FINAL DRAFT

SUGGESTED REVIEW APPROACH TO IN-SITU TESTING AT YUCCA MOUNTAIN

(Section 8.3.2
— Planned Tests, Analyses and Studies —
Repository Program)

Prepared for:

U.S. Nuclear Regulatory Commission

Prepared by:

Itasca Consulting Group, Inc.
Suite 210
1313 5th Street SE
Minneapolis, Minnesota 55414

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Prepared for: U.S. Nuclear Regulatory Commission
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Task Description: This report presents four parts of a suggested approach for reviewing rock mechanics/design aspects for one subsection (8.3.2) of the Site Characterization Plan for a proposed high-level nuclear waste repository at Yucca Mountain. The four parts (I – Areas of Review, II – Acceptance Criteria, III, Review Procedures, and IV – References) generally follow the format of NRC Standard Review Plan (NUREG-0800).

Prepared by: Itasca Consulting Group, Inc.
Suite 210
1313 5th Street SE
Minneapolis, Minnesota 55414

Author:	Reviewer:
______________________	______________________
Loren J. Lorig	Jaak Daemen
Itasca Consulting Group, Inc.	Consultant
	(University of Arizona)
Date: ______________	Date: ______________

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(Section 8.3.2, Planned Tests, Analyses, and Studies
— Repository Program)

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PREFACE

This report presents four parts (Sections I, II, III and VI) of a suggested approach for reviewing rock mechanics/design aspects for one subsection (8.3.2) of the Site Characterization Plan for a proposed high-level nuclear waste repository at Yucca Mountain. Format for the suggested review approach is based on NRC Standard Review Plan (NUREG-0800) which contains six sections:

I. Areas of Review

II. Acceptance Criteria

III. Review Procedures

IV. Evaluation Findings (not included)

V. Implementation (not included)

VI. References

Although this report is intended to be site specific for Yucca Mountain, only Section III presents discussions which are specific to the anticipated Yucca Mountain conditions. The general format and content of this report were discussed during meetings with NRC Division of Waste Management personnel on 14 August, 18 September and 19 December 1986.

The section numbers used herein are taken from the "Annotated Outline for Site Characterization Plans (Rev. 4)" (February 15, 1985), prepared by the mutual agreement of BWIP, NNWSIP, SRP and DOE-HQ. Subsection 8.3.2 (Repository Program) is part of Section 8.3 (Planned Tests, Analyses and Studies) of Chapter 8 (Site Characterization Program).

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(Section 8.3.2 — Planned Tests, Analyses and Studies — Repository Program)

I. AREAS OF REVIEW

The review described for this section is limited to rock mechanics/design aspects of the in-situ test program. Other aspects are to be reviewed by other disciplines.

NNWSI Repository Program Status

The NNWSI Repository Program has been detailed by MacDougall (1985) and Jackson (1984). Additional information is available from meeting documents (e g., "Subsurface Design Concepts for the NNWSI", Parsons Brinkerhoff, February 1986) and from NRC/NNWSI correspondence. Some proposed testing relating to the repository program is described in NNWSI documents (e.g., Vieth et al., 1985).

Review Preliminaries

Review of Section 8.3.2, Repository Program, will require familiarity with a number of directly-related sections—in particular,

Section 1.3.2.3, Existing Stress Regime — The reviewer should compare concepts concerning the existing stress regime reported here with those presented in Section 2.6, Existing Stress Regime.

Section 1.4, Seismology of Candidate Area and Site — This section will describe the natural and UNE-induced seismicity of the candidate area and site. Repository design must account for design basis dynamic ground motion. The reviewer should compare the vibratory ground motion at the site (Subsection 1.4.2 1) with the design basis earthquakes and UNEs presented in Subsection 6.1.2.

Section 1.6, Drilling and Mining — This section will discuss the behavior of excavations at the NTS (particularly, the G-Tunnel) as well as near-by mines. This information, therefore, forms part of the empirical data base for excavation behavior in the local area.

Chapter 2, Geoengineering — This chapter will present a summary of the existing state of knowledge of the mechanical, thermal, and thermomechanical properties of the rock units as well as in-situ stress conditions that form the basis for the conceptual design of the geologic repository. The reviewer should be familiar with the entire chapter.

Chapter 6, Conceptual Design of a Repository — This chapter summarizes information presented in the conceptual design report. The reviewer should be familiar with all aspects of this section. Of particular interest to the reviewer will be the identification of design assumptions which require testing verification. In particular, the reviewer should be familiar with the following sections and subsections:

6.1 — Design Basis

6.2 — Current Repository Design Description

6.2.1 — Background
6.2.2 — Overall Facility Design
6.2.3 — Repository Operations
6.2.4 — Design of Surface Facilities
6.2.5 — Shaft and Ramp Design
6.2.6 — Subsurface Design

6.3 — Assessment of Design Information Needs

6.3.1 — Introduction
6.3.2 — Design of Underground Openings
6.3.4 — Strength of Rock Mass
6.3.6 — Construction
6.3.7 — Design of Surface Facilit
6.3.8 — Repository System Compon Performance Requirements

Section 7.1, Emplacement Environment - .is section will describe the waste package environment, incluci he host rock immediately adjacent to the waste package. The re .er should be familiar with this section to determine the rela...on between proposed tests that support design of the engineered barrier system and the range of anticipated repository conditions.

Section 8.1, Rationale for Planned Site Characterization Program — According to the Annotated Outline, Section 8.1 "will present the logic behind the identification and prioritization of information needs and the collection and utilization of information." However, viewgraph copies from the SCP Issues Hierarchy and Performance Allocation Meeting (3-4 March 1987) show that SCP Section 8.1 will provide a "general introduction to the site characterization process" (which uses an issues-based approach to planning site characterization). In either case, the reviewer will need to be aware of all aspects of this section.

Section 8.2, Issues To Be Resolved and Information Required During Site Characterization — According to the Annotated Outline, this section will discuss "the origin of issues, the relationships of issues to the program and the manner in which the program deals with issue resolution." However, viewgraph copies from the SCP Issues Hierarchy and Performance Allocation Meeting (3-4 March 1987) show that SCP Section 8.2 will discuss "rationale for conducting site characterization". In either case, the reviewer will need to be aware of all aspects of this section.

Section 8.3.5, Performance Assessment Program Plan — The reviewer should be familiar with all aspects of this section.

Repository Conceptual Design in Support of Site Characterization Plan for NNWSI — This document, which is also known as the Conceptual Design Report, will be included as an appendix to the Site Characterization Plan and is summarized in Chapter 6 of the SCP. This document provides very detailed information on all aspects of the repository conceptual design. The reviewer should be familiar with all aspects of this report, but particularly

Chapter 2 — Bases for the SCP Conceptual Design

Chapter 4 — Design Description

Chapter 6 — Performance Objectives

Chapter 7 — Design Analyses

Chapter 8 — Design Issues

The reviewer should be familiar with appendices and studies which discuss

(1) expected temperatures for borehole walls and drifts after spent fuel emplacement;

(2) borehole liner stresses;

(3) ventilation cooling;

(4) feasibility of disposing of nuclear waste in a horizontal configuration;

(5) pre-closure radiation safety;

(6) equivalent energy density;

(7) effect of porosity on emplacement drift stability;

(8) Cove III temperature calculations;

(9) items important to safety, waste isolation, and retrievability at Yucca Mountain; and

(10) thermomechanical analyses.

II. ACCEPTANCE CRITERIA

A. Basic Acceptance Criteria

1. Regulatory Requirements

The information provided in the SCP is acceptable if it meets the requirements of 10CFR60, Section 60.17, and if it contains sufficient information identified in Section 8 (Part B) of the Standard Format and Content of Site Characterization Plans for High-Level-Waste Geologic Repositories (Regulatory Guide 4.17) so that the relevant requirements of the regulations listed below are met.

a. 10CFR60.15(b)
b. 10CFR60.15(d)(4)
c. 10CFR60.21(c)(1)
d. 10CFR60.21(c)(4)
e. 10CFR60.21(c)(6)
f. 10CFR60.21(c)(12)
g. 10CFR60.21(c)(14)
h. 10CFR60.31(a)(1)
i. 10CFR60.43(a)
j. 10CFR60.43(b)(3)-(4)
k. 10CFR60.51(a)(4)
l. 10CFR60.72
m. 10CFR60.111
n. 10CFR60.112
o. 10CFR60.113
p. 10CFR60.122(a)
q. 10CFR60.122(b)(5)
r. 10CFR60.122(b)(8)
s. 10CFR60.122(c)(2)
t. 10CFR60.122(c)(20)-(24)
u. 10CFR60.130 (last sentence)
v. 10CFR60.131(b)
w. 10CFR60.133
x. 10CFR60.151
y. 10CFR60.152

2. Regulatory Guidance

The Regulatory Guide and other documents provided by the NRC staff to aid the DOE in meeting the requirements of the regulations in (1), previously, include:

Regulatory Guide 4.17, Standard Format and Content of Site Characterization Plans for High-Level Waste Geologic Waste Repositories

GTP: Design Information Needs in the Site Characterization Plan (Final), December 1985

GTP: In-Situ Testing During Site Characterization for High-Level Nuclear Waste Repositories (Final), December 1985 (This GTP summarizes guidance which has been given to DOE through technical correspondence, documented technical meetings, and other mechanisms provided by the NRC/DOE Procedural Agreement (49FR3870, dated May 29, 1983.)

GTP: Interpretation and Identification of the Extent of the Disturbed Zone in the HLW Rule (10CFR60) (Draft), June 1986

GTP: Items and Activities in the HLW Geologic Repository Program Subject to 10CFR60 QA Requirements (Draft), July 1986

GTP: Waste Package Reliability Analysis for High-Level Nuclear Waste Repositories, December 1985

Issue-Oriented Technical Position (ISTP) for NNWSI (Draft), September 1984)

Revised Modeling Strategy Document for HLW Performance Assessment

Summary of the NRC/DOE Meeting on the Level of Detail for Site Characterization Plans and Study Plans, 7-8 May 1986

B. Specific Acceptance Criteria

Specific acceptance criteria which will form the basis for the staff's determination that the requirements of the above regulations and recommendations of the referenced guide and other documents are met as follows.

Planned Studies, Tests and Experiments

Acceptability of planned studies, tests and experiments described in Sections 8.3.2.1 through 8.3.2.5 will be determined by the degree to which the DOE has:

(1) presented analysis which reflects the rationale for selection of specific test methods and procedures. Various features or components of the rationale may appear in separate sections or subsections of Chapter 8 of the SCP. Table 1 presents the lists of 15 "required" features and the subsection (from the Annotated Outline) in which the features are likely to be discussed.

(2) described the specific study, test or experiment in detail. The specific requirements are given in Regulatory Guide 4.17 (pp. 57 and 58), reproduced here:

"For each test or experiment . . . , the testing and instrumentation that will be necessary for the investigation should be described. The description should include testing method and testing apparatus, data collection systems, methods of analysis and reduction of data, and the applicability and limitations of the testing and instrumentation in acquiring the necessary information.

"Planned tests or experiments should be designed (1) to reflect state-of-the-art precision and accuracy in the use of instrumentation or equipment and method of analyses, (2) to employ a scale that will result in representative data, (3) to permit reproductibility and traceability of results, and (4) to statistically determine experimental uncertainties."

