the disturbed zone seal treatment (e.g., pressure grouting) and leakage past the lining.

6.4.1 Liner Closure

At intervals down the shaft, particularly at intersections with new geologic strata or high lithophysae content, shaft closure should be manually monitored (periodically) using a tape or rod extensometer. These measurements are primarily qualitative and give trends as to the stability of the liner and the surrounding rock mass. It is particularly important to monitor closure at the excavation brow, where the shaft station for the ES facility or the upper demonstration room has been constructed.

6.4.2 Examination of the Extent and Properties of the Damaged Shaft Zone

The extent and properties of the damaged zone are required to directly address 10CFR60 regulations. The damaged zone around the shaft could provide a major potential pathway for radionuclide transport from the facility, and therefore detailed documentation of the effects of mining on the rock mass disturbance needs to be documented. As the shaft construction proceeds, geologic recordings of the blasting need to be made and used to design blasts which will result in minimal disturbance or damage. At selected intervals down the shaft, radial boreholes (3 minimum) should be drilled to explore the depth and character of the damaged zone. The holes should be at least three shaft radii in length. Careful drilling practice needs to be used to preserve fracturing in as near in-situ conditions as possible. The fracture frequency in the core as a function of radial distance should be logged but will not likely provide reliable data. A borescope with video attachment can be used to film the hole walls and determine the aperture of fracturing as a function of radial distance from the shaft wall. The permeability as a function of radial distance determined by constant head gas injection (or other standard technique) can also be determined within the rock mass using small packed intervals. The utility of these measurements is questionable since small packed intervals are ne-

cessary to define what is expected to be a sharp gradient of permeability with radial direction. It is important, however, to attempt to quantify the permeability as a function of radial distance (i.e., damage) from the shaft. These holes can be left for re-examination at later times, or can be used as radial extensometer boreholes.

6.4.3 Shaft Wall Displacement and Liner Stress Change

A standard method for documenting the rock mass response to shaft construction is to monitor the radial displacement of the rock and the induced stresses in the concrete liner [see, for example, Beus and Board (1986)]. This is commonly accomplished by placing radially-oriented multipoint borehole extensometers (MPBX) in the rock mass directly at the shaft bottom, and monitor the inward displacement of the rock as the excavation proceeds. Additionally, concrete flatjack pressure cells can be placed in the liner as it is poured to determine the stresses exerted by the closure of the rock mass as it loads the liner. Typical layouts for the extensometers and pressure cells are shown in Fig. 26. The results of the instrumentation are compared to models of rock response and rock/liner interaction to determine: (1) the stability of the shaft; and (2) test the ability of the models to predict rock mass and rock support response/interaction.

Fig. 26 Location of Hydraulic Pressure Cells in Concrete Shaft Liner for Determination of Liner Tangential Stresses

6.4.4 Treatment of Shaft Data

Several of the measurements discussed here require remote data acquisition. The DAS will obtain the raw and converted data and preferably should supply plots of raw and converted data as a function of time. Most of the measurements described are used as qualitative measurements of stability; however, the mechanical response of the liner may be compared to analytical or numerical techniques for examining support-structure interaction problems (e.g., Daemen, 1975; Hoek and Brown, 1980; Lorig, 1984). The measurements of aperture and permeability within the disturbed zone will provide base data for use in performance assessment of the shafts.

6.5 ES Facility Testing

6.5.1 Introduction

One of the geotechnical questions which exists at the Yucca Mountain site is whether openings can be excavated which will remain stable under repository conditions over the retrieval period without resorting to extraordinary means of support. In addition, it needs to be demonstrated that the response of the rock mass to excavation and thermal loading is predictable using empirical, analytic, and numerical approaches. The need for predictability arises from the lack of empirical data regarding thermally-loaded excavations. The argument was put forward earlier that the logical approach to in-situ testing at Yucca Mountain is an interactive approach—i.e., one in which the gross response of the rock mass is determined under the varying rock mass conditions which are likely to be encountered within the actual repository. This approach is based heavily on the need to demonstrate the response of the rock mass and excavations under conditions typical of the proposed repository environment. This philosophy lessens the requirement for numerical models to predict performance based only on point tests and small-scale thermomechanical loadings. The development of a "validated" numerical model will provide the ability to extrapolate the rock mass response to different thermal loadings or rock conditions. This is required because large-scale thermomechanical tests cannot be conducted under all possible geologic conditions present in the ES.

With this approach in mind, the following testing has four components: (1) constitutive model testing; (2) exploration drifting; (3) multiple, full-scale repository excavation at ambient temperature; and (4) multiple excavation at elevated temperature.

An integral part of this testing is the verification of a constitutive (i.e., yield or strength) model for the rock mass and the testing and verification of rock mass response models. The ultimate objectives are:

- (1) to demonstrate the ability to construct stable repository openings under variable ground conditions and to determine the rock support requirements under ambient and elevated temperature;
- (2) to verify a constitutive model (i.e., strength criterion) which can reasonably encompass the variable geologic structures and temperature conditions; and
- (3) to demonstrate the predictability of rock mass response under variable ground conditions and thermal loading histories.

6.5.2 Constitutive Model Testing

The suggested iterative approach (as shown previously in Fig. 24) involves initial determination of the constitutive response of welded tuff in-situ. In particular, this testing is aimed at confirmation or further development of the constitutive model (and properties) already determined through laboratory and G-Tunnel testing. The most reasonable tests to determine large-scale thermomechanical constitutive properties would seem to be the heated block test (Zimmerman et al., 1986) or some form of the plate-bearing test (ISRM, 1979). The heated block test has the advantages of complete control over thermal and mechanical boundary conditions, allowing the ability to perform simple or complex load path applications. The previous heated block testing at G-Tunnel (Zimmerman et al., 1986) should provide the basis for the ES testing. The same basic method of testing is justified with one exception: the G-Tunnel experience showed that the unconfined vertical surface of the block resulted in propagation of horizontal fractures in the block upon lateral load. The effects of these fractures on measurements within the block were never fully explored. It would seem prudent to explore the use of confining tendons or jacks applied to the vertical surface of the blocks for control of the out-of-plane confining pressure. This method was used by the Basalt Waste Isolation Program in a test conducted in basalt (Cramer et al., 1986).

The heated block test is used to: (1) provide estimates of in-situ mechanical and thermal properties; and (2) provide a verification tool ("test bed") for constitutive models—i.e., use block test data to investigate approaches such as equivalent continuum and ubiquitous or compliant joint models.

