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Resolution Strategy for Geomechanically-Related Repository Design and Thermal-Mechanical Effects (RDTME)

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RESOLUTION STRATEGY FOR GEOMECHANICALLY-RELATED REPOSITORY DESIGN AND THERMAL-MECHANICAL EFFECTS (RDTME)

April 2003

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EXECUTIVE SUMMARY

This document provides an approach to resolution of the geomechanically-related Repository Design and Thermal-Mechanical Effects Key Technical Issue agreements. These Key Technical Issue agreements were jointly developed between the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission staffs at the Technical Exchange and Management Meeting held on February 6-8, 2001, in Las Vegas, Nevada. A list of the agreements and their exact wording can be found in Appendix A. This document reviews these agreements and gives a detailed background regarding their derivation and resolution.

The Key Technical Issue Agreements

Geomechanically-related Repository Design and Thermal-Mechanical Effects agreements (see Appendix A) can be subdivided into five primary areas:

A. Rock mass properties and geotechnical characterization

1. Development of a basic understanding of how the structural characteristics of the repository host horizon impacts rock mass behavior and, consequently, the design and performance properties. This work can be used to establish a connection between geologic characteristics and their use in models and calculations.

2. Develop an understanding of the variability of geologic structure and, using the developments of the above item, identify how variability affects rock mass thermomechanical behavior.

3. Enhance the database of thermomechanical materials properties of repository rock units, including mechanical and thermal testing of lithophysal rocks, estimation of the mechanical properties of rock fractures, and determination of the time-dependent response of lithophysal rocks. Development or choice of proper constitutive models for the different distinct rock units is a portion of this effort.

B. Modeling

1. Determination or development of the proper type of modeling tools to use for sensitivity studies of excavation stability under gravitational, thermal and seismic loading. Specific agreements cited in the Key Technical Issue include:

   a. Under what circumstances are continuum and discontinuum models appropriate?

   b. Under what circumstances are two- and three-dimensional models appropriate?

   c. Under what circumstances are assumptions of rock mass homogeneity or anisotropy appropriate?

2. Determination of the proper model boundary and initial conditions

    a. Need to address the initial stress state for models and inclusion of thermally induced stress history from regional models applied to local scale models for problems such as rockfall

    b. Need to address special boundary conditions for dynamic analyses, including non-reflecting and free-field boundaries

    c. Need for development of preclosure and postclosure site-specific ground motion time histories

3. Seismic Stability

    a. Use of site-specific ground motions

    b. Use of appropriate dynamic models for estimation of rockfall induced by seismic shaking

    c. Methodology for inclusion of geologic structure and its variability into models for estimation of rockfall

4. Thermal and Long-term Degradation

    a. Need to examine potential for thermal-stress induced rockfall

    b. Need to examine impact of long-term static fatigue of the rock mass and its impact on drift degradation and rockfall

5. Ground Support and Drift Degradation

    a. Verification of the functional and operational requirements and specification of ground support during the preclosure period

    b. Development of a plan for observation and maintenance of the ground support

    c. Estimation of the effect of postclosure in situ thermal and seismically induced stresses on the degradation and potential rockfall of the emplacement drifts. Included here is the potential effect of time-related static fatigue mechanisms in intact rock and joints.

Resolution Strategy

The strategy described in this document for resolving the above primary areas involves a phased approach based on the following combination of analyses, studies and calculations (Figure i).

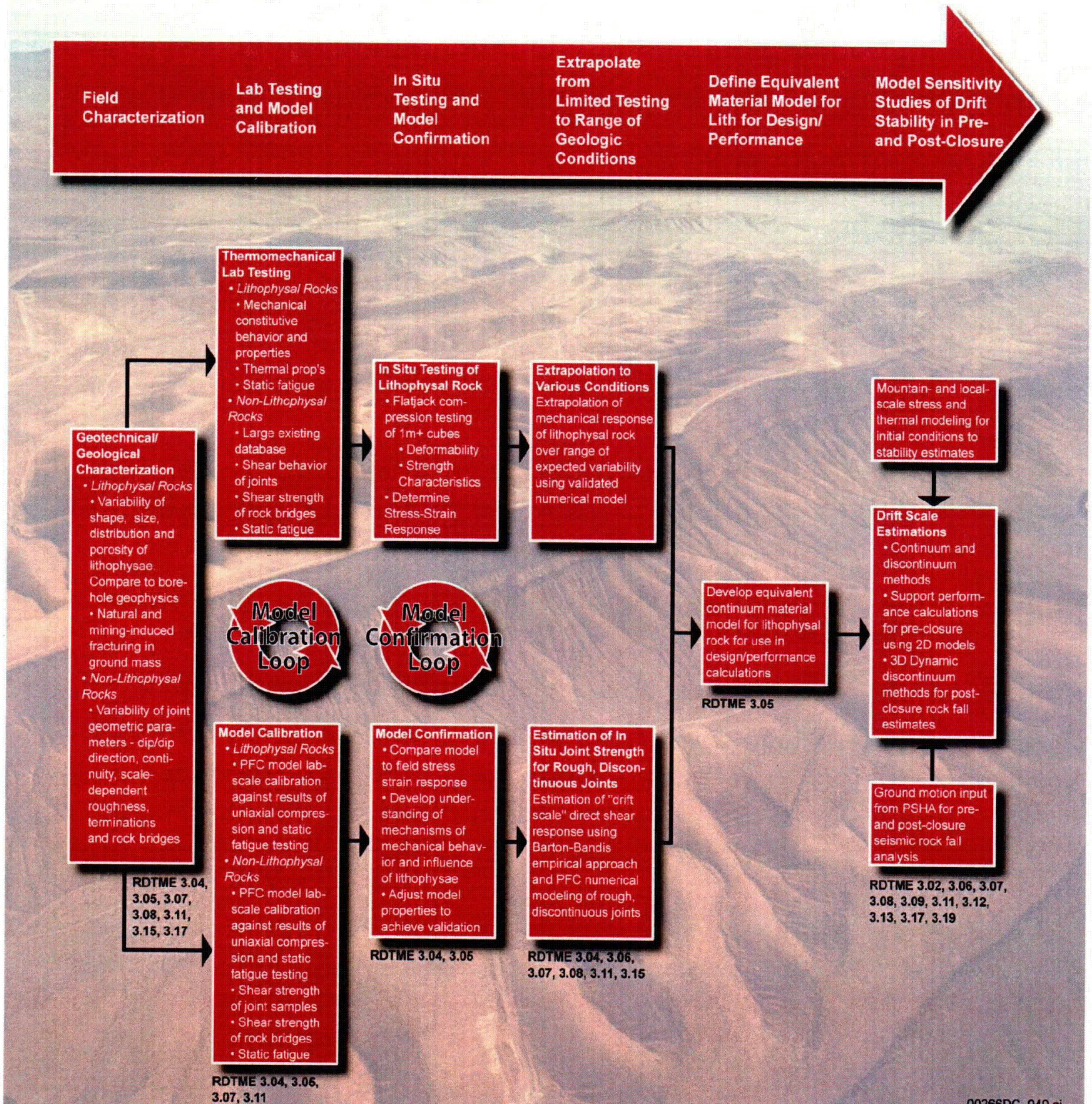
- Evaluation and geotechnical analysis of the existing, extensive geological mapping and geotechnical field characterization data from surface and underground mapping of lithology, structure and rock quality.
- Perform additional laboratory and in situ thermomechanical testing, primarily of lithophysal rocks, to provide information for confirmation of the material models and property ranges to be used in design and performance sensitivity studies.
- Calibration and validation of numerical models capable of representing the thermomechanical behavior of lithophysal and non-lithophysal rocks.
- Use of the validated models to explore the impact of geologic variability (porosity, lithophysae shape and distribution, fracture density) on the geomechanical response, primarily of lithophysal rocks. Validated models are used to supplement the materials properties data base by extrapolating the effects of geologic variability.
- Thermally and time-related model sensitivity studies to examine preclosure ground support and postclosure drift degradation and seismic stability issues.

There are two points of particular importance in this strategy:

1. Because the performance of the tuff rock mass is primarily a function of geologic structure (e.g., fractures and lithophysal porosity), modeling tools must be based on geologic information gathered from the field and laboratory. It is the goal of this strategy to demonstrate a direct linkage between the basis of our models and the geologic reality in the field.

2. Because the behavior of the rock mass, particularly the lithophysal rocks, is porosity- and size-dependent, rock mass property derivation via typical "empirically based" rock mass classification schemes or "statistically based" testing programs using small core samples are not particularly applicable to lithophysal rocks.

   The porosity- and size-dependence means that, for rock mass properties estimates, reliance must be placed on performing a limited number of large-core laboratory and in situ tests to determine the thermal and mechanical properties of this material. Since this will necessarily result in a relatively small data base, our goal is to validate numerical models with the lab and field testing to provide a predictive capability that will represent the basic mechanisms of mechanical behavior of the lithophysal rocks. These validated numerical models can then be used for "test bed" extrapolation purposes to examine effects such as the impact of lithophysae size, shape and porosity on rock material model and property ranges.



NOTE: Process starts with compilation and analysis of basic geotechnical mapping, followed by laboratory and field testing and model validation to develop rock mass property estimates for design and performance sensitivity studies.

Figure I General Approach to Resolution of the Geomechanically-Related Key Technical Issue

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ACRONYMS AND ABBREVIATIONS

BSC	Bechtel SAIC Company, LLC
CAD	computer-aided drafting
DOE	U.S. Department of Energy
ECRB	Enhanced Characterization of the Repository Block
ESF	Exploratory Studies Facility
KTI	Key Technical Issue
MCTE	mean thermal coefficients of thermal expansion
MTHM	metric tons of heavy metal
NRC	U.S. Nuclear Regulatory Commission
ORD	Office of Repository Development
Q	quality system
RDTME	Repository Design and Thermal-Mechanical Effects
RMR	Rock Mass Rating
RQD	rock quality designator
TBM	tunnel boring machine
UCS	uniaxial compressive strengths
URL	Underground Research Laboratory
USBR	U.S. Bureau of Reclamation
YMP	Yucca Mountain Project

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1. INTRODUCTION

In September of 2000, the U.S. Nuclear Regulatory Commission (NRC) issued an Issue Resolution Status Report (NRC 2000). The Key Technical Issue (KTI) agreements on Repository Design and Thermal-Mechanical Effects (RDTME) were jointly developed at the Technical Exchange and Management Meeting held on February 6-8, 2001 in Las Vegas, Nevada. In that report, a number of geomechanically-related issues were raised regarding the determination of rock properties, the estimation of the impacts of geologic variability, the use of numerical models, and the examination of drift degradation and design approach to the ground support system for the emplacement drifts. Ultimately, the primary end products of the KTI agreement resolution processes are an assessment of the preclosure stability of emplacement drifts and the associated ground support requirements. There is also an assessment of the postclosure degradation of the excavations when subjected to thermal and seismic-related stresses as well as in situ loading over time.