Table 1

"REQUIRED" FEATURES OF RATIONALE FOR IN-SITU TESTING AND PROBABLE CORRESPONDING SCP CHAPTER 8 SUBSECTIONS

"Required" Features Related to the Repository Program for Rationale for In-Situ Testing [1]	SCP Subsection[2]
(1) all relevant issues requiring resolution by in-situ testing and measurements	8.2.1
(2) the information needs for the license application (identified on the basis of 10 CFR Part 60 requirements and the level of uncertainty in predicting the performance of the repository)	8.2.1.1[3]
(3) the availability of existing tests to provide all the information needed	8.3.2
(4) the capabilities and limitations of available tests and measurement methods	8.3.2
(5) the need, if any, to develop new tests	8.3.2
(6) the effects of testing on long-term repository performance	8.3.2
(7) the extent of the underground test facility required to assess host rock variability properly and to assess the effect of that variability on design and performance	8.3.2.2
(8) the extent of the underground facility needed in order to minimize or avoid interference among tests	8.3.2.1

[1]from pp. 5-6 of the GTP on In-Situ Testing

[2]from the Annotated Outline for Site Characterization Plans (Rev. 4, February 1985)

[3]from Draft SCP, Section 8.1

Table 1 (continued)

"Required" Features Related to the Repository Program for Rationale for In-Situ Testing[1]	SCP Subsection[2]
(9) the sufficiency of subsurface geologic mapping, geophysical testing, and core drilling to assess the characteristics of the host rock and the variability of its properties	8.3.2.2
(10) the representativeness of the in-situ test location compared to the entire volume of rock that must be assessed in determining compliance with the U.S. Environmental Protection Agency limits for releases to the accessible environment	8.3.2.2
(11) the basis for selection of a particular scale and duration of testing	8.3.2
(12) justification for conducting or not conducting coupled/interactive (THMC) tests	8.3.2.3
(13) extent of credit taken for the performance of important components of the barrier system, engineered and natural	8.1.2.2[3]
(14) the sufficiency (amount, scale and duration) of geological, hydrological, geomechanical, geochemical, thermal, and coupled/interactive testing to make findings on compliance with the performance objectives on a scale that is sufficient to realistically represent the inhomogeneities and discontinuities of the rock being tested	8.3.2
(15) description of the manner in which data from surface borehole testing and laboratory testing on small-scale samples will be integrated with the in-situ test results	8.3.2.2

(2) continued

"For each test or experiment requiring short-term or long-term monitoring, describe the goal of the monitoring and the techniques to be used. The description should include specifications for the monitoring system, the instrumentation and data collection systems, the methods of analysis and reduction of data, and the applicability and limitations of the monitoring system in acquiring the necessary information. Identify and evaluate alternative methods of testing and analysis that might achieve the same goals as the methods proposed."

(3) clearly stated the relation of the test to information in Part A and to the unresolved issues discussed in Section 8.2. In particular, the relation of the planned study, test or experiment to the demonstration of meeting system component performance requirements should be described.

(4) shown that the conditions under which tests are run represents, as closely as possible, the realistic repository environment.

(5) presented criteria for determining sufficient number of tests.

(6) provided an lanation showing how the planned scale and duration will be sufficient to allow assessment of compliance with 10CFR60.

(7) described how the quality assurance program will be applied to testing data collection and analyses.

(8) identified each planned test that involves the use of radioactive materials, provided information on the quantity of radioactive material to be used, including its curie content, explained why this is the minimum quantity of radioactive material necessary for testing, and described plans for the retrieval of such radioactive material following testing.

(9) described any planned tests or investigative activities that may affect the capability of the site to isolate high-level waste, described possible ways in which the tests or investigation activities could have such an effect, and provided information on measures to be taken during testing to prevent such occurrences.

8.3.2.1 Overview

In addition to criteria listed previously under Planned Studies, Tests and Experiments, acceptability of this subsection will be determined by evidence that DOE has:

(1) briefly described and presented graphically in this section or elsewhere:

(a) "key milestones to be used to mark progress,

(b) data analyses to be performed,

(c) use of acquired data, including both direct use of the tests and experiments as well as integration of results of tests and experiments to resolve identified issues and identify new issues, and

(d) stages in the site characterization program where options would be assessed and decisions would be made as to how (or whether) to proceed" (Regulatory Guide 4.17, p. 59)

(2) constructed the presentation of milestones, activities, analyses, etc. so that tasks accomplished and tasks still to be accomplished can be identified readily

(3) identified "which tests will be completed at the time of construction authorization application and which tests and long-term monitoring activities will continue after that" (GTP on In-Situ Testing, p. 12)

(4) considered, in planning the testing schedule, the long lead time required by some tests in order to develop equipment and procedures" (GTP on In-Situ Testing, p. 12)

(5) considered "the amount and variety, scale, and duration of testing needed" to provide sufficient information by the time the license application is submitted

(6) included

(a) "criteria to determine whether the amount and variety of testing is sufficient" (GTP on In-Situ Testing, p. 13),

(b) discussion of the "scale of testing and its implications for site characterization" (GTP on In-Situ Testing, p. 13), and

(c) discussion of "how the data from such long duration tests (if any) will be used in the repository design" (GTP on In-Situ Testing, p. 13)

(7) described, in this section or elsewhere, "the underground test facility to be used for the in situ at-depth testing portion of the site characterization program. The description should include a detailed technical rationale for the proposed underground testing that addresses the quantity, quality, and scales of data needed to resolve licensing information needs. Based on this rationale, the description should provide a detailed layout of the planned excavation, including design dimensions, boring locations, and the planned location within the test facility of each anticipated test or experiment. In addition, details of construction, including the location of the underground test facility with respect to the conceptual design of a repository appropriate to the site, should be provided. Particular attention should be paid to to shafts excavated and borings made for the underground test facility and their locations with respect to possible future shafts and excavations. An analysis of the potential impact of insitu at-depth testing on the integrity of the site should also be included" (Regulatory Guide 4.17, p. 58)

(8) shown that sequencing of tests progress in a logical manner

(9) shown that spatial or temporal proximity of tests will not interfere with obtaining or analyzing results

(10) considered the need for flexibility to account for the exploratory, developing nature of the investigations

8.3.2.2 Verification or Measurement of Host Rock Environment

In addition to criteria listed previously under Planned Studies, Tests and Experiments, acceptability of this subsection will be determined by evidence that DOE has

(1) shown the underground openings to "be of sufficient extent so that the variability in the host rock and adjacent strata can be properly assessed" (GTP on In-Situ Testing, p. 13)

(2) discussed the adequacy of exploratory drifting to establish representative design parameters for the entire repository block.

8.3.2.3 Coupled Interactive Tests

In addition to criteria listed previously under Planned Studies, Tests and Experiments, acceptability of this subsection will be determined by evidence that DOE has

(1) established that coupled/interactive testing is not needed and provided technical evaluation identifying the volume of rock for which no performance credit is taken, or

(2) adequately described plans for direct testing of the coupled behavior, including specification of the scale and duration of the planned tests and description of how the scale and duration will be adequate to assess compliance with 10CFR part 60.

Referring to (1), above, NRC has stated (GTP on In-Situ Testing, p.14; also 4.17, pp. 53-54) that coupled/interactive testing "may not be needed if the following conditions are met:

(1) In evaluating overall repository performance, no credit is taken for that portion of the rock that cannot be evaluated without direct testing of coupled/interactive effects.

(2) Components of the natural system (that is, geologic, hydrologic, and geochemical) for which performance credit is taken are characterized adequately for evaluation of overall repository performance.

(3) Components of the engineered barrier system, such as the waste package, are designed with adequate conservatism with respect to the coupled/interactive behavior that will be encountered. Examples of conservatism in design could include (a) limiting thermal loading and (b) thickening of waste container walls.

(4) The tests that support the design of the engineered barrier system are carried out under a much wider range and more adverse conditions than anticipated. This means that the design of the tests takes into account conditions above and beyond the full range of behavior that is expected to be encountered under a given thermal load." (GTP on In-Situ Testing, p. 14)

8.3.2.4 Design Optimization

No specific acceptance criteria are associated with this subsection.

8.3.2.5 Repository Modeling

In addition to criteria listed previously under Planned Studies, Tests and Experiments, acceptability of this subsection will be determined by the degree to which DOE has

(1) described both the analytical techniques, codes and models expected to be important for site analysis and the associated data requirements (type and quantity) either directly or by reference to other sections—i.e.,

(a) Section 6.1.3, Analytical Tools for Geotechnical Design,

(b) Section 8.3.5.4, Substantially-Completed Analytical Techniques, and

(c) Section 8.3.5.5, Analytical Techniques Requiring Significant Development,

(2) summarized available data directly or by reference to other sections,

(3) described plans for development, utilization, documentation, verification, and validation of models and codes either directly or by reference to other sections,

(4) shown directly in this section or elsewhere that codes are either publicly available or, if proprietary, are readily available to the NRC, and

(5) identified and described tests and analyses which will yield information concerning the host rock and environment necessary for repository design.

III. REVIEW PROCEDURES

The staff review is conducted in two phases. The first is the acceptance review of the SCP to evaluate its completeness based mainly on the acceptance criteria in Section II. In the second phase, a more thorough review is made, examining the SCP to see that

(1) reasonable interpretation has been made of existing data;

(2) anticipated results are achievable; and

(3) existing uncertainty levels will be reduced.

The following sections present considerations to be kept in mind during the second phase of the review.

8.3.2.1 Overview

The following discussion addresses general considerations which should be kept in mind when reviewing the overview section. Discussion areas are:

(1) zone of influence;
(2) end effects;
(3) test sequencing; and
(4) scoping calculations.

Zone of Influence — The concept of zone of influence is important in the site characterization process because it may provide considerable simplification in the interpretation of results. The discussion of this concept with regard to mechanical stress which follows is based largely on Brady and Brown (1985). The essential idea of a zone of influence is that it defines a domain of significant disturbance. It differentiates between the near field and far field of a perturbation. The perturbation may be a change in stress conditions (i.e., generation of an opening) or a change in thermal conditions (i.e., introduction of a heat source). The extent of an opening's effective mechanical near-field domain can often be examined using a two-dimensional elastostatic analysis. For example, the stress distribution around a long circular hole of radius r in the hydrostatic stress field of magnitude p is given by the Kirsch solution as

$$\sigma_{rr} = p \left[1 - (a/r)^2 \right]$$

$$\sigma_{\theta\theta} = p \left[1 + (a/r)^2 \right] \qquad (1)$$

Using the Kirsch solution, it is readily calculated that, for

$$r = 5a, \ \sigma_{\theta\theta} = 1.04p, \text{ and } \sigma_{rr} = 0.96p$$

(i.e., on the surface defined by r = 5a), the state of stress is not significantly different (within ± 5%) from the field stresses. The general rule is that openings lying outside one another's zones of influence can be analyzed by ignoring the presence of all others. For example, for circular openings of the same radius, a, in a hydrostatic stress field, the mecnanical interaction between openings is insignificant if the distance between their centers is greater than or equal to 6a. It is important to note that, in general, the zone of influence of an opening is related to both excavation shape and pre-mining stresses. It should also be noted that, in markedly anisotropic rock, or for plastic discontinuous behavior, the influence zone could be larger than predicted by elastic analysis.

Similar considerations can be made for the zone of influence of heat sources, although the problem is not as straight forward for thermoelasticity because temperatures and stresses are a function of time. Nevertheless, results for simple problem geometries are easily obtainable and useful in assessing the zone of influences.

For example, an estimate of the radius of influence can be obtained from the expression [Carslaw and Jaeger (1959), p. 257]:

$$\frac{T_r}{T_o} = e^{-(r^2/4Kt)} \qquad (2)$$

where T_r = temperature of radius r,

T_o = temperature at radius r=0,

r = radius,

K = diffusivity, and

t = time.