The data and models generated from analysis of the heated block test can be used as the basic tools for analysis of full-scale excavation response tests as described in the following sections. It is not suggested here that a program of many such tests be initiated in an attempt to provide "average" values. An iterative approach requires additional testing only as it is indicated by inability to predict large-scale rock mass response adequately in further full-scale testing.

6.5.3 Single Heading Excavation to Explore Variability of Topopah Springs Response

The variability within the Topopah Springs unit resulting from variance in fracture frequency, lithophysae content, etc. will produce variable response of the excavations. It is the intent of this testing to provide measurements of the range of response of the excavations under the varying ground conditions present in the Topopah Springs. The amount of drifting necessary is questionable. These headings perform several functions in addition to providing mechanical data on ground response. In particular, they are used to provide basic geologic data on rock mass conditions across the site, and are used to predict the variability of conditions under which waste is to be emplaced. The present heading geometry does not provide significant exploration to the southern reaches of the repository block. A heading driven south from the ES, intersecting the Ghost Dance fault, and driven to the conceptual repository boundary would provide needed data on the southern portions of the site.

An indirect means of materials property measurement can be obtained by "back analysis" of the field measurement with the models developed from previous testing. Back analysis provides a means of determining the probable range of in-situ properties as well as confirmation of general features of the model.

The design of the ES facility needs to address the following points:

- (1) the facility design must not compromise the waste isolation integrity of the site;

- (2) provide for sufficient lateral exploration of the repository horizon so that a reasonable range of in-situ conditions can be experienced;
- (3) allow flexibility in adjustment of design to accommodate in-situ testing changes, if necessary; and
- (4) the ES must be compatible with the repository design.

The ES facility and drifts to boundary faults should provide a sufficient lateral exploration area to test the range of Topopah Springs ground conditions. The upper demonstration room will examine conditions in a zone of high lithophysae content. The drifts will be advanced by conventional drill and blast. Geologic and geotechnical mapping will follow the face advance as will rock instrumentation. Every 15 m to 30 m, simple closure points should be installed in the roof and walls for determination of total drift closure (Fig. 27). These instruments are read using a collapsible rod extensometer. The points are installed as close to the working face as possible, and read after every blast for the first few blast rounds, followed by a decreasing intensity of readings until equilibrium is obtained. A time history of deformation is obtained which can be used for model comparison as well as determination of support effectiveness.

Fig. 27 Closure Points in Detail

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At approximately 60m intervals, a more detailed examination of the rock response is determined. Here, rod extensometers with 5 or 6 anchors are installed in holes drilled radially in the roof and walls (Fig. 28). The mining should be stopped at each installation to allow the extensometers to be installed as close to the working face as possible to maximize the amount of displacement subsequent to continued excavation. To avoid blast damage, the instrument heads are recessed and protected by a blast screen. Hydraulic anchors have proven to be excellent under dynamic loads (Board and Beus, 1989) and are quickly installed. A minimum deep anchor length of 3 tunnel diameters is required to provide a zero motion reference for the instrument. Electronic displacement transducers are used, and the data recorded by the DAS. Several types of data plots can be made—for example, displacement as a function of time and face advance and displacement as a function of radial distance for various times. Example data plots from similar instrumentation within the Silver Shaft in Idaho is given in Fig. 29.

Fig. 28 Detail of Extensometer Installation Method

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Fig. 29 Example Plots of Displacements from Rod Extensometers Placed in the Walls of a Shaft to Monitor Radial Displacement As the Face is Advanced (These plots are from four different shaft horizons; the arrows indicate times of blasting.) [Board and Beus, 1989]

At several instrumentation stations, in-situ stress measurements may be performed from a small alcove driven into the drift wall (Fig. 30).

As the drift is advanced, a regimen of geotechnical observation and recording of ground conditions must be established. This should include visual observations, borescopic examinations, cross-hole ultrasonic velocity, and gas permeability in radial boreholes, photography, and periodic testing of roofbolt anchorage. This can be done through determination of anchorage strength by a standard pull test. It is also possible to instrument the bolts for strain or load. Based on the results of observation, varying methods of roof support may need to be used.

Fig. 30 Geophysical and Stress Measurement Alcoves From Exploration Drift

A great deal of instrumentation, manual measurement, and observational data will be obtained from the single heading drifting. From this data, conclusions can be reached regarding the:

- (1) stability of the openings/conservatism in rock support design;
- (2) depth and character of the zone of disturbed rock;
- (3) effects of geologic variability on rock response and support requirements; and
- (4) suitability of present empirical, analytical and numerical methods and constitutive models for prediction of rock mass response.

The stability of the openings can be determined from visual observation as well as from analysis of displacement versus time. The closure should stabilize shortly after the heading has advanced a few diameters beyond the instrumentation position. If not, additional ground support may be required. Through the present excavation plan, the orientation of the drifting with respect to the principal stresses and the geologic structure (and, thus, ground conditions) will vary. This data base should be sufficient to determine the utility of the empirical support classification scheme and to identify changes necessary within the Topopah Springs.

The depth of the damaged zone around these single openings can be determined by plotting the radial displacement versus radial distance at equilibrium. That portion of the curve which departs from elastic behavior may be considered to have undergone yield. This conclusion can be examined in light of radial permeability and cross-hole ultrasonic measurements as well as borescopic observation.

The point was made in previous discussions that the confidence in models is obtained not through a single test comparison but through a process of comparison and adjustment as excavation and testing proceeds. The single heading excavation provides a very simple, initial geometry for numerical and analytical models comparison. It is desirable to consider several calculational and constitutive models initially be chosen for comparison (e.g., elastic, Hoek and Brown, Mohr-Coulomb, compliant joint). Intact data from the laboratory, as well as rock mass properties from the G-Tunnel heated block test, can be used initially for comparison purposes. As the excavations proceed through varying ground conditions, it should be possible to narrow in on the re-

quired rock mass properties for bounding the measured response. Because the openings are small, with no influence from other excavations, it is likely that there will not be significant yielding. A better test of the constitutive models will occur during the full-scale, multiple excavation testing since significant yield may occur there.

6.5.4 Multiple Excavations

The objective of the multiple excavation test is to excavate full-scale repository drifts in a prototype repository panel and determine the resulting rock mass response. The knowledge gained from the single excavation tests should be applied directly to support specifications and prediction of excavation response. After completion of excavation of the prototype panel, thermal loading will be applied to the system to study the thermomechanical response of the rock mass on a large scale.

The objectives of the multiple excavation test are to (1) demonstrate the excavation and response of full-scale repository drifts in welded tuff and (2) to provide the opportunity for determination of the rock mass mechanical behavior through measurement and back-analysis of data.