Subsequent to that report, several teleconferences were held with the NRC to discuss technical differences. The outcomes of those discussions were formulated into agreements for resolution at the NRC/DOE Technical Exchange and Management Meeting on RDTME held in February of 2001.

As a result of the February RDTME Technical Exchange with the NRC, a number of agreements related to geomechanical design and performance assessment must be addressed. This report specifically addresses how the DOE proposes to resolve those agreements related specifically to geomechanical concerns. The specific RDTME agreements addressed by this document are listed in Appendix A.

The RDTME agreements cover a number of technical issues regarding the assessment methodologies and rock mechanics data available to support these assessments. These agreements address such concerns as:

- The robustness of estimates of rock mass properties
- The robustness of numerical models and the physical representations of rock mass structure and input loading conditions used in these models for performance evaluations
- The representation and assessment of the impact of the spatial variability of properties
- The methodology for representing time-related degradation of strength in the modeling approach and its impact on excavation stability and rock mass performance
- The ability to establish conservatism in the calculations
- The ability to predict the performance of ground support measures over preclosure time frames
- The ability to predict postclosure drift degradation due to various factors including seismic shaking, thermal loading and static fatigue.

Because of the complexity of RDTME agreements (particularly dealing with lithophysal rock, for which little contemporary experience is available), the Office of Repository Development (ORD) convened a panel of experts to assess these items and the means for resolving them. The panel consisted of experts in the fields of geology, geotechnical assessment, and mining engineering, both from within and outside the ORD. The members of this panel are listed as authors or acknowledged in this paper.

In May of 2001, the panel conducted a three-day series of meetings in Las Vegas. During these meetings, the panel reviewed the current geomechanical design and performance assessment methodology and discussed the issues associated with the approach. They also looked at the types of tests conducted to date, the results of these tests, and all currently available data. Finally, they toured the Exploratory Studies Facility (ESF) and the Enhanced Characterization of the Repository Block (ECRB) Cross-Drift to view the rock mass and test areas firsthand. The panel came to three basic conclusions:

- The current base of geomechanical data (Appendix B) is incomplete in certain areas.

- Large-scale laboratory and in situ testing is required to assess the geomechanical design and performance properties of the lithophysal rock. Empirical techniques alone (common to the mining and construction industries) were judged inadequate for estimating site-specific mechanical properties of the lithophysal rocks.

- Alternative and/or additional modeling applications are needed.

Based on these findings, the panel formulated a plan and proposed a series of tests needed to understand the rock behavior and provide adequate input for a design.

Following this meeting, individual participant organizations developed proposals regarding laboratory and in situ testing and numerical modeling methods that could be used to more confidently predict the behavior of the lithophysal and nonlithophysal rocks. The geotechnical panel reconvened in June of 2001 to review test proposals, prioritize the work, and finalize their recommendations for resolution.

This report provides a proposed approach toward resolution of these issues, as suggested by the panel, and developed in the months since their discussions. However, there are a number of key junctures in the plan that will require review and reassessment in order to come to resolution. Meetings will be conducted at the key junctures in the process to update the NRC on progress, changes, or additions to the program. This plan may be adjusted over time as new information is gained, altered, or new approaches are required.

Figure 1 and Figure 2 are intended to demonstrate this approach for the two primary end-products of the geomechanical program: rock support and drift degradation analyses.

In developing the issues, methodologies and approaches presented in this document, it was necessary to perform a number of scoping calculations. These calculations (e.g., stresses around excavations, estimates of possible yielding mode and yielding extent into the rock mass) are given purely for preliminary estimation or demonstration purposes and have thus not been subjected to rigorous checking.

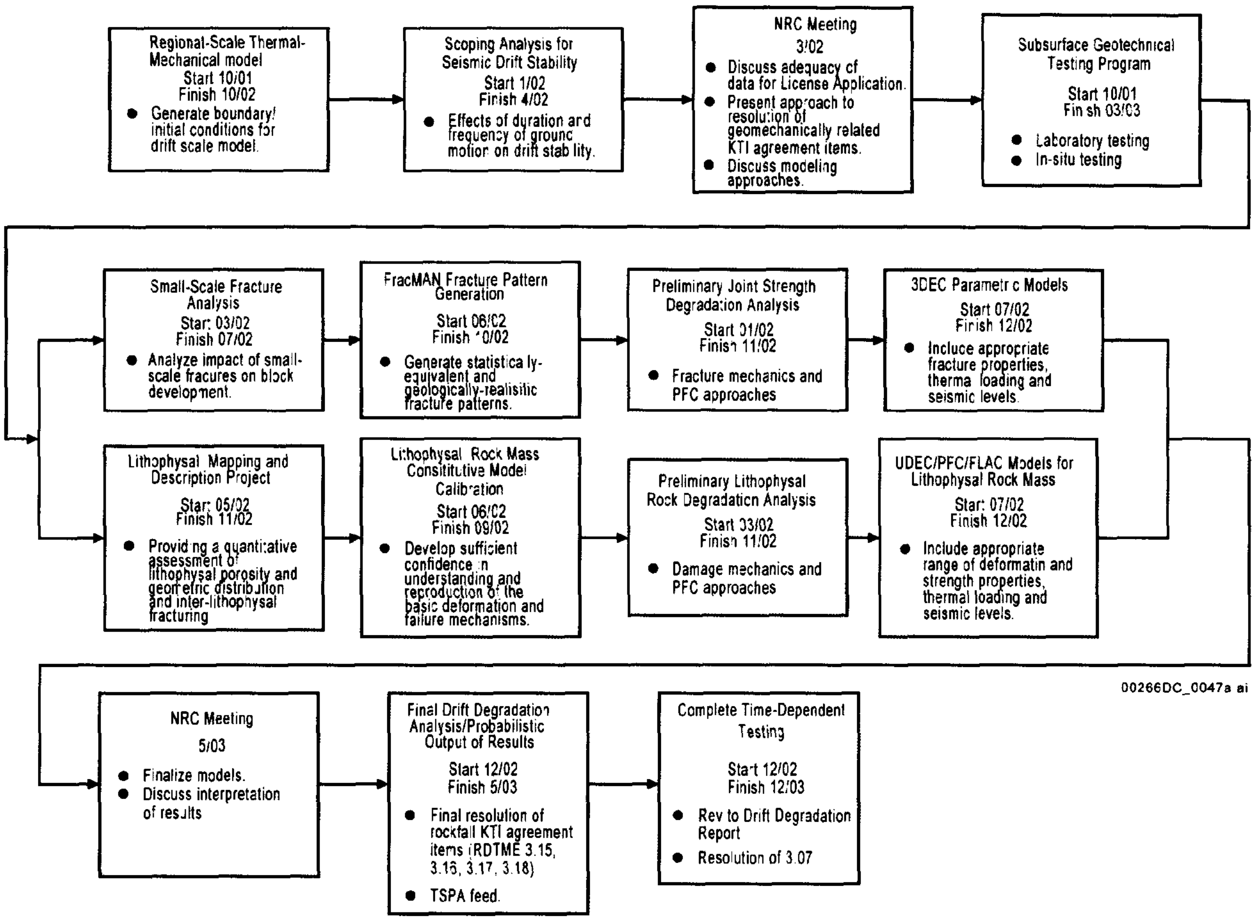

Figure 1. Resolution Flow Chart of Key Technical Issue Agreements for Rockfall and Drift Degradation

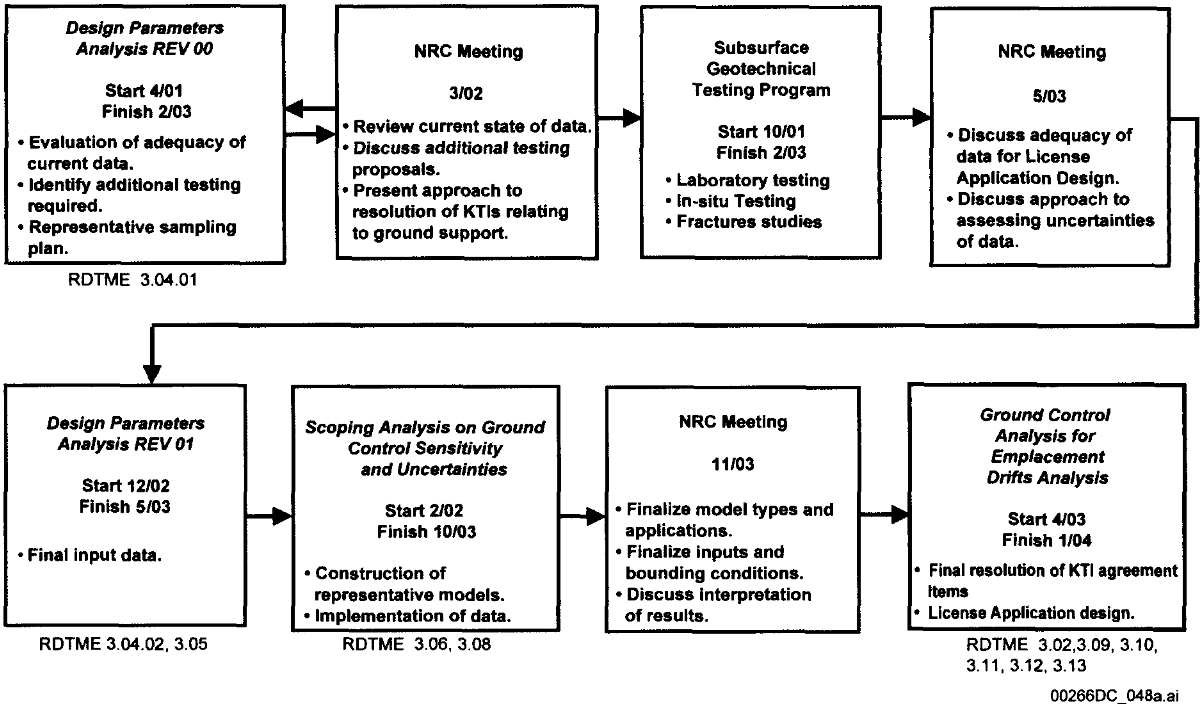

Figure 2. Resolution Flow Chart of Key Technical Issue Agreements for Ground Support Design in the Emplacement Drifts

2. THE REPOSITORY DESIGN AND THERMAL MECHANICAL EFFECTS AGREEMENTS AND HOW THEY ARE BEING ADDRESSED

2.1 GENERAL DISCUSSION OF AGREEMENTS

Geomechanically-related RDTME agreements (Appendix A) can be subdivided into five primary areas:

A. Rock mass properties and geotechnical characterization

1. Development of a basic understanding of how the structural characteristics of the repository host horizon impacts rock mass behavior and, consequently, the design and performance properties. This work can be used to establish a connection between geologic characteristics and their use in models and calculations.