If it is assumed that t = 10 years, K = 30.6 m²/year and R = 70m, then Eq. (2) indicates that the temperature at 70 meters will be less than 2% of the temperature at r=0.

In addition, Hart (1981) presents analytical solutions for temperature, stresses, and displacements due to exponentially-decaying or constant, infinite line heat sources. Nowacki (1962) presents the analytical solution for the case of an instantaneous point heat source in an infinite region. Temperatures and stresses at a time of 10 years, shown in Fig. 1, result from application of a point pulse heat source for 0.1 years. The figure shows that, for this very particular case, the zone of influence is limited to about 2 meters. For more complex problem geometries, numerical analysis may be considered to determine the zone of influence.

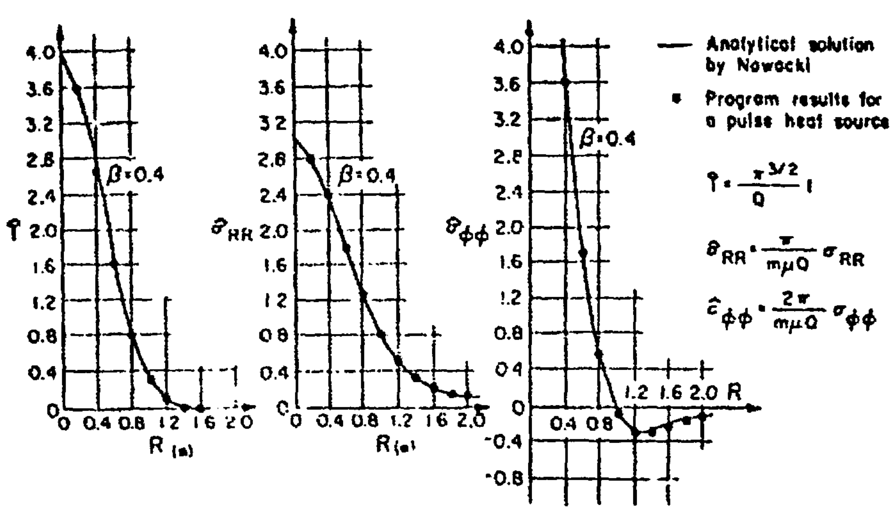


Fig.1 Temperature and Stresses Resulting From an Instantaneous Heat Source (comparison between Nowacki's published solution and that obtained using STRES3D) [St. John and Christianson, 1980]

<u>End Effects</u> — End effects are significant for three major reasons: (1) two-dimensional analysis of test results is appropriate only if ends are sufficiently distant, so that stresses and displacements vary only in the plane of analysis; (2) confirmation of stability of excavations requires that the beneficial effect(s) of a near-by end not be present; and (3) measurements of convergence, among others, requires recognition that some displacement may occur before it is feasible to install instrumentation.

An estimation of the longitudinal extent of the zone around the heading of a circular excavation (for a hydrostatic stress initial stress state) within which the ground mass stress and radial displacement magnitudes are functions of the longitudinal position relative to the tunnel face has been made by Ranken et al. (1978). These authors concede that it is difficult to delineate precise boundaries that separate the transition zone from the undisturbed ground ahead of the excavation and the final equilibrium state behind the face, because the boundaries are not indicated by abrupt change in medium behavior. Nevertheless, the authors suggest that the picture obtained from available data is that of a transition zone of 3-D response extending over a total distance of approximately six times the maximum radius of the plastic zone, R, that forms around the unlined tunnel. If no plastic yielding occurs, this distance is approximately 6a, where a is the tunnel radius. Figure 2 illustrates the longitudinal extent of the zone and its relation to the position of the advancing tunnel face.

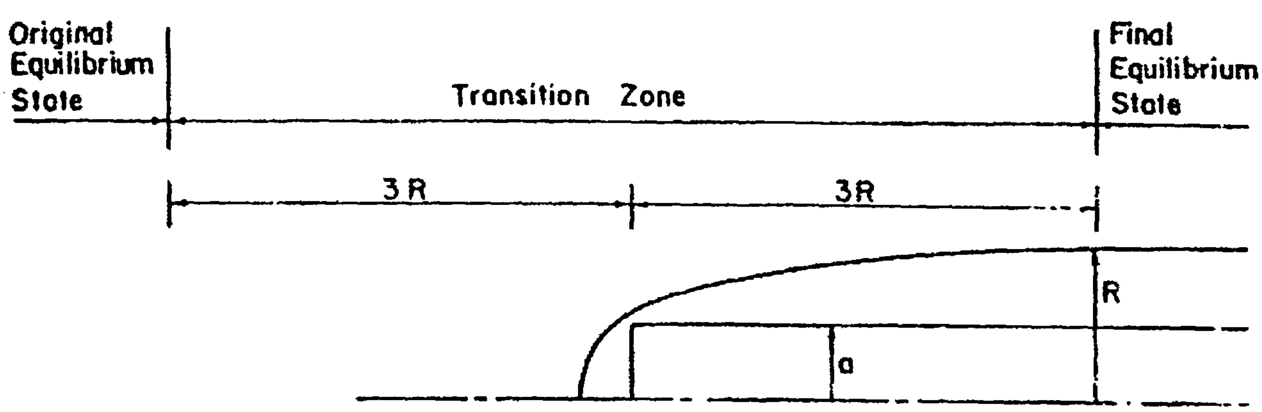


Fig. 2 Transition Zone of Three-Dimensional Variation of Stress and Displacement — Tunnel Lined Far Behind the Face (Ranken et al., 1978)

Ranken et al. (1978) make similar observations for excavations lined near the face which indicate that the liner significantly influences the longitudinal extent of the transition zone They estimate that this zone extends out ahead of the excavation to a distance of about 3 radii of the plastic zone which forms around the lined tunnel and to a distance of ohe tunnel radius behind the leading edge of the liner.

As a practical application of this concept, consider the proposed layout at the 1200 ft ES Main Test Level (U.S. DOE, 1985), as shown in Fig. 3. This figure indicates that the longitudinal extent of cross-sections B and C is insufficient to reach the desired final equilibrium state.

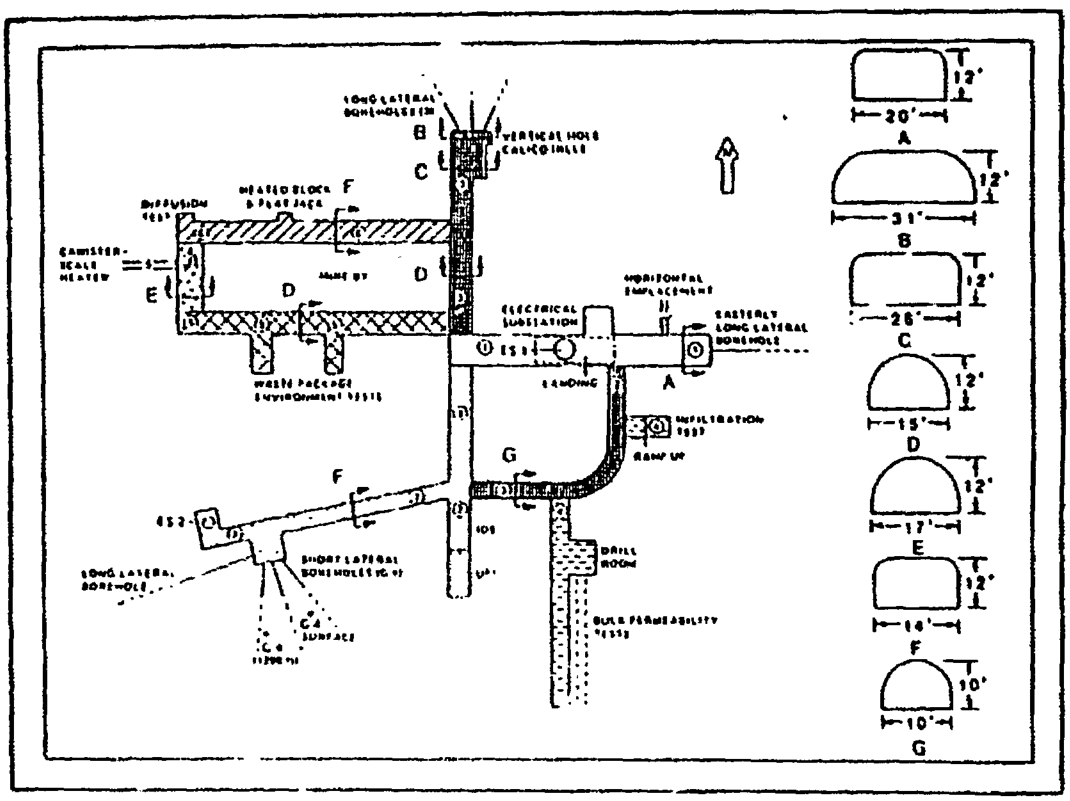


Fig. 3 Proposed Layout at the 1200 ft. ES Main Test Level [U.S. DOE, 1985]

Test Sequencing — For the NNWSI, testing sequence and duration are of critical importance, especially with regard to time-dependent properties. The following quote from Blacic et al. (1986) provides the rationale for determining time-dependent properties.

> A quantitative determination of these time-dependent phenomena will require careful measurements on target-horizon tuff samples held at simulated repository conditions for long time periods. For example, it is not known what effects might be anticipated during heating and cooling cycles in unsaturated devitrified tuff such as the Topopah Spring Member, which is the potential host rock at Yucca Mountain. Detailed examination of tested samples should identify the physical-chemical mechanisms involved. In addition, the difficult task of determining the rates of the processes leading to changes in mechanical properties will be required. Once these rates (or at least reasonable estimates) are determined, they can be incorporated in design and performance models to predict or bound the mechanical response of the host rock mass over both the operational time of the repository and after closure.

The logical result of this, and the concern expressed in the GTP is that tests which are intended to assess time-dependent properties, such as strength, be initiated as early as possible in the testing program and be allowed to continue through the performance confirmation period.

Scoping Calculations — A set of scoping calculations should be presented for each field test planned. These calculations should bound the likely temperatures, displacements, and stress fields. The purposes of such calculations include:

(1) provision of instrumentation which is capable of making measurements in the predicted range of response in the instrument environment;

(2) provision of a framework for planning, executing, and interpreting the instrumentation program; and

(3) provision of preliminary estimates of response for comparisons with observed measurements required for validation by section 8.3.2.5, Repository Modeling.

8.3.2.2 Verification or Measurement of Host Rock Environment

According to the Annotated Outline, this section "will identify and describe the site characterization program tests and analyses which will define the geologic/geotechnical environment of the host rock for three conditions:

(1) pre-waste emplacement;
(2) post-subsurface excavation; and
(3) post-waste emplacement.

All tests and analyses will likely yield some relevant data (e.g., rock mass modulus, joint spacing, etc.) important for each condition. However, some tests are specifically designed to characterize the geomechanical host rock environment for each of these conditions, as shown in Table 2.

All tests involving heat would be used to characterize the post waste emplacement condition. Many of these tests are discussed in more detail under Coupled/Interactive Tests.