The simple demonstration of excavation and support technology will provide the information necessary to establish that stable excavations can be constructed prior to thermal loading. Many of the information needs regarding constructability relate to the empirical data obtained from the demonstration.

The second objective of the multiple excavation test is to study the mechanical response of the rock mass. Two general approaches are possible for subjecting the rock mass to loading change. Flatjacks or rams can be used to provide controlled stress boundary conditions, or the excavation itself can be used to create stress redistribution in the mass. The use of controlled stress boundary conditions is preferable for determining the mechanical behavior of the rock, but size limitations, number of tests, and cost make this approach unreasonable. Additionally, it is important to subject the rock to realistic stress distributions as occurs around openings. For model verification, the constant stress induced by artificial loading can produce an inadequate test comparison.

Excavation alone, on the other hand, subjects a large volume of the rock mass to loading change and provides a measurement of actual response. However, the constitutive properties must be de-

terminated from back-analysis using analytic or numerical techniques, thus adding considerable uncertainty.

The second approach is preferred in this case. Analysis of the data from this test will indicate the ability of models to predict the ambient rock mass response. The error in these predictions will be a result of an inadequacy in the state of knowledge of the material model, rock mass properties, and in-situ conditions or, perhaps, an inadequate numerical representation of the material model. Assuming the in-situ conditions and a properly constructed model, the remaining sources of uncertainty lie in a knowledge of the constitutive properties. The degree of uncertainty which can be tolerated can only be related to its effect on performance prediction. If the degree of uncertainty is such that the site cannot meet performance standards for the worst-case analysis, then the uncertainty is too high. Definition of the confidence of predicted response versus measured response across the site is extremely important. Perhaps a statistical evaluation of the uncertainty of predictability of response can be used to define confidence levels. Further thought must be given to the topic of field validation of models before allowable uncertainties can be set.

6.5.4.1 Test Design — There are many possible geometries which can be used to perform a multiple excavation experiment; one is given here as an example. Two basic emplacement drift cross-sections are given in the CDSCP (U.S. DOE, 1988) for vertical and horizontal emplacement. The mine-by geometry and drift sequencing given in Fig. 31 is provided to examine stability of both cross-sections. The smaller initial excavations are used as instrument and observation galleries for the full-scale vertical and horizontal emplacement rooms. The spacing between these drifts must be carefully designed to produce accurately measurable response at one drift due to excavation of the second without producing unstable ground conditions. This is beyond the scope of this document. The length of the drifts should be great enough to simulate plane strain conditions, thereby simplifying subsequent data analysis.

Fig. 31 Example of Multiple Full-Scale Excavation Test Geometry (Small instrumentation/observation drifts are driven first, followed by the full-scale emplacement drifts. The spacings of the drifts need to be such as to produce measurable displacements and stress response.)

6.5.4.2 Test Operation — The instrumentation headings are driven full face for their complete length. At three instrumentation stations along their length, three multi-point rod extensometers are used to determine the displacement of the drift and the formation of the yield zone around it. As stated previously, these instruments must be placed immediately at the working face. As in the single excavation description, a geologic and geotechnical mapping of the drifting should be completed, crosshole ultrasonics and neutron probe measurements taken, and a periodic program of rockbolt pull testing established. In addition, a series of constant head gas injection (or other) tests in boreholes oriented from the small instrumentation headings toward the larger excavations provide a baseline measurement of the hydraulic conductivity of the Topopah Spring. It is also recommended that no shotcrete be used for support so that the rock surface may be examined and photographed. An important aspect of the multiple heading tests is the use of microseismic monitoring as a means of determining the zones of failing rock around the excavations and the stability of the rock mass. An acoustic emission system capable of monitoring a broad band of seismic events, and recording, locating and plotting them, should be installed prior to and during excavation.

After completion of the first headings, instrumentation will be installed into the pillar area to monitor the effects of the subsequent excavations to determine the following information:

- (1) the strains (displacement) in the pillar and around the second excavation as it is driven;
- (2) the stress change in the pillar;
- (3) the growth of the damaged zone around the second excavation;
- (4) the change in gas conductivity as a function of excavation and rock disturbance; and
- (5) the change in ultrasonic velocity as a function of damage to the rock mass.

Three basic instrumentation stations are used: multi-point borehole extensometers (mpbx), deflectometers, and stressmeters. A number of holes are also provided for manual measurements of cross-hole ultrasonics, neutron probe moisture, time domain reflectometry, constant head injection gas, and cross-pillar closure.

The displacements of the pillar and the rock mass surrounding the second excavation are determined from the mpbx and deflectometer

readings. The mpbx will yield values of displacement as a function of radial distance from the second drift. The displacement measurements are restricted to the direction of the hole axis. The deflectionometers determine the angular change of the axis of the borehole (i.e., displacement) by means of accelerometers or strain gauged "knuckles". They give displacements perpendicular to the hole axis and thereby provide data in the orientation normal to the mpbx. Several holes drilled completely across the pillar from drift 1 to drift 2 can be used for tape extensometer determination of the total lateral pillar strain. These can be referenced to the deep anchor of the drift 1 radial extensometer to provide an absolute reference of pillar motion.

Pillar stress change can be determined by one of a number of devices—none of which has been proven to be completely satisfactory. Perhaps the simplest device to use is the vibrating wire or strain-gauged solid inclusion stressmeter. More than one can be placed in a hole, and they can be constructed in a rugged fashion; its calibration is subject to installation technique and is non-linear. Other gauges which determine borehole displacement require a modulus for conversion to stress. The proper choice for this value is always open to question.

In addition, a number of manual measurements will be made. Time domain reflectometry (TDR) can be used in an attempt to monitor the growth of the disturbed zone as the second drift is excavated. This technique involves grouting a coaxial cable(s) in a borehole and determining the length of the cable to a break or neck. As the damaged zone grows through sliding along joints or new fracture propagation, the cable will break (Fig. 32). The break is detected from drift 1 by passing an electromagnetic pulse down the cable and monitoring its reflected pulse. Several sets of cross-hole ultrasonic boreholes are used to detect the change in the rock mass upon excavation. Constant head gas injection can also be performed radially from the second drift to attempt to define the hydraulic conductivity of the damaged zone. Other measurements such as boreoscopic examination of the pillar can be performed as well.

All of the above instruments are to be installed prior to excavation of drift 2 and allowed to attain some background level prior to excavation. The full scale drifts are driven separately by slashing (horizontal emplacement) or by heading and bench (vertical emplacement), with a rate slow enough to ensure that no data are lost. In other words, excavation rate needs to be controlled by the needs of the experimenters, not vice versa.