2. Develop an understanding of the variability of geologic structure and, using the developments of the above item, identify how variability affects rock mass thermomechanical behavior.

3. Enhance the data base of thermomechanical materials properties of repository rock units, including mechanical and thermal testing of lithophysal rocks, estimation of the mechanical properties of rock fractures, and determination of the time-dependent response of lithophysal rocks. Development or choice of proper constitutive models for the different distinct rock units is a portion of this effort.

B. Modeling

1. Determination or development of the proper type of modeling tools to use for sensitivity studies of excavation stability under gravitational, thermal and seismic shaking. Specific agreements cited in the KTI include:

   a. Under what circumstances are continuum and discontinuum models appropriate?

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2. Determination of the proper model boundary and initial conditions

   a. Need to address the initial stress state for models and inclusion of thermally induced stress history from regional models applied to local scale models for problems such as rockfall

   b. Need to address special boundary conditions for dynamic analyses, including non-reflecting and free-field boundaries

c. Need for development of preclosure and postclosure site-specific ground motion time histories.

C. Seismic Stability

1. Use of site-specific ground motions

2. Use of appropriate dynamic models for estimation of rockfall induced by seismic shaking

3. Methodology for inclusion of geologic structure and its variability into models for estimation of rockfall.

D. Thermal and Long-term Degradation

1. Need to examine potential for thermal-stress induced rockfall

2. Need to examine impact of long-term static fatigue of the rock mass and its impact on drift degradation and rockfall.

E. Ground Support and Drift Degradation

1. Verification of the functional and operational requirements and specification of ground support during the preclosure period.

2. Development of a plan for observation and maintenance of the ground support.

3. Estimation of the effect of postclosure in situ, thermal and seismically induced stresses on the degradation and potential rockfall of the emplacement drifts. Included here is the potential effect of time-related static fatigue mechanisms in intact rock and joints.

2.2 RESOLUTION STRATEGY

2.2.1 Overall Approach

The strategy described in this document for resolving these issues is based on the following combination of analyses, studies and calculations (see also Figure 1 and Figure 2).

- Evaluation and geotechnical analysis of the existing, extensive geological mapping and geotechnical characterization data from surface and underground mapping of lithology, structure and rock quality.

- Additional laboratory and in situ thermomechanical testing, primarily of lithophysal rocks, to provide information for confirmation of the material models and property ranges to be used in design and performance sensitivity studies.

- Calibration and validation of numerical models capable of representing the thermomechanical behavior of lithophysal rocks.

- Use of the validated models to explore the impact of geologic variability (porosity, lithophysae shape and distribution, and fracture density) on the geomechanical response, primarily of lithophysal rocks. Validated models are used to supplement the material properties data base by extrapolating the effects of geologic variability.

- Numerical model sensitivity studies to examine preclosure ground support and postclosure drift degradation and seismic stability issues.

There are two points of particular importance in this strategy:

1. Because the performance of the tuff rock mass is primarily a function of geologic structure (e.g., fractures and lithophysal porosity), modeling tools must be based on geologic information gathered from the field and laboratory. It is the goal of this strategy to demonstrate a direct linkage between the basis of the models and the geologic reality in the field.

2. Rock mass property derivations via typical "empirically based" rock mass classification schemes or "statistically based" testing programs using small core samples are not particularly applicable to lithophysal rocks because the behavior of the rock mass is porosity- and size-dependent.

The porosity- and size-dependence means that, for rock mass property estimates, assurance must be provided by a limited number of large-core laboratory and in situ tests to determine the thermal and mechanical properties of the material. Since this will necessarily result in a relatively small data base, the goal is to closely couple numerical models with the lab and field testing to provide a predictive capability that will represent the basic mechanisms of mechanical behavior of the lithophysal rocks. These validated numerical models can then be used for "test bed" extrapolation purposes to examine effects such as the impact of lithophysal size, shape and porosity on rock material model and property ranges.

2.2.2 Geological and Engineering Methods Proposed to Resolve RDTME KTI Agreements

The basic geological and engineering methods, described in detail in this document, include the following:

- **Geological Characterization**–This includes geological mapping and engineering geologic description of joints and lithophysae in the ESF and ECRB. Techniques include analysis of the extensive existing data base of full periphery structure maps, which are detailed line surveys of fracturing that includes fracture orientation, trace length, alteration and roughness information. The FracMAN program (FracMAN, 10114-2.511-00 V.2.511) will be used with these data as a basis for development of statistically representative fracture volumes, which will then form the basis of input to numerical analysis of rockfall in the non-lithophysal rocks.

Lithophysae panel mapping studies conducted in the lower lithophysal unit within the ECRB, combined with surface-based geophysical porosity studies, will form the basis for estimating the geometric characteristics and variability of lithophysae. This information will be used for input to thermal and mechanical models of porosity-dependent properties.

- **Materials Property Measurement**–Analysis of the existing rock properties data base (Appendix B) has identified additional data collection needs. The data base will be enhanced through additional testing and through validation and extrapolation of numerical models capable of representing lithophysal rock behavior. The required additional data includes estimates of joint shear constitutive behavior and thermomechanical properties of lithophysal rocks. Joint shear response will be determined using laboratory direct shear tests on large and small samples. This will be supplemented by large-scale field roughness estimates that will be used in empirical relations for estimating shear strength and dilation for each major joint set. Lithophysal rock properties are both size and porosity-dependent, necessitating the use of large sample sizes. A laboratory program of thermomechanical testing of large diameter (12 in. [30.5 cm]) core samples will be conducted to derive mechanical and thermal properties of rock samples large enough to contain many lithophysae. A number of in situ heating and compression experiments (1-m scale) will be conducted for deformation modulus, strength and thermal conductivity measurement on a representative scale. It is proposed to validate the numerical PFC 2D (PFC 2D, 10828-2.0-00 V.2.0) and PFC 3D (PFC 3D, 10830-2.0-00 V.2.0) modeling program (collectively referred to as "PFC" in remainder of document) against the laboratory and field testing of the lithophysal rock. The PFC program is a large displacement, discontinuum "micromechanical" modeling tool that physically represents the mechanical behavior of bonded particle materials such as rock. It has the advantage of allowing holes in the rock as well as interlithophysal fracturing, and thus provides a methodology for representing and understanding the basic mechanical response of lithophysal rocks through back-analysis of compression testing. Since only limited access to the repository horizon is available and only a limited number of large-scale compression tests are possible, the validated numerical model will be used to supplement the test data by extrapolation. In other words, the model will be used as a numerical "test bed" for exploring the impact of lithophysae shape, size, distribution and porosity on its mechanical properties and failure modes. Finally, time-dependent strength properties (i.e., static fatigue) need to be determined for nonlithophysal and lithophysal materials.

- **Modeling and Design Tools**–Although empirical methods are typically employed in rock engineering for design, they have only limited applicability here due to the general lack of experience base in lithophysal rocks and to the complex loading states generated by heating and seismic forces. Therefore, numerical models will be used as primary methods of design and performance assessment, with empirical methods as confirmatory tools. The non-lithophysal rocks are typical, strong, fractured materials whose behavior is expected to be largely controlled by the fracture geometry and surface properties, and will be anisotropic in nature. Consequently, reliance for rockfall analysis under thermal and seismic loading is placed on the use of three-dimensional discontinuum analysis methods (e.g., 3DEC [3DEC, 10025-2.0-00 V.2.0.]). The thermomechanical behavior of the lithophysal rocks is expected to be isotropic, but controlled by lithophysal porosity. It is the intention of the project to develop a rock mass constitutive model to describe the shear and possible compaction response of the material, whose material properties are porosity-dependent. The approach suggested is to embed this constitutive response into two-dimensional numerical models for purposes of representation of yield and deformation response to thermal and seismic load. To enable estimates of physical rock degradation and rockfall, two-dimensional discontinuum modeling approaches (i.e., UDEC [UDEC V.3.0, 10173-3.0-00 V.3.0]) will be used as described in detail in this document. A program of model calibration and validation against the field tests, and current tunnel observations in the ESF and ECRB, is planned to provide confidence in their application. Preclosure ground support design will be accomplished using a combination of empirical methods as used in industrial practice, which will be confirmed using numerical analysis techniques.

2.3 OVERVIEW OF THE RESOLUTION STRATEGY FOR EACH GEOMECHANICALLY-RELATED KEY TECHNICAL ISSUE AGREEMENT

The relevant geomechanically-related issue agreements and an overview of the resolution strategy is given in Appendix A for each of the KTI agreements covered by this document. Details of the overall resolution strategy are given in Sections 5 and 6 of this report. The following KTI agreements are addressed in this report with quoted pertinent sections:

2.3.1 RDTME 3.02

Provide the critical combinations of in-situ, thermal, and seismic stresses, together with their technical bases, and their impacts on ground support performance. The DOE will examine the critical combinations of in-situ, thermal, and seismic stresses, together with their technical bases and their impacts on preclosure ground support performance. These results will be documented in a revision to Ground Control for Emplacement Drifts for SR, ANL-EBS-GE-000002 (or other document) supporting any potential license application. This is expected to be available to NRC in FY 2003.

2.3.2 RDTME 3.04

Provide in the Design Parameter Analysis Report (or some other document) site-specific properties of the host rock, as a minimum those included in the NRC handout, together with the spatial and temporal variations and uncertainties in such properties, as an update to the information contained in the March 1997 Yucca Mountain Site Geotechnical Report. The DOE will: (1) evaluate the adequacy of the currently available measured and derived data to support the potential repository licensing case and identify areas where available data may warrant additional field measurements or testing to reduce uncertainty. DOE will provide a design parameters analysis report (or other document) that will include the results of these evaluations, expected to be available to the NRC in FY 2002; and (2) acquire data and/or perform additional analyses as necessary to respond *to the needs identified in 1 above. The DOE will provide these results prior to any potential license application.*

2.3.3 RDTME 3.05

Provide the Rock Mass Classification Analysis (or some other document) including the technical basis for accounting for the effects of lithophysae. The DOE will provide a rock mass classification analysis (or other document), including the technical basis for accounting for the effects of lithophysae, expected to be available to NRC in FY 2002.