The following discussion addresses general considerations which should be kept in mind when reviewing the section on verification and measurement of host rock environment. Discussion areas are:

(1) in-situ stress measurement;
(2) convergence monitoring;
(3) heading directions for exploratory drifts;
(4) mine-by evaluation;
(5) construction-related observations;
(6) block test;
(7) plate load tests;
(8) slot strength testing; and
(9) rock mass mechanical strength

Table 2

PROPOSED TESTS AND HOST ROCK GEOMECHANICAL CONDITIONS TO BE SIMULATED

TEST	Pre-Waste Emplacement	Post-Subsurface Excavation	Post-Waste Emplacement
In-Situ Stress Measurement	1	3	3
Convergence	3	1	3
Mine-By	3	1	3
Construction-Related Observations	3	1	3
Plate Load Test	3	1	2
Slot Strength Test	3	1	2
Canister-Scale Heater	3	3	1
Small-Scale Heater	3	3	1
Heated Block	3	2	1
Room-Scale Thermomechanical	3	2	1

KEY: 1 = primary use
2 = secondary use
3 = relevant data

In-Situ Stress Measurement — In-situ stress measurement methods developed to date exploit two separate and distinct principles in measurement methodology. The most common procedure is based on determination of strains in the wall of a borehole, or other deformations of a borehole, induced by overcoring. Suitable gauges for such borehole measurements include USBM gauges, CSIRO gauges, or door-stopper gauges. If sufficient strain or deformation measurements are made during the stress-relief operation, the six components of the field stress tensor can be obtained directly from experimental observations using solution procedures developed from elastic theory. A direct consequence of this is that, at a minimum, Young's modulus and Poisson's ratio for the rock must be known or assumed. In using a triaxial strain cell, six independent observations must be made of the state of strain in six positions/orientations on the hole wall. From this, six independent simultaneous equations of the following form may be established:

$$[A]\{p\} = \{b\} \tag{3}$$

where {p} represents a column vector of the six stress components. The position/orientations of the strain observations must be selected to ensure a well-conditioned coefficient matrix [A] (Brady and Brown, 1985). Redundant observations should be made to determine a logically averaged solution for the field stress tensor. These should be used to determine a locally averaged solution for the ambient state of stress in the zone of influence of the stress determination.

Determination of the state of stress in a jointed and fractured medium, such as found at Yucca Mountain, will likely be complicated by the spatial heterogeneity of the stress distribution. Results of a comprehensive program of measurement of in-situ stress state reported by Brady et al. (1986) suggest that stresses may be locally "locked in" and that, if field measurements are made at spacings less than the mean spacing of joints, the results may not be representative of the average in the medium.

Errors in absolute stress measurement with borehole deformation gauges are believed to be 20 to 100% in magnitude and 10 to 25% in direction (Hall and Hoskins, 1972). The primary source of error is in the assumptions required to convert deformations to stress rather than in the functional operation of the gauge (Pratt and Voegele, 1984).

The second type of procedure is represented by flatjack measurements and hydraulic fracturing. The flatjack method requires:

(1) a relatively undisturbed surface of the opening constituting the test site; and

(2) a rock mass which behaves elastically in that displacements are recoverable when the stress increments inducing them are reversed.

These requirements eliminate this method as a method at NNWSI if excavations are developed by drill and blast.

Hydraulic fracturing, on the other hand, is, in some sense, more simple than the overcoring method in that the elastic properties of the rock do not need to be measured or assumed. However, uncertainty as to interpretation of the fluid pressure-flow behavior during crack initiation and propagation (e.g., the effects of changing fracture path, and changing permeability and fluid penetration into the rock as the hole is pressurized) result in an associated uncertainty in the calculation of maximum and minimum stresses. The fundamental assumptions in analysis of hydraulic fracturing results are that a principal stress is parallel to the borehole axis, the tensile strength of the rock can be determined, and the rock is isotropic and elastic.

Pratt and Voegele (1984) reviewed laboratory tests of hydraulic fracturing by others and concluded that the tests predicted the maximum horizontal stress to within ± 25%, vertical and minimum horizontal stress to within ±10%, and the stress orientation to within ±10%. They also suggest that the percentage error in the minimum horizontal stress may be dependent on the ratio of horizontal stresses and the magnitude of the minimum stress.

In reviewing the significance of in-situ stress measurement in rock mechanics, Fairhurst (1986) concludes by stating that "Difficulties of interpreting the in-situ measurements, especially in the practically important situations where discontinuities and inhomogeneities in the rock mass have a significant but uncertain influence, make the focus on stress-determination unrewarding."

He argues that a more effective design strategy is to give greater emphasis to the overall effects of interaction between stress state, rock mass properties, and excavation geometry. Convergence measurement, described in the next section, is the primary example of such an integrated effect.

<u>Convergence Monitoring (Shaft and Exploratory Drifting)</u> — The effects of spatial variability of the rock mass can often be determined by exploratory drifting and measurement. At NNWSI, the primary sources of spatial variability will likely result from differences in discontinuities, faults, and lithophysal content. It therefore is desirable that the exploratory drifting experience as wide a range of conditions as possible within the obvious limitations on drifting length. Ideally, the amount of actual drifting should be governed by the repeatability of ground conditions and/or the ability to confidently predict rock mass response. Other considerations affecting the amount of exploratory drifting are discussed in Gates et al., 1983 (NUREG/CR-2959, pp. 12-13).

At a minimum, the convergence monitoring should consist of the following.

1. Measurements at regular intervals (or closer, as ground conditions vary) of closure points from roof to floor and wall to wall should be made to provide a time history of opening displacements.

2. Rod extensometers with 5 or 6 anchors drilled radially in the roof and walls should be installed at larger intervals. The furthest anchor should be installed outside the zone of influence of the excavation. The extensometers should be installed at the face— preferably, from a previous excavation.

Displacement measurements are valuable when measurements are taken regularly throughout the entire excavation period. Additionally, interpretation of measurements is enhanced by supplemental information, including visual observations, borescopic examinations, cross-hole ultrasonic velocity measurements, geologic mapping, construction records, and periodic testing of roofbolt anchorage (if used).

A valuable discussion of the advantages and disadvantages of 13 displacement measuring instruments is provided by Pratt and Voegele (1984). These authors also provide similar discussions of stressmeters used to measure increases in compressive stress. Measurements of increases in compressive stress surrounding excavations should be made to confirm results predicted by numerical analysis.

The analysis of recorded data is discussed extensively by Cording et al. (1975). Interpretation of displacement-time and displacement-depth plots for extensometers installed in a tunnel are shown in Fig. 4. The measurements for Case A would be obtained if all of the rock movement involved separation planes A. Measurements such as shown for Case B would be obtained if separation occurred on both planes A and B. Measurements indicated by Case C would be obtained if the block bounded by planes B and B' were to move into the opening. Figure 5 shows typical extensometer data for two chambers in tuff at the Nevada Test Site. "The tuff was of excellent quality, massive, and almost unjointed" (Cording et al., 1975). Elastic displacements were computed using both finite element and closed-form solutions for the increment of excavation taking place after the extensometers were installed.

Single-heading excavations provide a very simple initial geometry for model comparison. As excavations proceed, it should be possible to narrow in on the required rock mass properties and in-situ stresses for bounding the measured response. If the excavations are small (approximately 3mx3m), it is likely that significant inelastic response will not be observed. Significant inelastic response will require excavation of larger cross-section or introduction of thermal stresses.

If the exploratory drifting is done with relatively small excavations, it will be necessary, at some point, to excavate larger cross-sections to confirm the stability of the prototype-sized excavations. These confirmations may be done as single heading excavations, or mine-by excavations, as discussed later.

Another use of the experimental drifts is in characterizing discontinuities through back analysis of block fall-out in unsupported areas. This approach has been used previously (e.g., Yow, 1986). It may also be possible to characterize joint properties by studying blocks which do not fall.

The issue of cross-sectional size of exploratory drifts is of fundamental importance to NNWSI. Certainly, full-size drifts afford the best opportunity for characterization. However, it is doubtful that it can be shown that full-size drifts are required everywhere for characterization purposes. It appears that DOE-Nevada wants to use full-size drifts everywhere, but DOE-Headquarters wants to keep the cost down. NRC is likely to be asked to given an opinion on this.

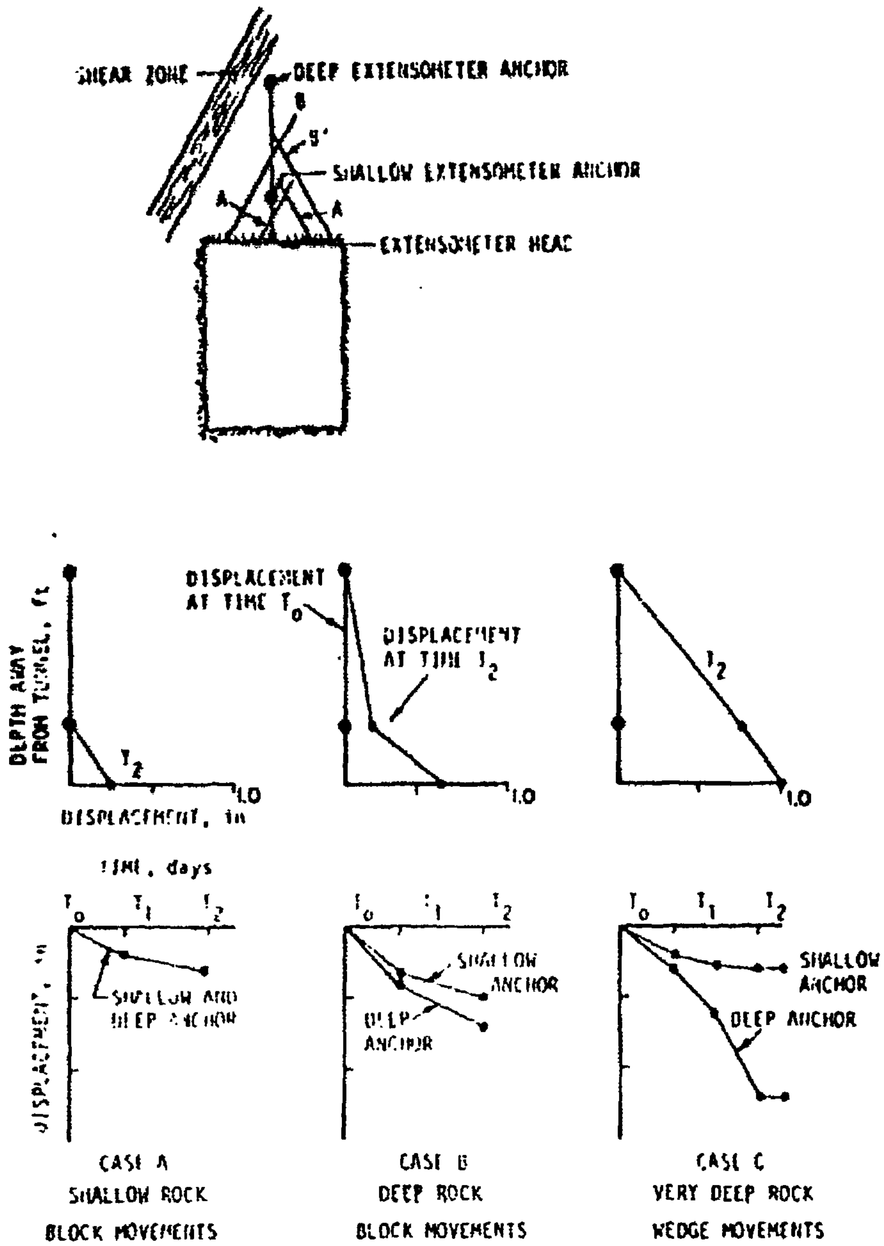


Fig. 4 Examples of Displacement-Time and Displacement-Depth Behavior for Extensometer Data [Cording et al., 1975]