Fig. 32 Schematic to Illustrate Use of TDR for Detection of Extent of Damaged Zone (Cable breaks are detected and related to joint shear displacement.)

6.5.4.3 Analysis of Data — The analysis of the instrument data is performed using a number of analytic and numerical techniques. A flowchart illustrating the analysis methodology is given in Fig. 33. The best estimate of rock mass properties and constitutive law determined from the single excavation testing is input to a number of numerical techniques which are used to analyze the plane excavation geometry. It is assumed from information in Chapter 6 of the CDSCP (U.S. DOE, 1988), that two primary continuum constitutive models will be used for data analysis: an equivalent elastic and compliant joint model. A discontinuum approach (Tiktinsky, 1988) may be useful as well in elucidating rock structure effects. Sufficient data are available for determination of the range of elastic and plasticity properties required to encompass the measurements. From these, a "best-fit" constitutive model and parameters can be developed. The range of the properties required to fit the data determines the confidence level in prediction of the mechanical response.

If the ability to define the proper constitutive model and properties cannot be shown (i.e., if the confidence interval is large), then it may be necessary to conduct additional large-scale, controlled mechanical tests for constitutive model development. A decision can be made to conduct additional large scale in-situ or laboratory tests at that time. Support performance for the full-scale excavations can be determined from the stability of displacements and observation as well as periodic pull testing of roofbolts.

Fig. 33 Data Analysis from Multiple Excavation Tests Using Numerical Models (Existing properties, plus those determined empirically or through back-analysis are used as initial input to several code approaches. Comparison is made to determine the optimum constitutive law and range of properties. Additional testing may be required if significant effects on performance result from inadequate knowledge of the rock properties.)

6.5.5 Emplacement Borehole Drilling

There is little question of the ability to drill and emplace waste in the vertical emplacement mode described earlier as one of the options for waste emplacement. Holes may require cleaning prior to emplacement, but there is no reason to expect massive instability. There is, however, little experience in the area of long horizontal hole drilling. Although major problems are not expected in drilling and lining these holes, it is nonetheless important to conduct trial runs of drilling, liner emplacement, hole outfitting and mock canister emplacement.

During drilling, records need to be kept on advance rate, fluid injection volumes, and problem areas. After drilling is complete, the hole needs to be examined with a videotaping borescope, a caliper log and directional survey need to be run. This can be followed by hole outfitting and emplacement testing and documentation.

6.5.6 Drift and Borehole Stability at Elevated Temperature

Perhaps the least understood geomechanical question in repository design is the long-term thermomechanical response of the underground openings. The current 50-year retrievability period requires that the various drifts and emplacement boreholes be maintained and stable over this time.

It is necessary to show that the combination of thermal loading density and excavation-induced stress do not result in excessive yield of the rock mass and instability of the openings during the retrieval phase for the suggested CDSCP gross thermal loading. It is also necessary to demonstrate that the response of the rock mass and support is predictable with a reasonable degree of confidence. The following two approaches have been taken by designers to determine the allowable gross thermal loading.

1. Use laboratory thermal properties and laboratory elastic properties reduced by some factor to account for jointing as input to a thermoelastic code. Determine the combined excavation and thermal stresses for a given gross thermal load and compare them to a value for the in-situ strength of the rock mass. The value for in-situ strength is based on some reduction factor from the uniaxial compressive strength, or on a yield criterion such as that proposed by Hoek and Brown (1980).

2. The second approach is similar to the first, with the exception that the numerical model embodies the yield criterion as a form of plasticity. The stability of the opening is determined numerically and is based on the resulting yield zone rather than an explicit calculation of rock strength.

Both approaches have been examined for the Yucca Mountain site (Johnstone et al., 1984), but have yet to be verified from field experience. The approach suggested here is to determine the stability of the emplacement holes by simply subjecting them to the design temperature and stress conditions while monitoring their mechanical and thermal response. Models of the rock mass response can be validated against these data.

Although a room-scale heating test is mentioned in the CDSCP, Chapter 8.3 (U.S. DOE, 1988), no discussion is given. It is not felt that single full-scale heater tests (e.g., Stripa) provide data of sufficient breadth to validate thermomechanical codes. We see a significant problem with confident application of room-scale design models whose validation is based on single heater tests which thermally load only small blocks of ground that are highly confined (kinematically).

Again, it is suggested that a practical engineering demonstration approach be taken to this problem by subjecting a large volume of ground to elevated temperature conditions prototypical of the repository. The rooms and pillar from the multiple excavation test provide an excellent geometry for conducting a room-scale thermomechanical test. Electrical heaters can be used to provide the thermal loading which is equivalent to (and surpass) the design gross thermal loading. The instrumentation (with supplemental temperature sensing and compensation) can be used to monitor the test.

6.5.6.1 Test Design — The design of a large scale heated room test requires extensive numerical modeling to define heater locations and power as well as test duration. This is beyond the scope of the present report, however the objectives of the design can be given.

1. At least several heaters which replicate the full scale dimensions and power of the waste canisters need to be used. This will allow study of borehole stability and canister temperature.
2. Provide for full-scale excavations and as-designed CDR support systems.

3. Heating of prototype emplacement drifts to near repository conditions of temperature and stress in a reasonable time frame. Thermal analyses are necessary to define the number, power and locations of heaters required to accomplish this goal.
4. Provide flexibility for adding experiments in the thermal environment if desired.

The small diameter drifts can be used for instrumentation galleries and access for heat source installation (Fig. 34). The full-scale emplacement drifts would be closed to ventilation to aid in heat retention.

Fig. 34 Plan View of Thermomechanical Test Showing Heater Locations (Note that three (approximate) of the heaters will be complete mock-ups of the actual canister emplacement scheme.)

6.5.6.2 Test Operation — The operation of this test is rather simple and involves the passive monitoring of the rock mass response via automated instrumentation, visual observation of rock support conditions in the rooms, and borehole wall conditions in the emplacement holes, numerous geophysical and hydrologic manual measurements, and periodic testing of the pull strength of the roofbolts. Area is available within the test facility for conducting performance tests on seals and seal components. For example, the following studies could be conducted.

1. Permeability of seal bulkheads and backfill to water and gas. Examination of contact seal of seal material to rock mass under thermal conditions.
2. Investigate the drainage capacity of drift floors under non-thermal and thermal conditions over extended time periods.
3. Change in dimensions and properties of the disturbed zone around the openings.