2.3.4 RDTME 3.06

Provide the design sensitivity and uncertainty analyses of the rock support system. The DOE will prepare a scoping analysis to determine the significance of the input parameters for review by NRC staff by August 2002. Once an agreed set of significant parameters has been determined by the DOE and NRC staff, the DOE will prepare an analysis of the sensitivity and uncertainty of the preclosure rock support system to design parameters in a revision to Ground Control for Emplacement Drifts for SR, ANL-EBS-GE-000002 (or other document) supporting any potential license application. This is expected to be available to NRC in FY 2003.

2.3.5 RDTME 3.07

The DOE should account for the effect of sustained loading on intact rock strength or provide justification for not accounting for it. The DOE will assess the effects of sustained loading on intact rock strength. The DOE will provide the results of this assessment in a design parameters analysis report (or other document), expected to be available to NRC in FY 2002.

2.3.6 RDTME 3.08

Provide the design sensitivity and uncertainty analyses of the fracture pattern (with respect to Subissue 3, Component 1). The DOE will provide sensitivity and uncertainty analysis of fracture patterns (based on observed orientation, spacing, trace length, etc) on the preclosure ground control system design in a revision to Ground Control for Emplacement Drifts for SR, ANL-EBS-GE-000002 (or other document) supporting any potential license application. This is expected to be available to NRC in FY 2003.

2.3.7 RDTME 3.09

Provide appropriate analysis that shows rock movements in the invert are either controlled or otherwise remain within the range acceptable to provide for retrieval and other necessary operations within the disposal drifts. DOE will provide appropriate analysis that shows rock movements in the floor of the emplacement drift are within the range acceptable for preclosure operations. The *analysis results will be provided in a revision to Ground Control for Emplacement Drifts for SR, ANL-EBS-GE-000002 (or other document) supporting any potential license application. This is expected to be available to NRC in FY 2003.*

2.3.8 RDTME 3.10

Provide technical basis for the assessment that two-dimensional modeling of emplacement drifts is considered to be adequate, considering the fact that neither the in-situ stress field nor the principle fracture orientation are parallel or perpendicular to emplacement drift orientation. The DOE will provide the technical bases for the modeling methods used in ground control analysis in a revision to Ground Control for Emplacement Drifts for SR, ANL-EBS-GE-000002 (or other document) supporting any potential license application. This is expected to be available to NRC in FY 2003.

2.3.9 RDTME 3.11

Provide continuum and discontinuum analyses of ground support system performance that take into account long-term degradation of rock mass and joint strength properties. The DOE will justify the preclosure ground support system design (including the effects of long-term degradation or rock mass and joint strength properties) in a revision to Ground Control for Emplacement Drifts for SR, ANL-EBS-GE-000002 (or other document) supporting any potential license application. This is expected to be available to NRC in FY 2003.

2.3.10 RDTME 3.12

Provide dynamic analyses (discontinuum approach) of ground support system performance using site-specific ground motion history as input. The DOE will provide appropriate analyses to include dynamic analyses (discontinuum approach) of preclosure ground support systems, using site-specific ground motion time histories as input, in a revision to Ground Control for Emplacement Drifts for SR, ANL-EBS-GE-000002 (or other document) supporting any potential license application. This is expected to be available to NRC in FY 2003.

2.3.11 RDTME 3.13

Provide technical justification for boundary conditions used for continuum and discontinuum modeling used for underground facility design. The DOE will provide the technical justification for boundary conditions used in modeling for preclosure ground control analyses, in a revision to Ground Control for Emplacement Drifts for SR, ANL-EBS-GE-000002 (or other document) supporting any potential license application. This is expected to be available to NRC in FY 2003.

2.3.12 RDTME 3.15

Provide field data and analysis of rock bridges between rock joints that are treated as cohesion in DRKBA modeling together with a technical basis for how a reduction in cohesion adequately accounts for thermal effects. The DOE will provide clarification of the approach and technical basis for how reduction in cohesion adequately accounts for thermal effects, including any additional applicable supporting data and analyses. Additionally, the adequacy of the cohesion reduction approach will be verified according to the approach described in Subissue 3, Agreement 22, of the Repository Design and Thermal-Mechanical Effects Technical Exchange. This will be documented in a revision to the Drift Degradation Analysis, ANL-EBS-MD-000027, expected to be available to NRC in FY 2003.

2.3.13 RDTME 3.16

Provide a technical basis for the DOE position that the method used to model joint planes as circular discs does not under-represent the smaller trace-length fractures. The DOE will analyze the available small trace-length fracture data from the Exploratory Studies Facility and Enhanced Characterization of the Repository Block, including their effect on block development. This will be documented in a revision to the Drift Degradation Analysis, ANL-EBS-MD-000027, expected to be available to NRC in FY 2003.

2.3.14 RDTME 3.17

Provide the technical basis for effective maximum rock size including consideration of the effect of variation of the joint dip angle. The DOE will provide the technical basis for effective maximum rock size including consideration of the effect of variation of the joint dip angle. This will be documented in a revision to Drift Degradation Analysis, ANL-EBS-MD-000027 in FY 2003.

2.3.15 RDTME 3.19

The acceptability of the process models that determine whether rockfall can be screened out from performance assessment abstractions needs to be substantiated by the DOE by doing the following: (1) provide revised DRKBA analyses using appropriate range of strength properties for rock joints from the Design Analysis Parameters Report, accounting for their long-term degradation; (2) provide an analysis of block sizes based on the full distribution of joint trace length data from the Fracture Geometry Analysis Report for the Stratigraphic Units of the Repository Host Horizon, including small joints trace lengths; (3) verify the results of the revised DRKBA analyses using: (a) appropriate boundary conditions for thermal and seismic loading; (b) critical fracture patterns from the DRKBA Monte Carlo simulations (at least two patterns for each rock unit); (c) thermal and mechanical properties for rock blocks and joints from the Design

Analysis Parameters Report; (d) long-term degradation of rock block and joint strength parameters; and (e) site-specific ground motion time histories appropriate for postclosure period; provide a detailed documentation of the analyses results; and (4) in view of the uncertainties related to the rockfall analyses and the importance of the outcome of the analyses to the performance of the repository, evaluate the impacts of rockfall in performance assessment calculations. DOE believes that Drift Degradation Analysis is consistent with current understanding of the Yucca Mountain site and the level of detail of the design to date. As understanding of the site and the design evolve, DOE will: (1) provide revised DRKBA analyses using appropriate range of strength properties for rock joints from a design parameters analysis report (or other document), accounting for their long-term degradation; (2) provide an analysis of block sizes based on the full distribution of joint trace length data from the Fracture Geometry Analysis for the Stratigraphic Units of the Repository Host Horizon, ANL-EBS-GE-000006, supplemented by available small joint trace length data; (3) verify the results of the revised DRKBA analyses using: (a) appropriate boundary conditions for thermal and seismic loading; (b) critical fracture patterns from the DRKBA Monte Carlo simulations (at least two patterns for each rock unit); (c) thermal and mechanical properties for rock blocks and joints from a design parameters analysis report (or other document); (d) long-term degradation of joint strength parameters; and (e) site-specific ground motion time histories appropriate for postclosure period. This will be documented in a revision to Drift Degradation Analysis, ANL-EBS-MD-000027, expected to be available to NRC in FY 2003. Based on the results of the analyses above and subsequent drip shield calculation revisions, DOE will reconsider the screening decision for inclusion or exclusion of the rockfall in performance assessment analysis. Any changes to screening decisions will be documented in analyses prior to any potential license application.

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3. REVIEW OF SITE GEOLOGY AND GEOTECHNICAL CHARACTERIZATION ACTIVITIES

3.1 INTRODUCTION – CURRENT DATA COLLECTION PROGRAM

Geologic and geotechnical data collection has been a central focus of the YMP since its inception in 1982. Several reports specifically discussing geotechnical data for underground excavations have been produced for the YMP. Prior to construction of the ESF, Brechtel et al. (1995) completed a report incorporating data from preconstruction drilling and surface mapping for construction of the North Ramp. Kicker et al. (1997) produced a similar report for the ESF Main Drift. Following excavation, four reports were produced summarizing the as-built geology and rock mass rating for the ESF (Beason et al. 1996; Barr et al. 1996; Albin et al. 1997; and Eatman et al. 1997). Finally, one report was produced summarizing the geology and geotechnical characterization of the ECRB Cross-Drift (Mongano et al. 1999).

Two systems of stratigraphic nomenclature are used in the presentation of data: thermal-mechanical (Ortiz et al. 1985) and lithostratigraphic (Buesch et al. 1996). Correlation between these two stratigraphic systems is given in Table 1.

A comprehensive series of mechanical property measurements were conducted on specimens prepared from cores recovered from boreholes NRG-5, NRG-6, NRG-7/7A, SD-9 and SD-12, and to a limited extent from core recovered from boreholes in the ESF (Appendix B). The sampling plan for laboratory-determined geotechnical properties of intact rock was designed for data analysis by thermal mechanical units that are relatively thick, providing a large statistical base. The numbers of measurements performed in determining the geotechnical properties of intact rock are presented in Section 4.2. It should be noted that the principal sampling was for the middle nonlithophysal unit (Tptpmn) while limited sampling, analysis and testing are available for the lower lithophysal and nonlithophysal units (Tptpll, Tptpln). Extensive new drilling of 12-in. (30.5-cm) diameter core is underway in the ECRB Cross-Drift and the ESF. The core from these holes is being used for additional thermomechanical testing of lithophysal rocks and for shear testing of joints.

Rock mass quality assessments were made to evaluate rock mass properties, tunnel stability, and ground support requirements. These assessments utilized the Norwegian Geotechnical Institute rock quality system (Q system) and data from boreholes and full-peripheral tunnel mapping from the ESF and ECRB Cross-Drift (Barton et al. 1974).

3.2 REGIONAL GEOLOGY

Yucca Mountain lies in southern Nevada, in the Great Basin, which is part of the Basin and Range structural/physiographic province. In the Yucca Mountain area, pre-Tertiary rocks (consisting of a thick sequence of Proterozoic and Paleozoic sedimentary rocks) underlie approximately 1000 to 3000 m of Miocene volcanic rocks (Gibson et al. 1990).