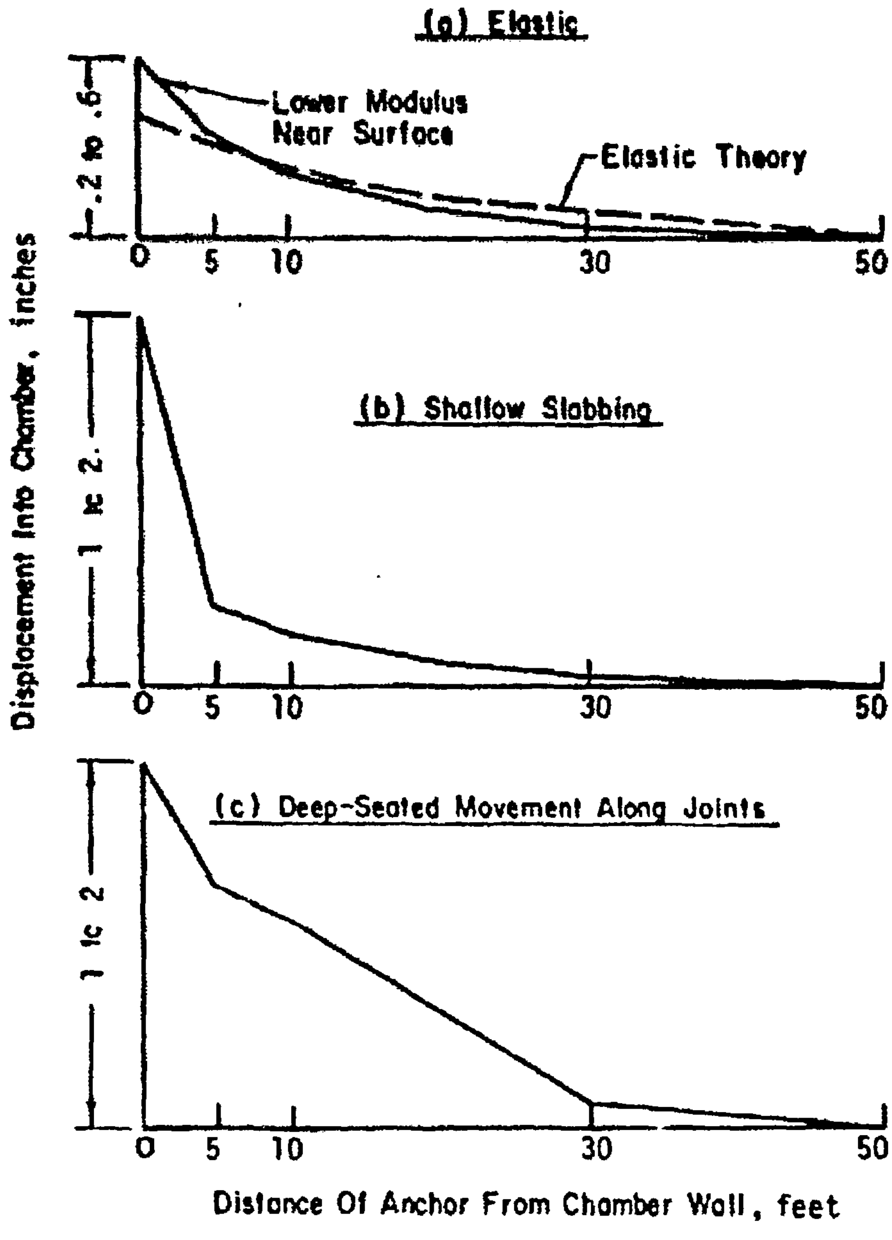


Fig. 5 Typical Displacements in a Large Deep Rock Chamber [Cording et al., 1975]

Heading Directions for Exploratory Drifts — Choices for heading direction of exploratory drifts may be governed by the following considerations.

1. If the directions of the proposed repository excavations are determined by criteria such as available space, ventilation requirements, etc., the exploratory drifts should parallel or coincide with the proposed repository excavation directions.

2. If certain underground features such as suspected faults or high lithophysal zones are to be explored, the exploratory drifting may be governed by the necessity to reach targeted areas.

3. In the absence of (1) and (2), some excavations may be oriented parallel and perpendicular to measured principal stresses. Analysis of excavations not directed parallel to principal stress components must take into account the antiplane stresses. The significance of the antiplane problem is described by Brady and St. John (1982).

4. In order to bound the range of likely stability conditions, a three-dimensional stability analyses may be made using the orientations of discontinuities mapped in the exploratory shaft. Such an analysis will predict heading directions which will likely encounter the greatest and least stability problems from a limit equilibrium point of view. Each of these directions may be investigated by exploratory drifting.

Mine-By (Sequential Drift-Mining) Evaluations — From the geomechanics point of view, mine-by tests can be seen as an extension of the exploratory drifting program. The objectives (purposes) cited by Vieth et al. (1985) for conducting sequential drift-mining evaluations are:

(1) to validate a geomechanical model based on measurements taken during drift mining for use in establishing predictive capabilities for repository design activities;

(2) to define limits for the relaxed zone around a drift using exploratory borehole and mechanical measurements in order to enhance repository designs;

(3) to continue and improve mining evaluations started during the Demonstration Breakout Room (DBR) Testings; and

(4) to relate air and water permeability measurements to each other for reference in hydrological calculations.

The first three of these objectives concern geomechanics issues. These three objectives are also addressed by careful convergence monitoring of shaft and exploratory drifts. The question to be asked, then, is what can be learned from a mine-by test that can not be learned (from the geomechanics point of view) from other methods. The obvious advantage of a mine-by is that instrumentation may be installed in the rock mass region that forms the second excavation.

In order for meaningful and useful results to be obtained, an assessment must be made of how important displacements ahead of the face differ from what would be predicted by elastic analysis. Such an analysis of radial displacements around a shallow tunnel in a weak frictional-cohesive material indicated that radial displacements at the face (Fig. 6) were not significantly different than the elastic displacements (Ranken and Ghaboussi, 1975). The fundamental assumption in such an analysis is that the rock behaves as a continuum. If continuum analysis is not appropriate, then both the results and analysis are likely to be very site specific.

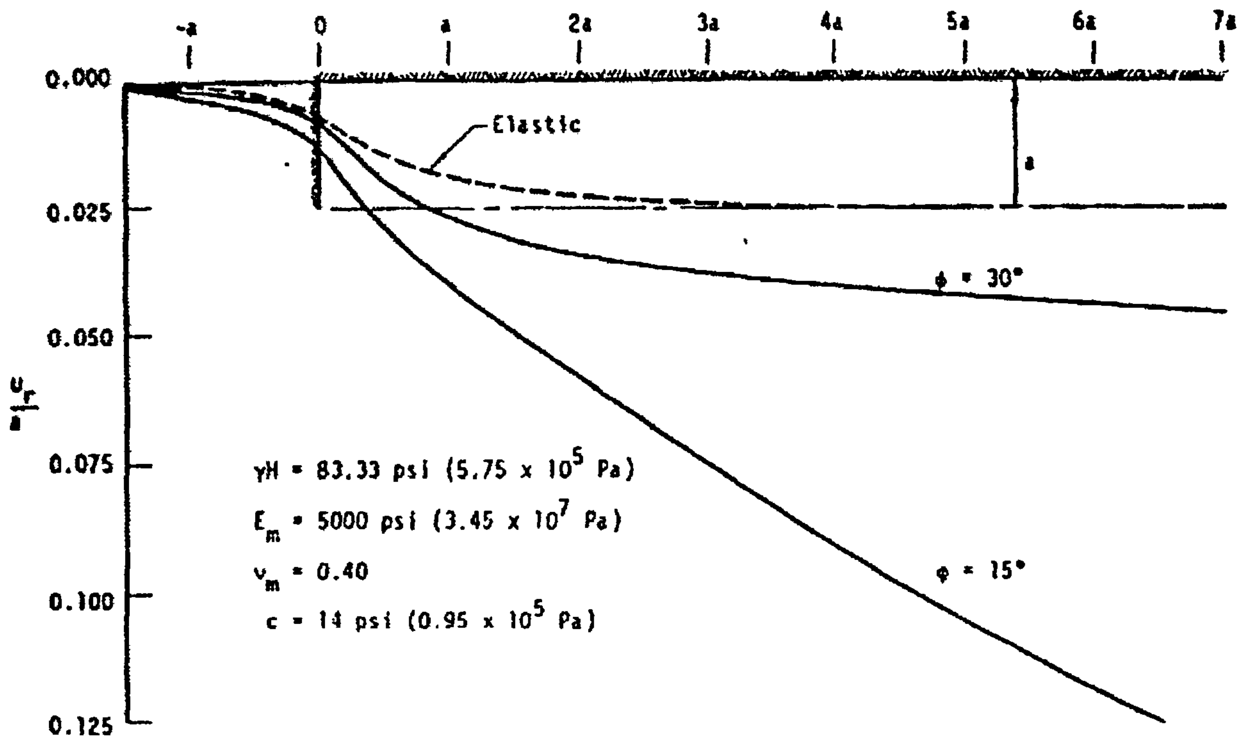


Fig. 6 Radial Displacements for an Unlined Tunnel in an Unlined Tunnel in an Elasto-plastic Medium — φ not equal to 0 [Ranken and Ghaboussi, 1975]

The prospect for obtaining meaningful geomechanical results from a mine-by test at NNWSI, therefore, relates to three major considerations:

(1) how important is characterizing behavior ahead of the face of an excavation;

(2) how representative the selected site(s) is(are) compared to the rest of the sites; and

(3) how important is providing a significantly different loading condition (i.e., pillar-type loading). If excavations are located close enough to each other to interact, a pillar-type loading results. This is important in model qualification because it is possible that some models may simulate single excavations well but might not represent multiple excavations well.

If a mine-by test is selected, it is advisable for several holes to be drilled completely through the pillar to measure absolute drift to drift convergence. This should eliminate questions related to horizontal displacement orientation as experienced in the Climax Spent Fuel Mine-by.

<u>Construction-Related Observations</u> — The near-field behavior of rock masses around excavations is affected not only by the physical properties of the rock mass and in-situ stresses but also by the construction activities related to generation of the excavation. Cording et al. (1975) give the following list of items which should be recorded at a minimum for construction-related observations:

(1) opening dimensions;

(2) amount of advance/round;

(3) overbreak (shape of perimeter, size of overbroken zone);

(4) orientation and pattern of blastholes, type of explosive, detonation and delay method used, total amount of powder, amount of powder in each delay, amount of powder in each hole, spacing and loading of perimeter holes, sequence of delays, length of holes; stemming, changes in procedures (Note: This information is usually available in a standard blasting report, but modifications often occur. See, for example, Climax Mine-By Test);

(5) support (weight, spacing, time of installation in the round, method of installation); and

(6) water conditions.

Block Test — Previously discussed tests (i.e., the mine-by tests and exploratory drifting) are limited in their usefulness by the fact that the far-field boundary conditions are not known and the geometry of discontinuities is not well known. Block tests seek to simplify the analysis procedure by studying the behavior of a small volume of rock with prescribed conditions. A primary focus of such tests is the evaluation of the rock mass constitutive model. Equivalent continuum constitutive models usually do not perform well in areas of high stress gradients and, therefore, any block test should, during the course of testing, seek to impose a high stress gradient on the block for evaluation with the constitutive model. Other block test requirements (suggestions) are presented by Zimmerman et al. (1986) and are based on results of the G-Tunnel Heated Block Test.

One question that must be asked is what new information can be obtained by performing a block test at Yucca Mountain beyond what was learned at G-Tunnel. Certainly, if the test were conducted in a rock mass containing a high lithophysal content, then supplemental information beyond the G-Tunnel data might be obtained.