The test can continue unimpeded for roughly three years prior to submittal of the Final Environmental Impact Statement. Testing could continue indefinitely beyond this stage, depending on the authorization of the construction permit as a portion of confirmation testing. In essence, then, we see this test as a continuous operation from ES testing through license application, construction authorization, and construction. It will thus provide initial thermomechanical response sufficient for the license application and a base of long-term data from which extrapolation for the full retrieval period can be made.

The rock response to be monitored during the thermomechanical testing and the instrumentation to be used is reviewed in Table 6. The instrumentation is largely the same as in the previous ambient temperature testing. The major exception is the measurement of temperature change in the rock mass through addition of thermocouple holes. As a result of this duality, all instruments must be designed and calibrated to operate at temperature levels of up to 200°C.

Table 6

ROCK RESPONSE VARIABLES
MONITORED DURING THERMOMECHANICAL ROOM-SCALE TEST

<u>VARIABLE</u>	<u>INSTRUMENTATION</u>
DISPLACEMENT	mpbx, deflectometer, extensometry
TEMPERATURE	thermocouples
STRESS CHANGE	stressmeter (either solid inclusion or displacement type)
ACOUSTIC EMISSION	AE system / broad band
DAMAGED ZONE GROWTH/ PROPERTIES	TDR, borescope
• Ultrasonic Velocity	cross-hole ultrasonics
• Permeability Change	constant head gas injection
SEALS PERFORMANCE	permeability of seals, bulkheads and their contact with rock mass at thermal conditions (area available for fluid drainage evaluation through drift floor during heating)

6.5.6.3 Analysis of Data — At the completion of the single and multiple excavation tests, the following should be accomplished:

- (1) definition of a constitutive model (i.e., yield function) for the rock mass;
- (2) determination of the range in rock mass properties required to account for range in measured data through the various intraflow structures;
- (3) identification and validation of numerical model(s) suitable for geomechanics design in tuff;
- (4) quantification of confidence (i.e., predictability) in the modeling capabilities;
- (5) determination of the conservatism in the rock support design for ambient temperature applications and establishment of opening stability;
- (6) determination of the extent of the excavation-induced disturbed zone; and
- (7) at least the short term performance of seals, back-fill and drainage under thermal loading.

The analysis of the data from this test attempts to extend these conclusions to the thermomechanical behavior of the rock mass as well.

6.5.7 Constitutive Model Definition, Model Validation

The constitutive model, or yield function, is determined primarily through back analysis of displacements of the openings and pillar under excavation and thermally-induced load. The validated codes from the multiple excavation test will be used to examine the thermomechanical test results. This will involve a comparison of the displacements at mpbx and deflectometer anchor-age locations and temperature at thermocouple locations with displacement and temperature estimates from the model. A parametric analysis of the data using a range of rock mass thermal properties will be required to bound the field data. Coupled effects such as temperature dependence of the thermal and elastic properties may be required. From these results, the confidence interval and best-fit properties can be determined.

6.5.8 Stability Analysis

The stability of the room and emplacement boreholes can be documented from displacement measurements, acoustic emission output, rock support performance, and visual observation.

Displacement data plotted as a function of time and radial distance will indicate the extent of yield and the extent of time-dependent behavior. The acoustic emission system will locate the position of noise generated by crack propagation and/or shearing along existing fractures. These phenomena have been associated with stable yield as well as violent instability (rockburst). There is no definitive method for relating the energy and frequency content of the emissions to the stability of the openings; however, a qualitative assessment can be made. Identification of dislodged blocks, opening of fractures, etc. provide a qualitative measure of the stability. Examination of the large diameter emplacement borehole surface using a high-temperature borescope will indicate any progressive instability. Both the Stripa and NSTF testing used borescopic examination and photography for determination of borehole stability. Periodic pull tests on rockbolts will indicate whether deterioration of the resin or grout bonding with temperature is occurring. Rockbolt load cells will also indicate whether slippage and decrease in the bond strength results from higher temperature.

6.5.9 Damaged Zone Extent and Properties

The change in the damaged zone extent and properties can be evaluated using time domain reflectometry, displacement measurements, borescopic examination, cross-hole ultrasonics, and constant head injection tests.

A new series of TDR cables should be installed after the multiple excavation test. During heating, manual readings of cable breaks indicate areas of induced fracturing or joint shear slippage. The radial displacement profile around the opening can be used to calculate strain. The borescopic examinations of the rock mass can be used to verify joint dilation (or closure) or shear under thermal expansion. The constant head injection tests are used to quantify the effects of heating on the permeability of the damaged zone. The temperature of the injection water should be controlled at the interval temperature to avoid thermal expansion problems. This technique recently was employed by Zimmerman et al. (1986) during the heated block test in tuff. Silicon rubber mechanical packers were fixed in place for the test time to avoid errors in placement as well as thermal expansion of the packer inflation gas.

Thermal loading will peak at the repository room periphery in roughly 15 years (see the Appendix). The time available for the thermomechanical test prior to licensing application is not long enough to experience peak loads; however, sufficient data should be available to confirm design and performance models. It is intended that this test continue in operation for extended periods as construction of the repository and fuel loading continue.

By necessity, the analysis of the test is based, to a great extent, on observation as the time increases. At some point, the effects of ventilation cooling for retrieval on the stability of the drifts can be examined simply by opening the area to forced ventilation.

6.5.10 Seals and Drainage Performance

An important part of the room-scale heating test needs to involve the long-term performance of seals (e.g., backfill, bulkheads, etc.) and drainage of the drift floor. As yet, little information is available on the design of these seals. Once greater detail is available on sealing plans, testing can be designed within the context of the room-scale test.