Table 1. Stratigraphic and Thermal Mechanical Units Relevant to the ECRB Cross-Drift

Unit Description	Stratigraphic Notation	Thermal Mechanical Notation
Upper Tiva Canyon, undifferentiated	Tpc	TCw
Lower densely-welded subunit of the Tiva Canyon Tuff	Tpcpv3	
Partially to nonwelded lower subzones of the Tiva Canyon Tuff	Tpcpv1-2	PTn
Pre-Tiva Canyon Tuff bedded tuff	Tpbt4	
Yucca Mountain Tuff	Tpy	PTn
Pre-Yucca Mountain Tuff bedded tuff	Tpbt3	
Pah Canyon Tuff	Tpp	
Pre-Pah Canyon Tuff bedded tuff	Tpbt2	
Topopah Spring Tuff: upper partially to non-welded zones	Tptrv2-3	
Topopah Spring Tuff: upper densely-welded vitrophyre	Tptrv1	TSw1
Topopah Spring Tuff: crystal-rich, nonlithophysal zone	Tptrn	
Topopah Spring Tuff: crystal-rich, lithophysal zone	Tptrl	
Topopah Spring Tuff: lithic-rich zone	Tptf	
Topopah Spring Tuff: crystal-poor, upper lithophysal zone	Tptpul	
Topopah Spring Tuff: crystal-poor, middle nonlithophysal zone	Tptpmn	TSw2
Topopah Spring Tuff: crystal-poor, lower lithophysal zone	Tptpll	
Topopah Spring Tuff: crystal-poor, lower nonlithophysal zone	Tptpln	
Topopah Spring Tuff: crystal-poor, lower densely-welded vitrophyre	Tptpv3	TSw3

The Miocene volcanic sequence exposed at Yucca Mountain includes units of the Paintbrush and Timber Mountain Groups (Sawyer et al. 1994). The Paintbrush Group consists of pyroclastic rock and lava that originate from the Claim Canyon Caldera (approximately 6 km north of the study area) and are from 12.8 to 12.7 million years old (Byers et al. 1976; Sawyer et al. 1994). The Paintbrush Group includes a homoclinal sequence consisting of four formations, the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Tuffs. These formations consist of pyroclastic-flow and pyroclastic-fall deposits with interbedded lava that dip 5 to 10 degrees to the east (Byers et al. 1976; Christiansen et al. 1977; Broxton et al. 1993). Two of these formations, the Topopah Spring and Tiva Canyon Tuffs, are voluminous, densely-welded, compositionally-zoned pyroclastic outflow sheets that grade upward from rhyolite composition to quartz latite composition (Lipman et al. 1966; Byers et al. 1976; Schuraytz et al. 1989). The tuff and ash flows of the Timber Mountain Group were erupted from Timber Mountain Caldera complex and consist of the Ammonia Tanks Tuff and the Rainer Mesa Tuff (Sawyer et al. 1994).

Yucca Mountain is bounded by the Yucca Wash to the north, by the Solitario Canyon fault to the west, and the Bow Ridge fault to the east. Alluvium-filled structural valleys, consisting mostly of alluvial fan deposits (fluvial and colluvial sediments) and some thin eolian deposits, lie adjacent to the Bow Ridge and Solitario Canyon faults on the east and west sides, respectively. The Yucca Mountain area is cut by steeply dipping normal faults which strike north to south and separate the Tertiary volcanics into blocks one to four kilometers wide (Scott 1990). The repository block is bounded by the Solitario Canyon fault to the west and the Ghost Dance fault to the east. Both faults dip steeply toward the west, and displacement, amount of brecciation, and number of associated splays vary considerably along their trace (Scott and Bonk 1984; Day et al. 1998). The Solitario Canyon fault has normal down-to-the-west displacement of about 260 m in the vicinity of the repository block. The Ghost Dance fault is in the central part the repository block and is a generally north-striking normal fault zone, with down to the west displacement. The Sundance fault is located in the north-central portion of the repository block. It is a northwest-striking, east-dipping normal fault with a maximum cumulative down-to-the-northeast displacement of 6 to 11 m (Day et al. 1998). Numerous smaller faults and fault zones are present throughout the repository block, generally north-trending with offsets less then 5 m (Mongano et al. 1999).

3.3 LITHOSTRATIGRAPHY AT THE REPOSITORY HORIZON

All of the rocks of the repository host horizon lie within the Topopah Spring Tuff, specifically within the crystal-poor member. The repository host horizon includes rock from the lower part of the upper lithophysal zone (Tptpul) of the TSw1 thermal mechanical unit, and all of the TSw2 thermal mechanical unit, including the middle nonlithophysal zone (Tptpmn), the lower lithophysal zone (Tptpll), and the lower nonlithophysal zone (Tptpln) (see Table 1 and Figure 3). These lithologies are described in this section (Mongano et al. 1999).

Tptpul–The crystal-poor upper lithophysal zone is exposed in both the ESF and ECRB Cross-Drift. The ECRB Cross-Drift begins in the upper central portion of the zone and it exposes rocks of the central and lower portions of the zone from Station 0+00 to 10+15. The upper portion of the upper lithophysal zone is also exposed in the hanging wall of the eastern strand of the Solitario Canyon fault zone from Station 25+90 to 26+57.5. In both exposures, the unit is moderately to densely welded, devitrified, and vapor-phase altered. In general, the rock appears grayish red-purple (5RP4/2) and contains 10 to 40 percent vapor-phase spots, stringers, and partings. The central and lower parts of the zone (Station 0+00 to 10+15) are composed of 0 to 15 percent pumice, 1 to 3 percent phenocrysts, 0 to 5 percent lithic fragments, 10 to 60 percent lithophysae, and 40 to 90 percent matrix. The upper part of the zone (Station 25+90 to 26+57.5) is composed of 5 to 15 percent pumice, 2 to 5 percent phenocrysts, less than 1 percent lithic fragments, 3 to 20 percent lithophysae, and 60 to 90 percent matrix.

Tptpmn–The ESF is excavated in the middle nonlithophysal zone from Stations 27+21 to 57+29, from 58+78 to 63+08, and from 70+58 to 71+68. The ECRB Cross-Drift exposes the middle nonlithophysal zone from Station 10+15 to 14+44. In general, the moderately to densely welded, devitrified and variably vapor-phase altered unit is composed of less than 5 to 10 percent pumice (locally 25 to 35 percent), 1 to 2 percent phenocrysts, 1 to 2 percent lithic fragments, 0 to 1 percent lithophysae, and 85 to 93 percent matrix. Vapor-phase spots, stringers, and partings comprise from 1 to 15 percent of the rock. Smooth, high-angle fractures are typical of the zone, but it also contains occasional low-angle, continuous shears and cooling joints. Another feature characteristic of the Tptpmn is the presence of low-angle concentrations of vapor-phase minerals. These features appear as continuous partings subparallel to the dip of the unit.

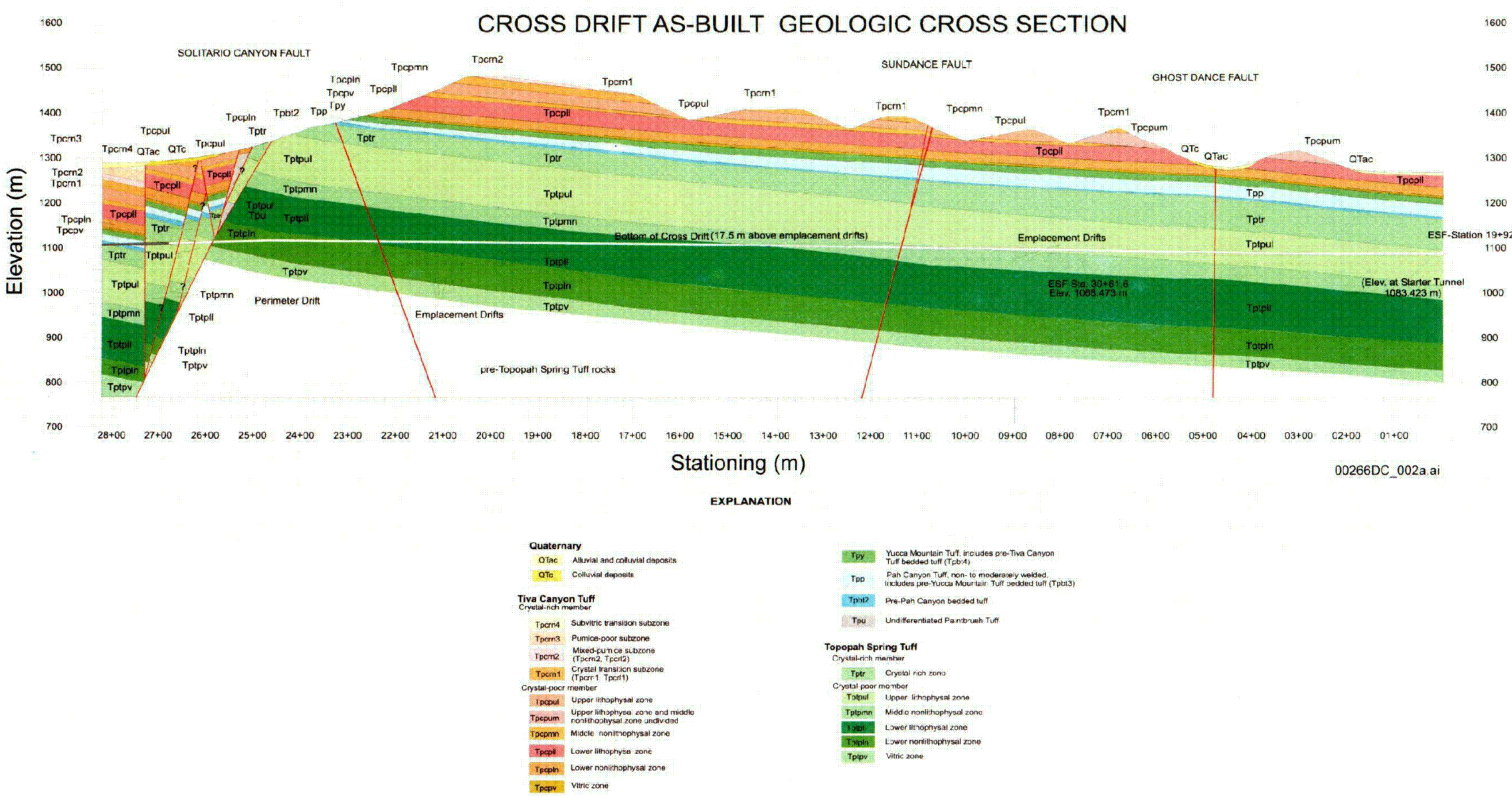


Figure 3. Geologic Cross Section through the ECRB Cross-Drift (approximately East–West)

C02

Tptpll–The ESF exposes a small portion of the upper contact of the lower lithophysal zone from Station 57+29 to 58+78. The lower lithophysal zone is exposed along the ECRB Cross-Drift from Station 14+44 to 23+26. In general, the moderately to densely welded, devitrified, and vapor-phase altered unit is composed of 3 to 7 percent pumice (locally 10 to 35 percent), 1 to 2 percent phenocrysts, 1 to 5 percent lithic fragments (locally 12 to 15 percent), 5 to 30 percent lithophysae (locally 1 to 5 percent), and 56 to 90 percent matrix. Lithophysae vary in size from ten centimeters to greater than 1 meter in diameter. Throughout most of the unit, vapor-phase spots, stringers, and wisps comprise between 3 and 12 percent of the rock. In several intervals, however, vapor-phase alteration products form 15 to 40 percent of the rock.