Plate-Loading Tests — The ISRM suggested method for performing a plate load test is given by Brown (1981). The authors suggest using a loaded area of about 1m in diameter but do not recommend an ultimate load capacity for obvious reasons. The relative merits of plate load tests are given by Stagg and Zienkiewicz (1974).

The fundamental purpose of in-situ testing is to influence such a large volume of rock that the results obtained will be representative of that region of the rock mass. Ideally, this requires that the linear dimension of the loaded areas be large compared to the discontinuity interval. With the ISRM suggested loaded area, the rock which will be effectively influenced is of the order of 1 to 2 meters, which may not be appreciably greater than the depth to which the rock has been disturbed during excav··ion operation. Results from tests on areas much smaller than ·his are liable not be to representative and will probably be closer to those obtained from laboratory tests on samples.

The magnitude of applied load is largely dependent on the size of the loaded areas—the load must be great enough to give reasonably measured deformations [Experimental errors greater than 0.01mm can invalidate test results when the rock mass modulus exceeds $3.5x10^4$ MPa (Benson et al., 1969)]. Typical reported loads used are 300 tons over an area of $1m^2$ and 720 tons over $1.2m^2$ (Stagg and Zienkiewicz, 1968).

An alternative to a plate load test is to use a cable-jacking test. The advantage of this test is that higher loads applied over larger loaded areas may be used, thus allowing a larger rock volume to be influenced. Loads of up to 1000 tons can be applied by using a single cable. A typical model is shown in Fig. 7.

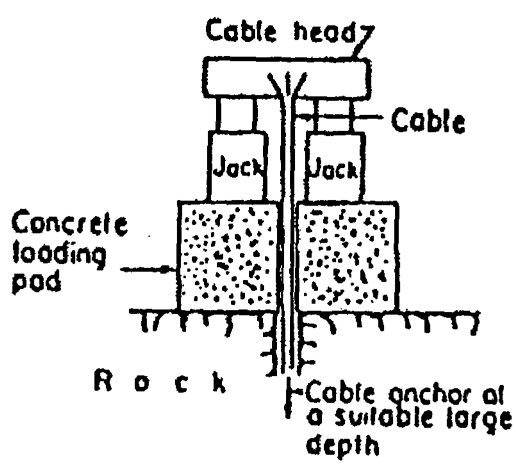


Fig. 7 Cable-Jacking Test [Stagg and Zienkiewicz, 1968]

With two adjacent cables (Fig. 8), loads tangential to the surface can be applied and information obtained about the variation of deformation moduli with direction of load.

Even if the rock mass is not highly anisotropic, a larger rock mass will be loaded using a double-cable system.

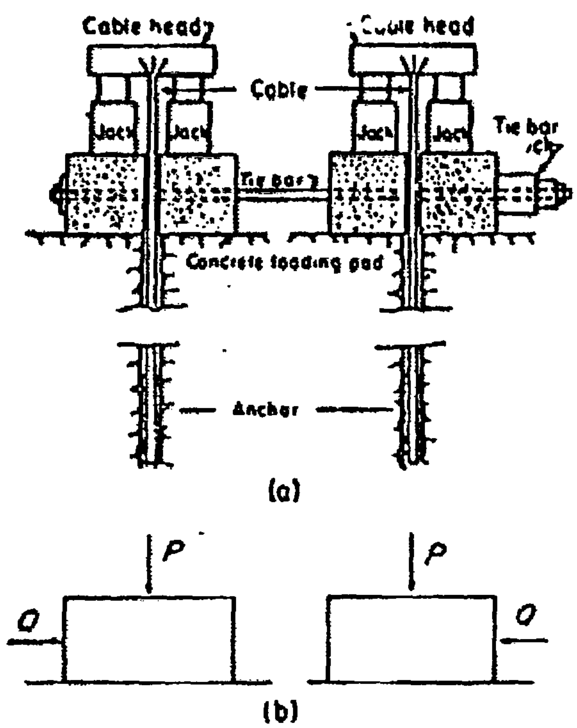
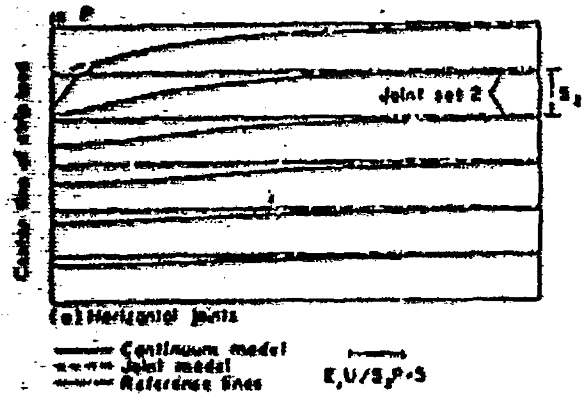


Fig. 8 The "Double-Cable" Test: (a) test arrangement; (b) diagrammatic loading [Sta., and Zienkiewicz, [1968]

Again, one reason which may be cited for conducting such tests is that they provide a basis for comparing equivalent continuum with discontinuum concepts. Differences in elastic behavior for plate-loading type situations are given by Singh (1973)—see Fig. 9. This figure shows that the differences between the continuum and discontinuum assumptions increase with decreasing shear deformational response (assuming the normal deformational response is unchanged).

Similar comparisons can be made for inelastic response as shown by Cundall and Fairhurst (1986) in Figs. 10 and 11.



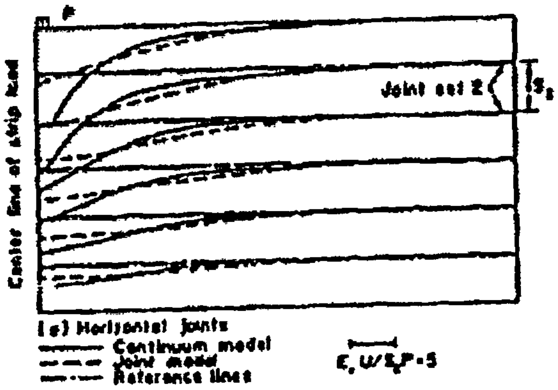


Fig. 9 Comparison of Vertical Displacements Beneath a Simulated Plate Load Test for Two Assumptions Concerning Material Behavior (i.e., continuum model and discontinuum model. In (a), the joint normal stiffness is assumed to equal the joint shear stiffness; in (b), the joint normal stiffness is assumed to be ten times greater than the joint shear stiffness) [Singh, 1973]

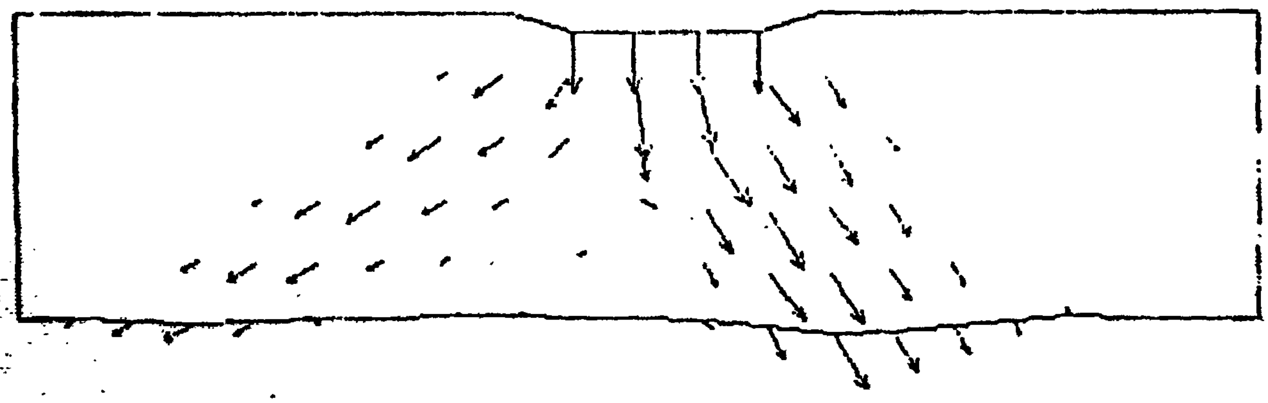


Fig. 10 Displacement Vectors and Boundary Deformation Resulting From Rigid Die Penetration Into a Ubiquitously-Jointed Continuum [Cundall and Fairhurst, 1986]

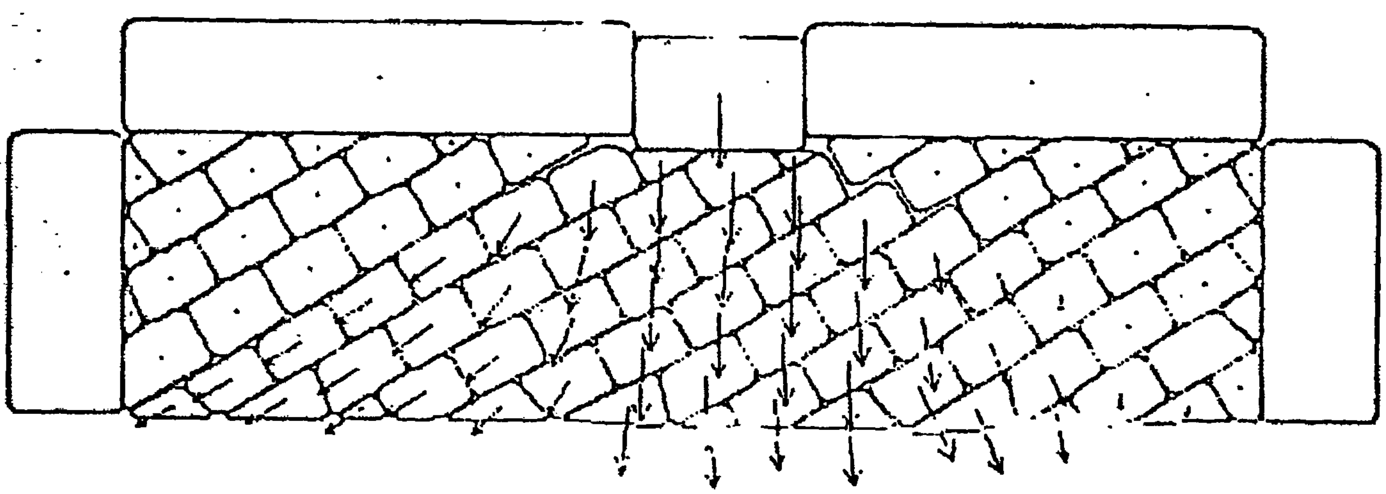


Fig. 11 Velocity Vectors and Displaced Block System Resulting From Rigid Die Penetration Into a Discontinuum (Compare to Fig. 10) [Cundall and Fairhurst, 1986]

In Fig. 10, a continuum model with "ubiquitous joints" is used. This constitutive model causes each element to act as if it contains a large number of slip planes oriented at given angles (in this case, 30°). As shown in this figure, shear bands extend along 30° lines while other bands extend from the point at right angles to the first. In Fig. 11, the simulation is repeated with a program which models assemblages of rock blocks. The joint friction angle and bounding conditions are identical to the continuum case discussed previously. Figure 11 shows that the movement is diffused over a large area and that shear bands do not form. The comparison of the two simulations demonstrate that ubiquitous joint simulations can be misleading as finite joint spacings can give rise to moments which resist the imposed distortions.