REFERENCES

- Barton, N., R. Lien and J. Lunde. "Estimation of Support Requirements for Underground Excavations," Design Methods in Rock Mechanics (Proc. 16th U.S. Symposium on Rock Mech., Minneapolis, 1975), pp. 163-178. New York: ASCE, 1977.
- Bellman, R. A., and M. L. Wilson. G Tunnel Heated Block Ultrasonic Velocity Measurement Results (Final). SAIC-84/ 1762. March 1985.
- Beus, M. J., and M. P. Board. "The Effect of Stress Field and Rock Mass Properties Around a Deep Mine Shaft, Based on In Situ Measurements During Construction," Proceedings of the 1986 Symposium on the Application of Rock Characterization Techniques in Mine Design (Michael Karmis, Ed.), pp. 72-79. Littleton, Colorado: Society of Mining Engineers, 1986.
- Board, M. P., and M. J. Beus. "In-Situ Measurements and Preliminary Design Analysis for Deep Mine Shafts in Highly Stressed Rock," USBM Report of Investigations, RI-9231, 1989.
- Bieniawski, Z. T. "Geomechanics Classification of Rock Masses and Its Application in Tunnelling," Proc. Third International Congress on Rock Mechanics (Denver, 1974), Vol. 11A, pp. 27-32. Denver: ISRM, 1974.
- Brady, B.H.G., and E. T. Brown. Rock Mechanics for Underground Mining. London: George Allen & Unwin, 1985.
- Brandshaug, T. "Stability of Disposal Rooms During Waste Retrieval," U.S. Nuclear Regulatory Commission, NUREG/CR-5335, March 1989.
- Call, R. D., J. P. Savly and D. E. Nicholas. "Estimation of Joint Set Characteristics from Surface Mapping Data," Site Characterization (Proc. 17th U.S. Symposium on Rock Mech., Snowbird, Utah, 1976). Utah: Engineering Experiment Station, 1976.
- Cramer, M. L., G. T. Berlin and R. E. Heath. "Block Test #1 Final Report: Results from Experimental and Numerical Analyses at Elevated Temperatures," Rockwell Hanford Operations SD-BWI-TD-023, January 1984.
- Daemen, J.J.K. "Tunnel Support Loading Caused by Rock Failure," Ph.D. Thesis, University of Minnesota, 1975; U.S. Army Corps of Engineers, Omaha, Nebraska, Report MR0-3-75, 1975.

Goodman, R. E. Introduction to Rock Mechanics. New York: John Wiley & Sons, 1980.

Hoek, Evert. "The Role of Modeling in the Design of Nuclear Waste Repositories — The Design Engineer's Viewpoint," Proceedings of a Workshop on Thermomechanical Modeling for a Hardrock Waste Repository (June 1979), pp. 33-43. Berkeley: Lawrence Livermore Laboratory, 1979.

Hoek, E., and E. T. Brown. Underground Excavations in Rock. London: Institute of Mining and Metallurgy, 1980.

Itasca Consulting Group, Inc. FLAC (Fast Lagrangian Analysis of Continua). Minneapolis: Itasca Consulting Group, 1988.

ISRM Commission on Standardization of Laboratory and Field Tests. "Suggested Method for Deformability Determination Using a Plate Test (superficial loading)", Int. J. Rock Mech. Min. Sci., 16, 195-214 (1979).

Johnstone, J. Keith, Ralph R. Peters, and Paul F. Gnirk. "Unit Evaluation at Yucca Mountain, Nevada Test Site: Summary Report and Evaluation" SAND83-0372, June 1984.

Lorig, L. J. "A Hybrid Computational Model for Excavation and Support Design in Jointed Media," Ph.D. Thesis, University of Minnesota, 1984.

MacDougall, Hugh R., Leo W. Scully, and Joe R. Tillerson (Compilers). Site Characterization Plan Conceptual Design Report. SAND84-2641. September 1987.

Mansure, A. J. "Expected Temperatures for Spent Fuel Borehole Walls and Drifts," Memo to R. J. Flores, Sandia Keystone Memo 6310-85-8, April 15, 1985.

O'Brien, Paul D. "Reference Nuclear Waste Descriptions for a Geologic Repository at Yucca Mountain, Nevada," SAND84-1848, September 1985.

Peters, Ralph R. "Thermal Response to Emplacement of Nuclear Waste in Long, Horizontal Boreholes," SAND82-2497, April 1983.

Pitts, Donald R., and Leighton E. Sissom. Schaum's Outline of Theory and Problems of Heat Transfer. New York: McGraw-Hill Book Company, 1977,

Stacy, T. R. "Seismic Assessment of Rock Masses," Proceedings of the Symposium on Exploration for Rock Eng. (Johannesburg, 1976), Vol. II. 1976.

St. John, C. M. "Reference Thermal and Thermal/Mechanical Analyses of Drifts for Vertical and Horizontal Emplacement of Nuclear Waste in a Repository in Tuff," SAND86-7005, May 1987.

St. John, C. M. "Thermal Analysis of Spent Fuel Disposal in Vertical Displacement Boreholes in a Welded Tuff Repository," SAND84-7207, November 1985.

St. John, Christopher, and Mark Christianson. "STRES3D: A Computer Program for Determining Temperatures, Stresses, and Displacements Around Single or Arrays of Constant or Decaying Heat Sources — User's Guide and Manual," University of Minnesota Report to Rockwell Hanford Operations, RHO-BWI-C-78, September 1980.

Stacy, T. R. "Seismic Assessment of Rock Masses," Proceedings of the Symposium on Exploration for Rock Eng. (Johannesburg, 1976), Vol. II. 1976.

Svalstad, D. K. and T. Brandshaug. "Forced Ventilation Analysis of a Commercial High-Level Nuclear Waste Repository in Tuff," SAND81-7206, December 1981.

Tiktinsky, David H. "Numerical Parametric Sensitivity Study of Thermal and Mechanical Properties for a High Level Nuclear Waste Repository," Key Questions in Rock Mechanics: Proceedings of the 29th U.S. Symposium (University of Minnesota, June 1988), pp. 429-440. Rotterdam: A. A. Balkema, 1988.

U.S. DOE. Consultation Draft Site Characterization Plan Overview, Yucca Mountain Site, Nevada Research and Development Area, Nevada (CDSCP). Nuclear Waste Policy Act, Section 113. January 1988. U.S. DOE, 1988

Zeuch, D., and E. Eatough (Compilers). "Reference Information Base for Nevada Nuclear Waste Isolation Project," Sandia National Laboratory Report SLTR 86-5005, 1986.

Zimmerman, R. M. "First Phase of the Small Diameter Heater Experiments in Tuff", Proceedings of the 24th U.S. Symposium on Rock Mechanics, pp. 271-282, June 1983.

Zimmerman, Roger M., Robert L. Schuch, Donald S. Mason, Michael L. Wilson, Michael E. Hall, Mark P. Board, Robert P. Bellman, and Mark L. Blanford. Final Report: G-Tunnel Heated Block Experiment. SAND84-2620. May 1986.

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APPENDIX:

THERMAL ANALYSIS OF REPOSITORY CONCEPTUAL DESIGN

NUMERICAL SIMULATIONS OF NEAR FIELD HEAT TRANSFER

NUMERICAL MODEL

The model used to perform the thermal calculations described here is the code STRES3D (St. John and Christianson, 1980). This code determines approximate three-dimensional temperature (and stress) distributions induced by constant or decaying heat sources in homogeneous media. The calculations are based on the closed-form analytic solution for temperature and stress distributions around point heat sources in infinite (or semi-infinite) elastic media. Superposition of effects from individual point sources is used to obtain the solution at each point in the media. The assumption of an infinite medium also precludes the explicit modeling of openings and potential effects of ventilation. However, it is possible to obtain upper- and lower-bound solutions to temperature distributions by assuming an infinite and semi-infinite body. This is described in greater detail below.