Tptpln–The Tptpln, exposed only in the ECRB Cross-Drift from Station 23+26 to 25+85, comprises moderately to densely welded, devitrified pyroclastic-flow material. It is generally composed of 3 to 20 percent pumice, 1 to 2 percent phenocrysts, 3 to 7 percent lithic fragments, 0 to 5 percent lithophysae, and 66 to 93 percent matrix. Vapor-phase alteration products form a minor component of the rock in some portions of the unit. Rocks of the lower nonlithophysal zone vary from a heterogeneous mix of grayish red and grayish orange pink (5YR7/2) to comparatively homogeneous pale red, light brown, pale brown, or grayish brown (5YR6/4). In proximity to the Solitario Canyon fault zone, the unit is brecciated and altered. In this area, the breccia matrix varies from moderate reddish brown to grayish orange pink to pale red; breccia clasts are locally bleached to very light gray adjacent to the fault plane.

3.4 GEOTECHNICAL CHARACTERIZATION

Geotechnical data were collected based on two empirical rock mass classification systems: the Q system (Barton et al. 1974) and the Geomechanics Rock Mass Rating system (RMR system) (Bieniawski 1989). Ratings are assigned to a five-meter length of tunnel using both rock classification systems. The use of this relatively short rating length may have the disadvantage of introducing variations in some evaluated parameters which may be expected to be stable; yet it has the advantage of capturing expected variations in more unstable parameters. For example, considering the Q system, one might assume the number of joint sets would be constant over a long reach of tunnel. Using a five-meter rating length permits evaluation of the actual occurrence of a particular joint set; therefore the rating value for the number of joint sets may vary within a ten-meter reach of tunnel. On the other hand, the five-meter rating length permits a description of the changes in fracture frequency represented by the rock quality designation (RQD). Overall, the five-meter rating length emphasizes changes in rock quality from one length to the next. When longer reaches of the tunnel or various stratigraphic units are compared, differences in the trends of the five-meter ratings and differences in the average ratings are meaningful.

Tptpul–The Tptpul (Station 0+00 to 10+15 and Station 23+26 to 25+85), the longest reach of the ECRB Cross-Drift, has the lowest RQD rating (36 poor), yet the highest Q system rating (14 good). Its RMR value (57 fair)[1] equals the RMR value of the Tptpll. Its lithophysae content range from 10 to 40 percent by volume. These cavities average 10 cm in diameter. Fractures are difficult to distinguish, with an average of only one joint set. No keyblocks are expected to form

[1] Note that the RMR or Q systems are based on fracturing and alteration as the primary structural features that weaken an in situ rock mass. There are no explicit allowances in these methods for lithophysae. Consequently, the lithophysae were accounted for through the RQD in attempting to apply this system to the Tptpul and Tptpll.

within this unit; however, there are occasionally some horizontal cooling joints. It has 11 faults, 1 fault zone, and 25 shears or shear zones.

Tptpmn–The Tptpmn (Station 10+15 to 14+44) has a mean horizontal RQD rating of 60 (fair), including lithophysae, and 62 (fair), excluding lithophysae. The projected Q rating from the predictive report agrees with this assessment. The RMR system rates the Tptpmn and the Tptpln as the highest, with a rating of 60 (fair). The unit is generally characterized by less than 3 percent lithophysae by volume. The Tptpmn has 430 meters of exposure in the ECRB Cross-Drift and has the least amount of fault/shear activity with a total of 1 fault zone, 6 faults, and 13 shears. It has an average of three to three+ random joint sets. The horizontal joint sets, or vapor-phase partings, cause significant problems with keyblocks at Station 10+80 to 11+55 and Station 13+10 to 13+15.

Tptpll–The Tptpll (Station 14+44 to 23+26) has a horizontal RQD rating of 42 (poor). Its tunnel-calculated Q rating is 7.9 (fair), the lowest in the ECRB Cross-Drift. The RMR system estimates for this unit at 57 (fair). The Tptpll is generally characterized by lithophysae of 5 to 30 percent by volume and range in size from 5 to 130 cm. The larger lithophysal cavities tend to be irregular or ellipsoidal features that exhibit prismatic fracturing. The unit has an average of two+ random joint sets; however no keyblock problems are apparent. The Tptpll has 4 faults and 30 shears exposed in 882 meters of rated tunnel.

Tptpln. The Tptpln (Station 23+26 to 25+85) has the best horizontal RQD ratings: 62 (fair), including lithophysae, and 67 (fair), excluding the lithophysal cavities. Its tunnel-calculated Q rating is 12.3 (good). The RMR system rates this unit a 60 (fair). This unit is characterized by generally less than three percent lithophysal cavities by volume. It has an average of three joint sets, with no keyblock problems. The Tptpln has 6 faults and 36 shear or shear zones.

3.5 DISCUSSION OF ENGINEERING CHARACTERISTICS OF ROCK MASS IMPORTANT TO GEOMECHANICAL DESIGN AND PERFORMANCE

As discussed in Section 6.1, the structure of the rock mass plays what is perhaps the most important role in defining the properties and structural response of the repository to thermal and mechanical loading. In particular, the fracture geometry and properties and the degree of lithophysal porosity are the primary geologic structures of importance. Extensive geotechnical mapping of fractures has been performed in the entire ESF and the ECRB Cross-Drift (CRWMS M&O 1998b, Mongano et al. 1999). Figure 4 shows a schematic of the Topopah Spring Formation illustrating the general occurrence of fracturing and lithophysae in the various sub-units of the flow. The occurrence of fractures and lithophysae are roughly inversely proportional. This is illustrated schematically in Figure 4 and demonstrated quantitatively in Figure 5, where the fracture density (fractures with trace length greater than 1 m), determined from detailed line mapping, and the approximate percentage of lithophysal porosity in the ECRB Cross-Drift are shown. The density of fractures with trace length greater than 1 m is significantly larger in the Tptpmn and Tptpln (20-35 fractures/10 m), as compared to 5 fractures/10 m or less in the Tptpul and Tptpll.

3.5.1 Fracturing

Full periphery and detailed line maps, consisting of a description of orientation, trace length, small and large scale roughness, and end terminations for all fractures with trace lengths of greater than or equal to one meter was performed in all drifts. The data base consists of over 35,000 entries and is recorded in CAD drawings as well as spreadsheets.

There are, in general, four sets of fractures in the Tptpmn with the following characteristics:

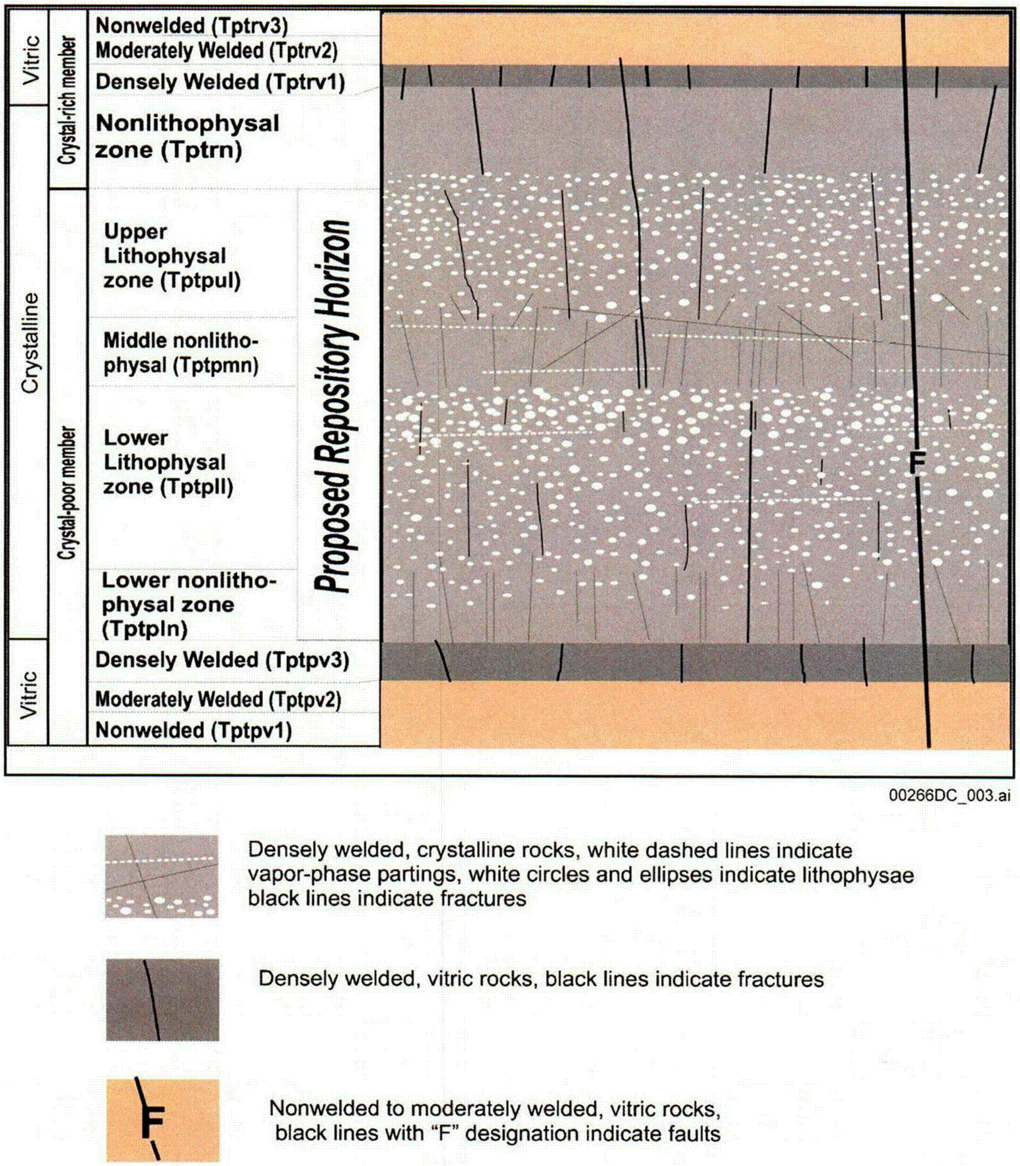
Table 2. General Characteristics of Fracture Sets in the Middle Nonlithophysal Unit