Slot-Strength Testing — The slot strength tests (Vieth et al., 1985) represent a new concept in strength testing. In theory, the slot strength test can supply significantly higher stress loads than the plate-loading test. A relatively undisturbed surface of the opening constituting the test site is required for successful application of the method. If such a site is found, interpretation of results is complicated by:

(1) complex 3-D problem geometry requiring 3-D analysis; and

(2) unknown or assumed state of stress around the excavation in which the test is to be conducted.

In view of the foregoing, slot strength testing must be considered a supplemental test for experimental purposes.

Rock Mass Mechanical Strength — Before addressing discussion of rock mass mechanical strength, it will be very important to determine what exactly needs to be known concerning rock strength in order that only those components of rock strength which are in question be addressed. Keep in mind that the "determination of the global mechanical properties of a large mass of discontinuous in-situ rock remains one of the most difficult problems in the field of rock mechanics" (Brady and Brown, 1985).

Because the stated objective of testing in this section is "measurement of the geologic/geotechnical properties necessary to model the repository design" (Annotated Outline, p. 59), it will be important to know which types of models are being considered and, more particularly, how the discontinuities in the rock mass are to be considered.

Classically, rock mass strength is viewed as consisting of two components: (a) strength of intact rock; and (2) strength of discontinuities. Three fundamental approaches may be considered for combining these two strength components.

(1) Empirical Approach

The most completely developed of the empirical approaches is that introduced by Hoek and Brown (1980). These authors give a strength criterion which would predict failure stresses for the rock mass. Unfortunately, their criterion did not include tuff nor does it describe the behavior of the material after failure. Application of this criterion to Yucca Mountain would require introducing nu-r--ous rock mass failures to develop an empirical ... base.

It ·ould be noted that values given in Table 12 of Hoe. and Brown (1980) may be extremely pessimistic (conservative)—i.e., the lower strength values are far too low and unrealistic (see, for example, St. John and Kim, 1986).

(2) Equivalent Continuum

In this approach, behavior of the intact rock and discontinuities are combined based on the theory of composite materials. Therefore, the joints are considered as a different material from the rock.

(3) Discontinuum Models

This approach considers the behavior of the intact rock and boundary interactions (joints) between intact rock separately.

Both of the latter two approaches require characterization of the intact rock material and the discontinuities. Note that it may be possible to use (3) to develop formulations for either (1) or (2).

Again, the type of model to be used will, to some extent, determine the requirements for testing. The most common strength criteria used for intact rock is the linear Mohr-Coulomb criterion, which requires determination of cohesion and internal friction angle from a series of triaxial test results. In order to model dilatant behavior, the dilatency angle must also be defined.

Brady and Brown (1985) suggest that, although widely used, Coulomb's shear strength criterion is not always a satisfactory criterion for rock material. They cite the following three reasons for this.

1. It implies that a major shear fracture exists at peak strength. Observations such as those made by Wawersik and Fairhurst (1970) show that this is not always the case.

2. It implies a direction of shear failure which does not always agree with experimental observations.

3. Experimental peak strength envelopes are generally non-linear. They can be considered linear only over limited ranges of σ_n or σ_3.

Part of the site characterization process should include a justification for the strength criterion used in the numerical model.

Discontinuity properties to be defined at a minimum include the normal stiffness, shear stiffness, cohesion, friction, and dilatency angle. An important consideration here is that any laboratory discontinuity testing should include constant normal stiffness shear tests as well as constant normal stress shear tests. The reason for this is that, whereas constant normal stress tests may reproduce discontinuity behavior adequately in the case of sliding on an unconstrained block of rock from a slope, it may not be suited to the determination of stress-displacement behavior of discontinuities isolating a block in the periphery of an excavation.

A quantitative description of the structure of the rock mass (which contributes to the strength of the rock mass) is accomplished through measurement or observation of the following discontinuity parameters (Brown, 1981):

(1) orientation;
(2) spacing;
(3) length (extent in 2-D);
(4) continuity;
(5) surface roughness;
(6) equivalent compressive strength of adjacent walls;
(7) aperture;
(8) infilling material; and
(9) water conditions.

In addition, the number of joint sets and characteristic features should be reported. Some of these parameters (i.e., continuity, roughness and equivalent compressive strength of adjacent walls) are exceedingly difficult to measure—especially underground.

Finally, some attempts have been made to measure rock mass strength in situ. Heuze (1980) presents a summary of in-situ rock strength testing. The reported tests are both bearing capacity and compression tests. The author was not able to reach a general conclusion concerning minimum test size for bearing capacity tests. With regard to compression tests, Heuze's 1980 data does not contradict previous observations by Bieniawski (1978), who observed that no further strength decrease occurs in tests with cube edges exceeding 0.5m. These observations are made on a very limited amount of data and do not imply that the strength testing beyond 0.5m is not needed.

8.3.2.3 Coupled Interactive Tests

In reviewing this section, one issue to be addressed is the extent to which the coupled processes need to be characterized. From the waste isolation point of view, characterization of the effect of coupled processes on radionuclide flux may not be possible or significant enough to warrant detailed definition through field testing. However, with regard to waste containment (e.g., canister loading) and retrievability (i.e., emplacement hole/liner and room stability), characterization of the thermal/mechanical/hydro/chemical environment through testing is desirable and technically more feasible.

The coupled processes are of greatest significance when in close proximity to the excavations and heat sources. The majority of non-linear effects occur in these areas of high temperature and stress gradient. The ability to describe these coupling processes on a large scale through the use of small-scale field testing is open to question. The reliability of tests without independent control of the various coupling parameters and without the ability to characterize the rock mass in detail is probably poor. An important consideration here is the concept of a "disturbed zone", which was introduced in 10CFR60 because it was recognized that adequate characterization of the behavior of that portion of the rock mass subject to high temperature and stress gradients may not be possible.

From the waste isolation point of view, it may be reasonable for the site not to take credit for the performance of the disturbed zone where the uncertainties in measurement and evaluation exist. Coupled interactive in-situ testing may, instead, focus on accurately understanding the performance of those components of the natural and engineered systems which affect waste containment and retrievability. These tests should be carried out under conservative ranges of temperature and stress conditions to bound the possible range of rock mass response.

The proposed coupled interactive tests related to the area of design/rock mechanics include:

- small-scale heater experiment
- canister(full)-scale heater experiment
- heated block test.

Previous tests at G-Tunnel have shown that the laboratory measured values for thermal expansion coefficient and thermal conductivity compared closely to those determined for the heated block test (Zimmerman et al., 1986). If it can be shown that a similar relation exists at Yucca Mountain, then the task of extrapolating these parameters throughout the repository will be simplified (i.e., possibly requiring only the laboratory testing of the range of materials expected to be encountered). It should be noted that none of the testing will likely be of sufficient duration to address the issue of temperature effects on compressive strength. This effect will need to be studied beyond the end of the site characterization period.

For the first two test types, a detailed description of the parameters to be evaluated, test methodology, limitations, reliability, recommended test program, and potential advancements in the state-of-the-art are given by Roberds et al. (1983). Significant considerations for these tests in tuff are presented in the following paragraphs.

Small-Scale Heater Test A small-scale heater test is planned for the high lithophysal-rich tuff to determine whether laboratory properties are sufficient for input to a thermal model of such rock (Vieth et al., 1985).

The limitations of the small-scale heater test include the following:

(1) effects of stress dependence on thermal or thermomechanical properties not evaluated;

(2) the rock volume affected may not be representative of the rock mass at the repository scale; and

(3) properties may be evaluated only over a relatively short time interval.

Reliability of the small-scale heater test is generally ensured by using redundant monitoring instruments and equipment.

The design criteria and recommendations for the small-scale heater test are given below (from Roberds et al., 1983).

> The recommended small-scale heater test array consists of a small heater (15.0cm or smaller) surrounded by a thermocouple array. The actual configuration and number of thermocouples used to measure the temperature field will be dependent on modeling.
>
> The design criteria and recommendations for the small-scale heaters should be such that:
>
> - heater output (Q) is measurable and thermocouples are utilized on the heater body to ensure that the heater temperature is uniform
> - heater is capable of operating over a range of heat outputs; in addition, the heater is capable of maintaining a constant heat output for the duration of each heating cycle
> - provision for two heating elements/power controllers, so that in the event of failure of one of the elements/power controllers the test can still be performed

- heater can withstand the maximum predicted borehole temperatures
- heater is provided with centering mechanism such as fins for borehole installation
- provision for a dewatering system if water inflow appears to be a problem at the site (i.e., to cause heater failure or convective heat transfer)
- heater is calibrated in the laboratory prior to installation

The small-scale heater installation consists of inserting the liner in the borehole. The annular space between the liner and the rock should be backfilled (e.g., sand) to minimize convective heat transfer.

The small-scale heater is centered in the liner and installed such that the horizontal midplane of the heater is at the specified test depth. Thermal insulation should be used above the heater to minimize heat loss along the borehole. A thermal insulation pad should be placed on the surface of the drift floor (or shaft wall) in the vicinity of the test to minimize heat losses due to ventilation.

The small-scale heater test will consist of heating the rock with a constant power output and monitoring temperatures over time until steady-state (or quasi-steady state) conditions are attained. The heat output can then either be increased, decreased or turned off, depending on the desired results.

Temperature measurements intervals should be more frequent during the transient state (perhaps every few minutes), while the intervals should be much less frequent during steady state conditions.

<u>Canister(Full)-Scale Heater Experiment</u> — The canister-scale heater test is concerned with examination of the detailed thermal, hydrological, mechanical, and chemical processes which occur within a few radii of the emplacement boreholes. Here, the structure of the waste canister, the overpack and backfill design, 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 stabil-

ity. These processes are of greatest concern on a "short" time-frame, when the peak temperatures are greatest. This occurs at timeframes less than 100 years and encompasses the retrievability period. However, the subsequent hydrochemical processes occur on a long-term time scale.

A single horizontal canister-scale heater experiment is planned at the repository horizon (Vieth et al., 1985). The objective of this test is to document the near-field rock behavior around the opening that envelops the waste package system. The limitations and reliability considerations for this test are the same as those for the small-scale heater test. The design and execution of the test are as follows, from Roberds et al. (1983).

> The full-scale heater test array will consist of a central full-scale heater surrounded by an array of instruments at various radial and vertical distances. The instruments utilized in the recommended full-scale heater test include
>
> - thermocouples
> - multiple-position borehole extensometers (MPBX)
> - borehole deformation gauges
> - water migration monitors (incorporated into flow measuring-dewatering system)
> - ventilation monitors
>
> The design criteria and recommendations for the full-scale heater are:
>
> - the heater should duplicate the geometry of a waste package
> - heater output (Q) is measurable and thermocouples should be utilized on the heater body to ensure that the heater temperature is uniform
> - heater is capable of operating over a range of outputs; in addition, the heater is capable of maintaining a constant heat output for the duration of each heating cycle

- provision for four heating elements/power controllers such that maximum heat output is possible in the event three heating elements/power controllers fail

- canister retrievability can be evaluated

- heater is calibrated in the laboratory prior to installation

The installation of the full-scale heater should simulate waste package emplacement and history as closely as possible, with the possible exception that water migration equipment may be utilized in the full-scale heater test and that such a system will not be utilized in the prototype waste package. Johnstone (1980) and Ewing (1881) report the use of equipment to remove water and steam in the borehole and measure flow-rates. The dewatering system serves to prevent anomalous temperature distributions in the rock resulting from convection and minimizes heater problems. The heater should be centered in the borehole such that the horizontal midplane of the heater corresponds to the desired test depth. At a minimum, it seems that an equal number of tests should be made without equipment to remove water and steam and without centering to test actual field conditions.