STRES3D has been compared extensively to analytic solutions and is currently in use in the NNWSI program (St. John, 1987). The accuracy with which the program represents the temperature distributions around canisters is dependent on the number of heat sources used to represent the canister. This is discussed in some detail by Christianson (1979). The detail required in simulation of the canister depends on the purpose of the simulation. It would appear that, for the purposes of the repository simulations given here, 5-10 point sources per canister is adequate for accurate near field temperature determination.

Input Properties

Two cases of rock properties (dry and saturated) are used for the Topopah Springs formation as bounding values. The relevant thermal properties, obtained from the CDSCP, are reviewed in Table I.

Table I

THERMAL PROPERTIES OF THE TOPOPAH SPRINGS
WELDED TUFF USED IN ANALYSES*

Case	Density (kg/m ³)	Thermal Conductivity (w/m K)	Specific Heat (J/cm ³ K)
dry rock	2340	1.91	1.88
saturated rock	2340	2.07	2.25

*"design" values, as reported in Chapter 2, Table 2-9 of the CDSCP

For each of the above property sets, both the vertical and horizontal commingled arrays are modeled using the emplacement geometry and properties described previously.

MODEL GEOMETRY

It is neither possible nor necessary to include every canister in the modeling analysis. St. John (1985) examined the radius of influence of a single canister as a function of time so that the required number of canisters to be modeled could be determined. The equation for temperature change at a distance, R, from a decaying point source of initial strength Q_0 is given by:

$$\Delta T = \frac{Q_0}{\pi^{3/2}} \exp(-At) \frac{\sqrt{\pi}}{4\kappa R} \exp\left(-\frac{R^2}{4\kappa t}\right) \operatorname{Re} \left[w \left[\sqrt{(At)} + \frac{iR}{\sqrt{(4\kappa t)}} \right] \right]$$

where A = decay constant,
 k = thermal diffusivity,
 t = time, and
 $w(z)$ = complex error function.

It is seen that the temperature change decays from the source approximately proportional to

$$\exp\left(-\frac{R^2}{4kt}\right)$$

St. John (1985) suggests that $R^2/4kt = 4$ [$\exp(-4) = 0.018$] is sufficient to ensure small temperature change. This requires that

$$R \geq 4 (kt)^{1/2}$$

where t is time in years.

For 100 years' time, $R \cong 200$ meters for $k \cong 26 \text{ m}^2/\text{year}$. The total length of emplacement drift available for waste emplacement is roughly 340 meters for a panel, thereby fixing the model canister boundaries in one direction. For simplicity, the array dimensions are made roughly square (approximately 340 m x 340 m), which is approximately sufficient for a 100-year time frame. Figures 1(a) and 1(b) illustrate the canister arrays used for horizontal and vertical emplacement. A total of 1332 and 1544 canisters are modeled in the vertical and horizontal emplacement schemes, respectively. Of primary concern is the peak temperature at the canister borehole wall throughout the repository, as well as the temperature rise at service drift locations. To reduce problem size, only the central canisters within the panel are finely discretized into a higher number of point sources. These central canisters (Fig. 2), are represented by five point sources, whereas the surrounding canisters are represented by one point source.

(a) Vertical, Commingled Canister Array Used in Numerical Model

(b) Horizontal, Commingled Canister Array Used in Numerical Model

Fig. 1 Illustration of Canister Arrays Used for Horizontal and Vertical Emplacement

(a) Vertical, Commingled Canister Array Used in Numerical Model

(b) Horizontal, Commingled Canister Array Used in Numerical Model

Fig. 2 Central Grouping of Canisters Where Near-Field Temperature Distributions Must be Accurately Known are Defined by Five Point Sources (All canisters elsewhere are discretized into one point source).

TEMPERATURE DISTRIBUTIONS IN THE CANISTER NEAR FIELD

Figure 3 shows the temperature distribution across the panel for commingled vertical emplacement, dry conditions, for times of 1, 5, 10, 20 and 100 years. The cross-section was taken for a line transverse to the panel drift strike at the location of a line of spent fuel canisters across the center of the panel. The temperature peaks correspond to emplacement drift locations. The peak temperatures near the canisters are not accurate because the particular points selected are of varying distance from the source. Therefore, the temperature peaks from these large-scale diagrams should not be taken as peak borehole or waste temperatures. The important points to note from these plots are that:

- (1) peak temperatures in the pillars between boreholes are reached after roughly 50-100 years; and
- (2) a stand-off distance from the last canister of about 42 meters is required to maintain access drift temperatures of 50°C or less at 50 years time. This temperature criterion is set by the NNWSI program for unventilated drifts as discussed by Mansure (1985) in Appendix A of the SCPCDR. This is, however, slightly larger than the 35 m stand-off, specified by Mansure, that was based on a non-commingled waste array with lower floor loading (0.612 kW/m of drift as opposed to 0.792 kW/m of drift for the present commingled array).

Figure 4 shows the temperature distribution across the panel for the case of commingled horizontal emplacement, dry rock conditions. The cross-section displayed here was taken along a line transverse to the borehole axis, thereby showing temperature peaks at the location of each spent fuel or DHLW canister. As in the previous plot, the peak temperatures from this diagram are not indicative of the peak borehole or waste temperatures because the sampling points do not necessarily coincide with waste form location.

Temperatures were calculated in the rock mass along a line directly down the center of a horizontal emplacement drift (Fig. 5). As seen in this figure, the average temperature for an unventilated emplacement drift is roughly 65°C at 50 years. This may be compared to the SCPCDR (p. 3-121):

Fig. 3 Temperature Distribution Across the Panel for Vertical, Commingled Array. (Note: temperature peaks do not correspond to peak borehole temperature at each canister location)

Fig. 4 Temperature Distribution Across the Panel for Horizontal, Commingled Array.

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Fig. 5 Temperature Profile Down the Center of Emplacement Drift for Horizontal Emplacement [after U.S. DOE, 1988, Fig. 6-64, p. 6-151]

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"Preliminary analyses [based on the average waste type and thermal output (Section 3.2.1)] indicate that, 50 years after emplacement, the rock mass at the wall of the emplacement drift may heat up to 53°C and, at the wall of the panel access drift, to 48°C."

The studies described here show an emplacement drift temperature approximately 12°C higher. This probably is the result of the somewhat higher GTL used in the present studies.