Set	Mean Azimuth/Dip	Mean Spacing (m)	Mean Trace Length (m)	Comment
1	122/84	0.5	2.3	Rough to smooth, planar
2	195/85	1.48	1.9	Smooth but curved
3	306/09	4.2	2.7	Vapor phase partings, rough, cohesive with coating minerals, planar
4	variable/20-45°	-	1.7	Random fractures with generally flat to moderate dip

Source: Mongano et al. 1999

The fractures, particularly the high angle sets (sets 1 and 2) have relatively short continuous trace lengths (Figure 6), with ends often terminating either against other fractures or in solid rock, leaving a solid rock "bridge" between joint tracks. Full periphery maps that logged all fracture traces with length greater than one meter were created behind the tunnel boring machine as the ESF and the ECRB Cross-Drift were driven. A typical full periphery map showing all fractures is shown in Figure 7 with these fractures subdivided into three sets (two sub-vertical, one sub-horizontal plus random) in the lower panels. Figure 8 shows the discontinuous nature of the fractures in each set. This figure shows a photograph typical of the wall of the ECRB Cross-Drift within the Tptpmn. During the detailed line mapping, the fracture traces were painted as seen in this photo. Each fracture termination was logged as being against another fracture, within solid rock, or continuous. The photo shows the common occurrence of fractures that terminate in solid rock (T-junctions) as opposed to continuous structures (arrowheads). The sub-vertical fractures, in particular, often have curved surfaces with large-amplitude (dozens of centimeters) asperities and wavelength of meters. Fractures often terminate in solid rock with discontinuous interconnection to adjacent joint tracks or against other joints.

The sub-horizontal vapor phase partings (Figure 9) are relatively continuous structures seen throughout the Tptpmn. These continuous, but anastamosing fractures are sub-parallel to the dip of the rock unit, and are filled with concentrations of vapor-phase mineralization (primarily tridymite and cristobalite). The surfaces are rough on a small scale, and, unlike the sub-vertical fractures, have cohesion as a result of the mineral filling.



NOTE: The greater intensity and more continuous fracturing occurs in the nonlithophysal units (Tptpmn and Tptpln), with more widely-spaced, shorter fractures occurring in the lithophysal rocks.

Figure 4. Schematic Illustration of the Structure of the Topopah Spring Formation

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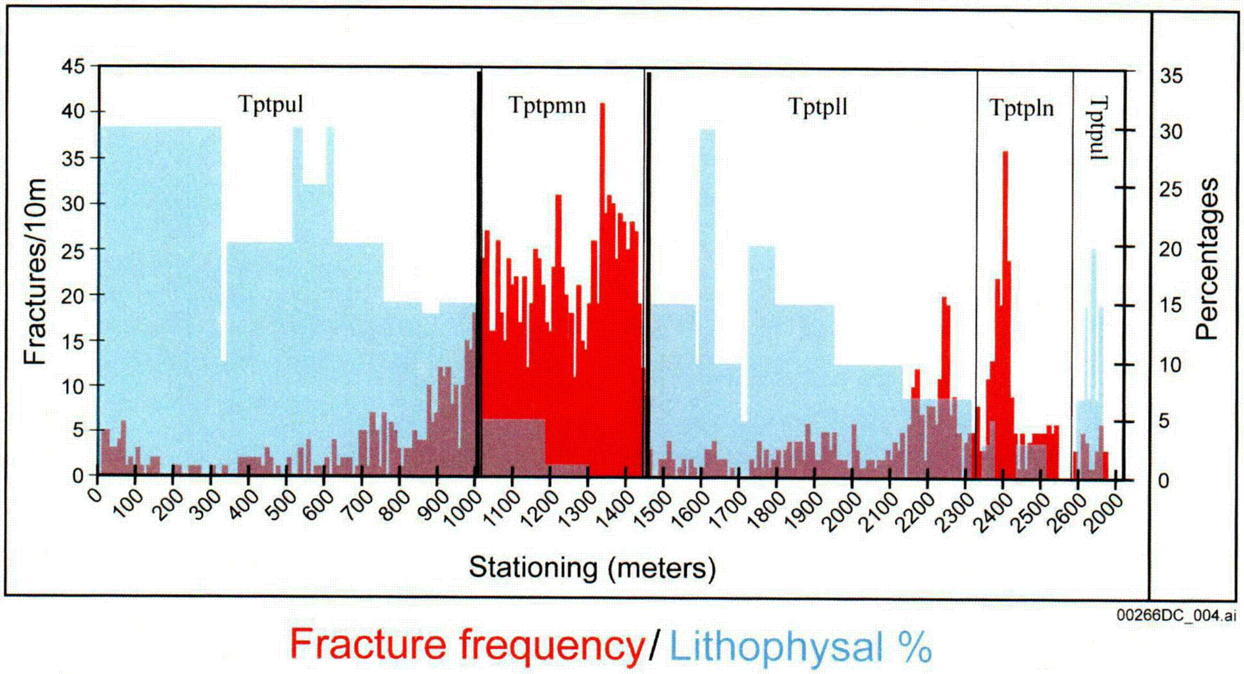

Source: Mongano et al. 1999.
NOTE: Note the inverse relationship between fracture density and lithophysal porosity.

Figure 5. Composite Plot of Fracture Frequency and Lithophysal Porosity as a Function of Distance along the ECRB Cross-Drift

The nature of the fracture geometry is extremely important to estimates of the stability of the rock mass, particularly under seismic shaking, as well as to estimates of the support function and level of required ground support. Most rock mass classification schemes are based on experience of rock masses with continuous joint sets that create regular, blocky masses (e.g., Hoek 2000). In the Tptpmn, the relatively short trace lengths and non-persistent joints create relatively few kinematically removable blocks. This is evidenced by the fact that only a very small number of rock blocks have actually been removed in the ECRB Cross-Drift. Those blocks removed actually occurred under the action of the TBM or were scaled out of the back and walls.

Short-length fractures (less than 1 m trace length), coupled with the lithophysae, are the most important features that govern stability in the Tptpll. Whereas the Tptpul tends to have little small-scale inter-lithophysal fracturing (Figure 10a), the Tptpll has abundant fracturing. Figure 10b, from the upper portion of the Tptpll, shows the intensive fracturing that exists between lithophysae. The fractures, which exist throughout the Tptpll, have a primary vertical orientation, and have lateral spacing of a few centimeters. In some cases, it is difficult to distinguish whether these fractures have been disturbed by mining, or induced by in situ stresses, or whether they are newly created by mining along a weakness fabric in the rock. However, it is clear that the Tptpll has a ubiquitous fracture fabric that is most evident when large diameter core is removed from boreholes. The core, although competent, has numerous fractured surfaces that break into small blocks when stressed (This is discussed further in Section 7.1.3.2). Lithophysae and occasional horizontal fractures tend to create blocks with dimensions on the order of about 10 cm or less on a side. Thin section analyses of the fracturing in the Tptpll and the Tptpmn