The thermocouple design considerations and installation procedure is similar to the small-scale heater test, with the exception that the thermocouples should be installed in the MPBX boreholes and borehole deformation gauge boreholes, thus eliminating the need for thermocouple only boreholes. With the test configuration proposed, adequate measurement of the temperature field should be possible.

The full-scale heater test is also designed to measure thermally induced displacements and strains. Multiple-position borehole extensometers (MPBX's) are used to measure the axial displacements in a borehole.

The recommended full-scale heater test consists of heating the rock in constant power output stages and measuring the rock mass response. The heating cycles should consist of several increases in heater output, followed by a cooling phase. The heater output should remain constant until after steady state (or quasi-steady state) conditions have occurred in the rock mass, before it is increased (or decreased).

Data collection intervals should be more frequent in the initial stages of the heater test, e.g., as often as every five minutes. The channel may be monitored every 15 to 20 minutes during the transition from heat-up to steady-state operation, and every hour during steady-state operation (Johnstone, 1980). Actual data collection times will depend on the site response. In addition, water migration should be monitored in tuff.

Following the cool-down period, the rock should be heated until borehole failure occurs (or until maximum heater output is attained). This will permit an evaluation of canister retrievability. In addition, post-test borehole conditions should be further characterized by the borehole techniques discussed earlier, namely, geophysical well logs, borehole TV logs, crosshole sonic velocities, and permeability tests and compared with initial survey findings.

An additional post-test characterization should include rock samples cored in the vicinity of the heater hole(s). The core should be examined in the laboratory to determine if any geochemical or alteration changes occurred as a result of the heater test. A supplementary small-scale heater test should be performed near the full-scale heater test to evaluate the scale effects of the two tests.

Heated Block Test — A heated block test similar to the G-Tunnel Heated Block Test is proposed at the repository horizon at Yucca Mountain (Vieth et al., 1985). The proposed test will likely follow closely the G-Tunnel Heated Block Test. If such a test is deemed appropriate, the recommendations listed by Zimmerman et al. (1986, pp. 12-9 and 12-10) should be considered.

Thermomechanical Room-Scale Test — A room-scale test previously had not been proposed at NNWSI, yet perhaps the least understood question concerning repository design is the long-term thermomechanical response of underground openings.

The testing plans written to date (Vieth et al., 1985) attempt to resolve this issue by conducting single-heater and block-type experiments. In these, an attempt is made to validate a thermomechanical code(s) using the data generated. The validated code(s) is(are) then used for room-scale design. Confident application of room-scale design models whose validation is based on tests which thermally load only small blocks of ground that are highly confined (kinematically) is questionable.

Alternatively, it is suggested that a practical engineering demonstration approach be considered 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 in the conceptual arrangement to provide the thermal load. The instrumentation (with supplemental temperature sensing and compensation) can be used to monitor the test.

One drawback of the test is the large amount of time required to heat the rock mass. The test should be in continuous operation from ES testing through license application, construction authorization, and construction. Thus, it will provide initial thermomechanical response for license application and a basis for long-term data. In short, such a test could provide demonstration of some aspects of the repository concept and the design's ability to satisfy design requirements of 10CFR60.

8.3.2.4 Design Optimization

This section will describe the design optimization studies and activities which require site characterization. Potential topics include

- refinement of design data needed to resolve design alternatives
- design performance verification for activities such as rock excavation and mining technique, waste package emplacement, and retrieval issues.

The specific areas likely to be discussed are:

(a) demonstration of feasibility of drilling long horizontal holes, replacing and retrieving waste; and

(b) evaluation of alternative support systems.

No specific review procedures are given for this subsection.

8.3.2.5 Repository Modeling

This section of the SCP will identify and describe planned repository design model and code development and utilization, verification and validation activities which require site characterization data. Potential subjects include repository component and subsystem models and their use in conducting performance, safety, and design optimization analyses.

Because there is no empirical data base from which performance can be assessed and because the timeframes of the analyses are so long, models (numerical, analytical) must be used to a great extent to predict performance of the repository. In order that the design and performance assessment process be made tractable, the repository must be divided into a number of physical scales: canister, room, repository, and regional.

Different models may be used for different scales, with each scale model providing appropriate but uncoupled boundary conditions for the physically neighboring scale models. A more rigorous approach couples two or more scale models into a single hybrid model. For example, the room scale near-field behavior may be modeled with distinct elements, taking into account the location and nature of discontinuities, whereas far-field behavior may be adequately represented using a boundary element scheme (see, for example, Lorig et al., 1986). A similar hybrid approach has been documented for finite element and boundary element methods (Brady and Wassyng, 1981). In any case, each scale model must be properly validated for use in the design and performance assessment process.

The discussion of numerical modeling methodology which follows is based on a recent report on the status of thermomechanical modeling (Itasca, 1987).

Basic Aspects of a Logical Methodology — A logical methodology for performing thermomechanical analysis must be followed in order to evaluate the reliability of the numerical models and to establish credibility in the analysis results. A general approach is presented by Brady and St. John (1982) for applications related to engineering rock mechanics. A diagram illustrating the basic aspects of this approach is reproduced in Fig. 12. The approach is an extension of the observational approach to geotechnical design and incorporates the reliance on advanced computational methods.

One aspect of the methodology is the formulation of a site geotechnical model based on site exploration and characterization. This includes information from laboratory and field testing supplemented with generic information on rock types when site-specific information is not available. Specific problems associated with formulation of the geotechnical model include scale effects, representativeness of testing, and definition of initial in-situ conditions.
A second aspect is the selection (or development) of an appropriate computer code for performing design calculations and the verification of this code (i.e., the process of ensuring that the code is computationally correct for all conditions under which it will be applied).

The site geotechnical model must then be incorporated into the computer code and the resulting numerical model must be validated (or qualified, as defined in Fig. 12) for the analysis of site-specific problems.

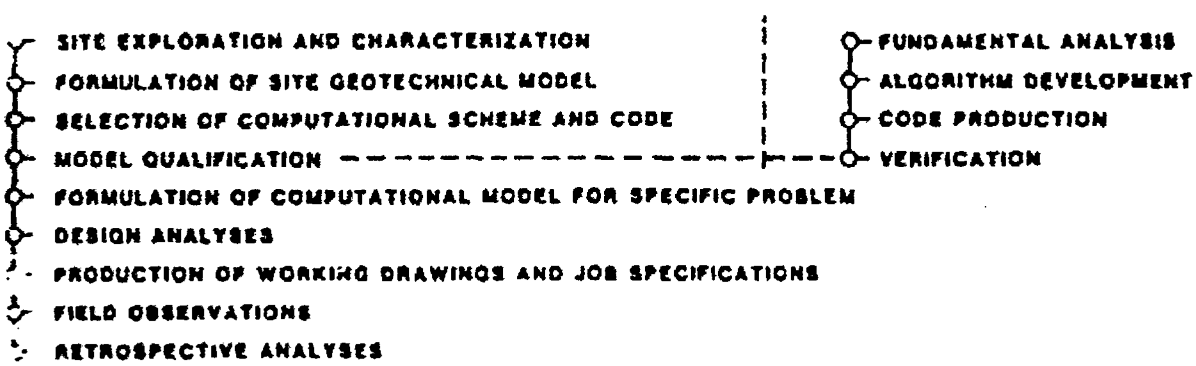


Fig. 12 A Logical Methodology for Semi-Quantitative Application of Advanced Computational Schemes in Rock Mechanics [Brady and St. John, 1982]

According to this approach, code verification can be performed in the absence of site-specific data. Brady and St. John (1982) contend that field tests "represent an extra level of complexity, compared with laboratory experiments, due to poor definition of experimental parameters" and, therefore, are not to be used in code verification.

Model Validation — The aspect of model validation is concerned with the demonstration that the numerical model of a specific site and geologic setting is an acceptable representation of both the thermal and mechanical processes affecting the site and the geologic character of the rock medium. Validation is necessarily an evolving process as more information becomes known, but a difficulty arises in defining the conditions to be achieved for model validation. Brady and St. John (1982) provide a rational criterion for the validation of a computation scheme. The decisive requirement, as stated by Brady and St. John, is "that for a given set of properly determined site parameters, the model can predict the response of the rock medium to some controlled perturbations, to some prescribed tolerance." For example, a validation exercise for a thermomechanical model could be the computational and experimental determination of mechanically- and thermally-induced stresses and displacements around a heated excavation test panel in the rock mass. The model would be considered validated by achieving a correspondence between the observations and predictions within a tolerance prescribed by the uncertainty in the input data.

Figure 13 illustrates the criterion for validation. Each rock mass parameter should be prescribed a specified level of confidence. Bounding predictions are then made using the model and the parameters within the confidence limits. If these bounds bracket the response measured in the field experiment, the model can be considered validated for application for processes and geologic settings similar to those of the experiment.

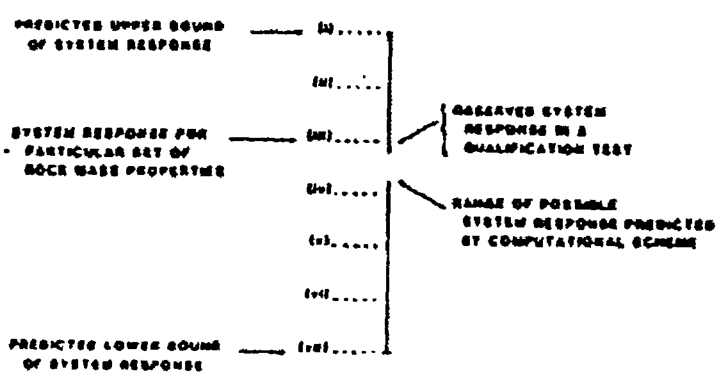


Fig. 13 Criterion for Validation of a Computational Methodology for a Specific Site by Predictions Bounding the Observed Response of a Test Site [Brady and St. John, 1982]

Model validation is particularly difficult for analyses related to retrievability and post-closure conditions, where the time scale of concern precludes a realistic experimental program. In such instances, Brady and St. John (1982) suggest that model validation may require demonstration that the model results are consistent with historical experience of analogous conditions.

<u>Equivalent Continuum Models</u> — As discussed earlier, the ability to perform even room scale analysis may require the use of an equivalent continuum model. The site characterization process provides a good opportunity for evaluating the performance of the equivalent continuum models. In addressing this issue, the effects of traditional limitations of, and objections to, such models should be evaluated.

The fundamental objections that can be raised on the validity of these equivalent models are given by Detournay and St. John, 1985.

- There is no interaction between joints (either within a set, or between sets). The stress state within the joints and matrix is homogeneous (the macroscopic normal and shear stress across the direction of each joint set is simply deduced from the overall stress using the Mohr transformation).

- The derivation of these equivalent continuum models does not follow the self-consistent method described by Hill (1967) for the characterization of composite materials. (This requires estimating the behavior of a joint in the discontinuous rock medium as that of a single discontinuity in the equivalent homogeneous body).

- The question of scale effect can not be addressed with the ubiquitous models because of lack of a characteristic length.

Strict adherence to assumptions underlying the equivalent continuum approach requires the following (Gerrard, 1983):

(1) discontinuities occur in sets, each of which can be recognized by its regular spatial pattern;

(2) the typical spacing between joints in a set is much smaller than the critical dimension of the problem under consideration (e.g., span of an underground opening); and

(3) either the relative movements on a particular joint set are limited or the spacings between the joints in the set are extremely small.

It should be noted that there appears to be very little quantitative information on the limits of applicability of equivalent continuum models. This issue deserves serious attention.

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