The temperature distributions surrounding a single canister are shown in Figs. 6 and 7 for a typical spent fuel canister and in Figs. 8 and 9 for a DHLW canister in the vertical, commingled emplacement mode. The temperature distributions are given for a radial line beginning at the borehole wall at the mid-height of the canister. The orientation of the line is shown in each figure and is either along the line connecting adjacent canisters or is oriented perpendicular to it.

As pointed out by Mansure (1985), as long as the gross thermal loading is constant, the most important factor in vertical fuel emplacement is the drift floor loading. In the SCPCDR, the floor loading used for non-commingled waste modeling studies (Mansure, 1985) was 0.612 kW/m (3.0 kW canisters on 4.9 m centers or 3.4 kW canisters on 5.55 m centers). The peak borehole wall temperature as a function of time as predicted in the SCPCDR is shown in Fig. 10. The peak temperature of roughly 225°C and 240°C is reached at about 17 years for the case of 3.0 and 3.4 kW canisters, respectively. In the present, commingled case, the initial floor loading is:

$$\begin{array}{rcl}
 \text{(1) Spent Fuel} & - & \frac{3.2 \text{ kW canister}}{4.57 \text{ m spacing}} = .699 \text{ kW/m} \\
 \text{(2) DHLW} & - & \frac{.42 \text{ kW canister}}{4.57 \text{ m spacing}} = .092 \text{ kW/m} \\
 & & \hline
 \text{Total} & & .791 \text{ kW/m}
 \end{array}$$

Thus, the floor loading is 29% higher initially for the commingled array. Figure 11 shows a peak borehole wall temperature of 240°C, reached after approximately 15 years for dry rock conditions. For saturated conditions, peak borehole wall temperature is roughly 210°C for vertical emplacement.

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Fig. 6 Temperature Distribution With Radial Distance for Spent Fuel Canister, Vertical Emplacement, Dry Rock Conditions

Fig. 7 Temperature Distribution With Radial Distance for Spent Fuel Canister, Vertical Emplacement, Saturated Rock Conditions

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Fig. 8 Temperature Distribution With Radial Distance for DHLW Canister, Vertical Emplacement, Dry Rock Conditions

Fig. 9 Temperature Distribution With Radial Distance for DHLW canister, Vertical Emplacement, Saturated Rock Conditions

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Fig. 10 Peak Borehole Wall Temperature as a Function of Time as Given in the SCPDR, Appendix A [Mansure, 1985] (Three canister initial powers are given, but floor thermal loading is kept constant by increasing spacing for higher power levels.)

The peak temperatures at the DHLW borehole are approximately 200°C for dry conditions and 175°C for saturated conditions, reached after 20 years time (Figs. 8 and 9). The borewall temperatures as a function of time for all waste form and rock properties are shown in Fig. 11. The peak temperature predicted for the borewall for the commingled vertical array are, in conclusion, somewhat higher (5-10%) than those presented in the SCPCDR for the non-commingled array due to the higher floor loading. The slightly higher temperatures predicted here do not appear to invalidate design calculations drawn from the CDSCP and SCPCDR studies.

Fig. 11 Peak Borehole Wall Temperature as a Function of Time for All Vertical Emplacement Runs

Figures 12 and 13 show the radial temperature distributions surrounding a typical spent fuel canister in the center of a horizontal, commingled panel for dry and saturated conditions. The borehole wall (assuming 0.94 m diameter boreholes) temperature for the dry thermal properties is about 240°C, or roughly the same as the vertical case. Again, the peak borehole wall temperatures for the saturated rock are about 10% lower than for the

dry case (Fig. 13). The peak temperature for the corresponding DHLW canisters is roughly 180°C . The borehole wall temperature as a function of time for both spent fuel and DHLW canisters is shown in Fig. 14. This can be compared to Fig. 15, which is the predicted borehole wall temperature for the SCPCDR.

Fig. 12 Temperature as a Function of Radial Distance for Typical Spent Fuel Canister (horizontal, commingled emplacement scheme, dry rock)

Fig. 13 Temperature as a Function of Radial Distance for Typical Spent Fuel Canister (horizontal, commingled emplacement scheme, saturated rock)

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Fig. 14 Borehole Wall Temperature as a Function of Time for Spent Fuel and DHLW Canisters in Horizontal, Commingled Emplacement

Fig. 15 Borehole Wall Temperature as a Function of Time for Spent Fuel in Horizontal Emplacement from NNWSI SCPCDR [MacDougall, 1987, Appendix E, p. 85]

As seen, the peak temperatures are about 25°C higher for the commingled case. This is probably the result of two factors:

- (1) higher power loading density per meter of borehole (0.656 kW/m in the present commingled case, as opposed to 0.582 kW/m for the SCPCDR studies [Mansure, 1985]); and
- (2) higher panel gross thermal loading for the commingled case (67 kW/acre as compared to 57 kW/acre).

The greater power loading density (13% higher) could probably account for this difference alone.

REFERENCES

Christianson, M. TEMP3D: A Computer Program for Determining Temperatures Around Single or Arrays of Constant or Decaying Heat Sources—Users' Guide and Manual. University of Minnesota Report to BWIP. December 1979.

MacDougall, H. R., L. W. Scully, and J. R. Tillerson (Compilers). Site Characterization Plan Conceptual Design Report. SAND84-2641. September 1987.

Mansure, A. J. "Expected Temperatures for Spent Fuel Borehole Walls and Drifts," Memo to R. J. Flores, Sandia Keystone Memo 6310-85-8, April 15, 1985.

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St. John, C. M. Reference Thermal and Thermal/Mechanical Analyses of Drifts for Vertical and Horizontal Emplacement of Nuclear Waste in a Repository in Tuff. SAND86-7005. May 1987.

St. John, C., and M. Christianson. "STRES3D: A Computer Program for Determining Temperatures, Stresses, and Displacements Around Single or Arrays of Constant or Decaying Heat Sources — User's Guide and Manual," University of Minnesota Report to Rockwell Hanford Operations, RHO-BWI-C-78, September 1980.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report presents an analysis of the in-situ geomechanical testing needs for the Yucca Mountain site, and discusses a possible testing program which addresses these needs. The testing needs are derived from 10CFR60 regulations, as well as simple thermomechanical canister- and room-scale studies. The testing approach suggested here is based heavily on demonstration and monitoring of full-scale rock mass response. This is accomplished through instrumented excavation of exploration drifting throughout the repository horizon, as well as thermal loading of full-scale repository excavations. Confidence in predictive models is developed through an "iterative" approach of model comparison to rock mass response. This program approach is opposed to one in which "point" testing is conducted a priori at determined locations in an attempt to statistically specify given rock properties.

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