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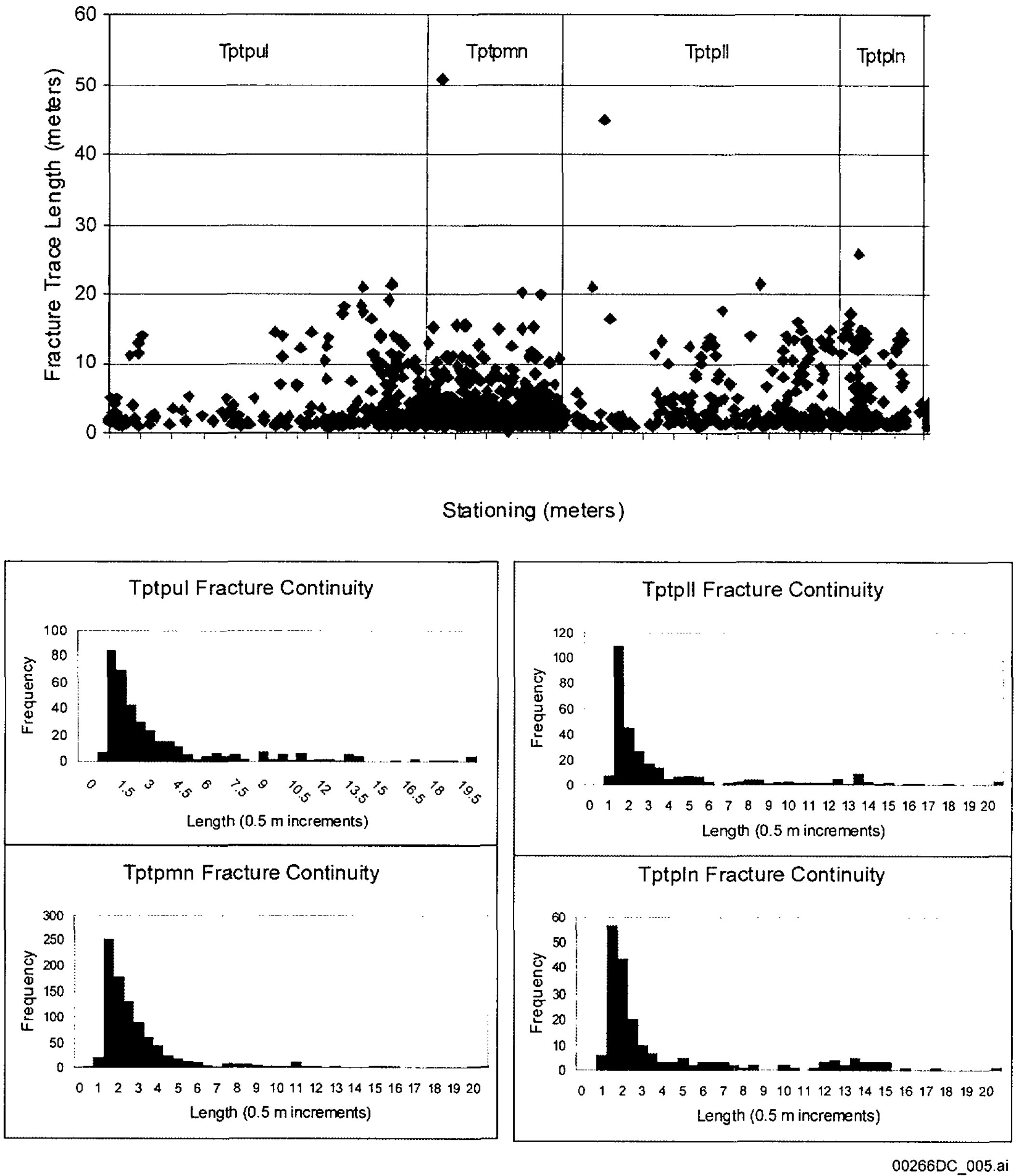
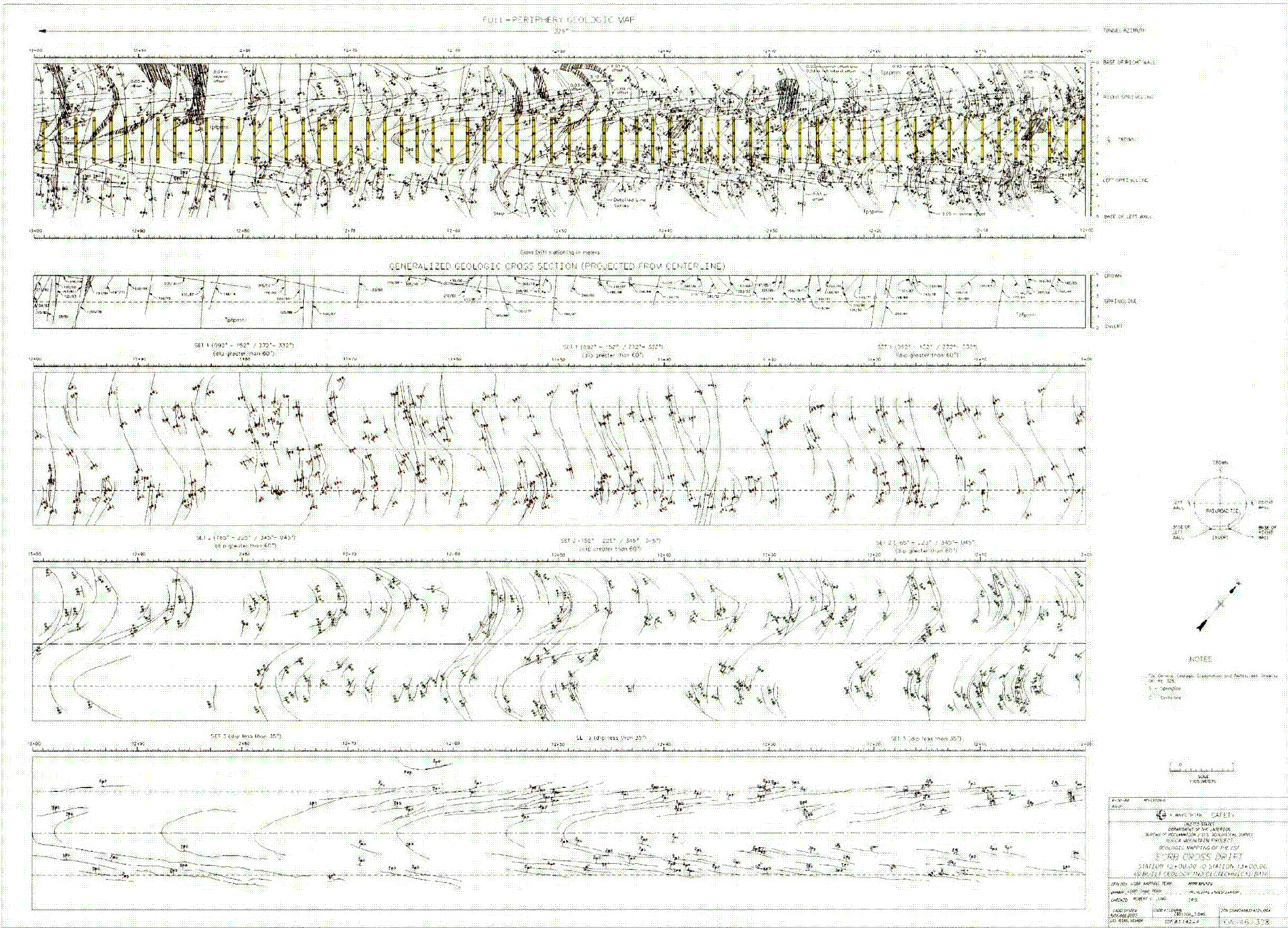
show vapor phase alterations on many of the fracture surfaces within the rock mass away from the tunnel wall, indicating there are numerous natural fractures (i.e., not mining-induced) and were formed during the cooling process.



Source: Mongano et al. 1999.

Figure 6. Fracture Trace Length as a Function of Depth in the ECRB Cross-Drift and by Sub-Unit of the Tptp from Detailed Line Surveys



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Source: DTN:GS990408314224.004.

NOTE: Fracture sets are subdivided into the two subvertical and subhorizontal sets for clarity.

Figure 7. llustrative Example of a Full Periphery Fracture Map from the ESF, Tptpmn

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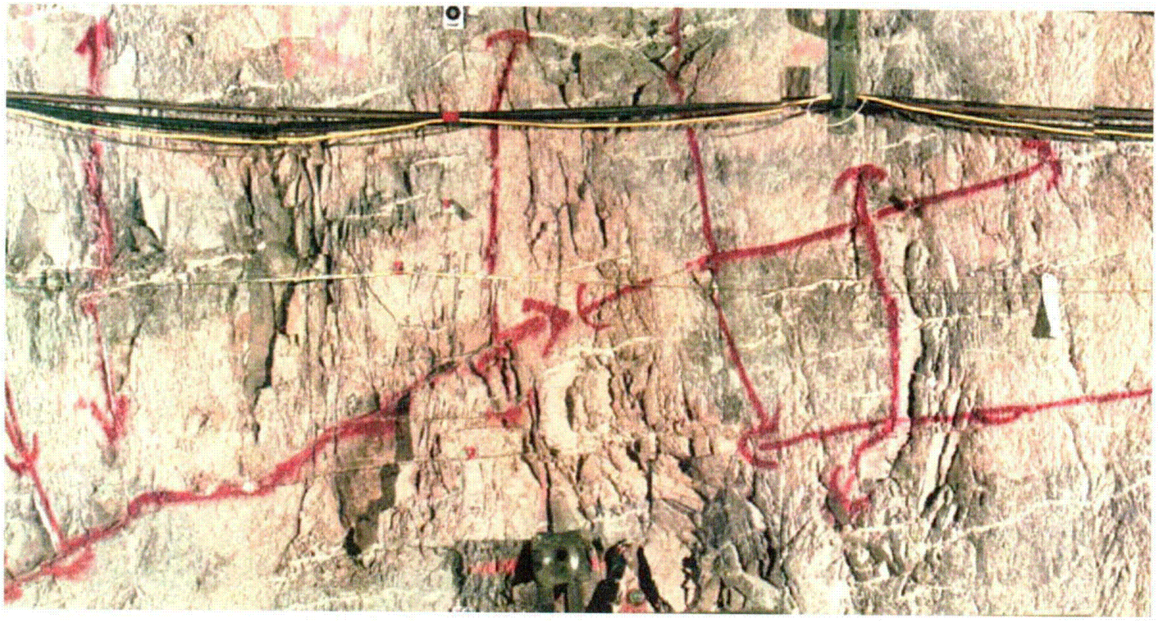
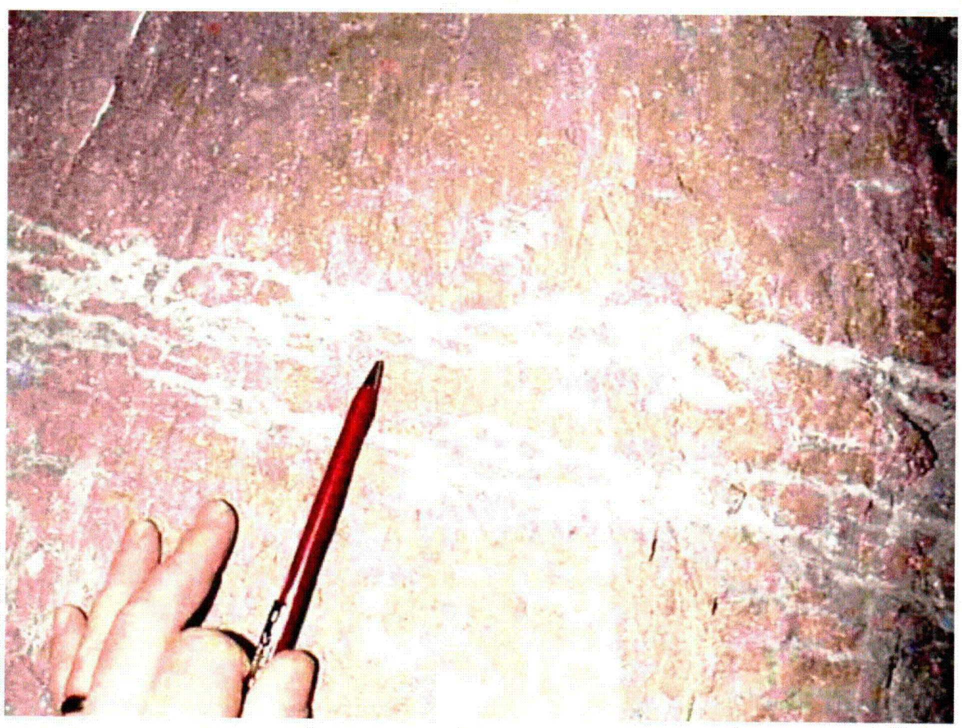


00266DC_007.ai

Source: Mongano et al. 1999.

NOTE: T-junctions on fractures indicate terminations; arrowheads show continuous features.

Figure 8. Fractures in Wall of the ECRB Cross-Drift in Middle Nonlithophysal Unit



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Source: Mongano et al. 1999.

Figure 9. Low-Angle Vapor-Phase Partings in Tptpmn

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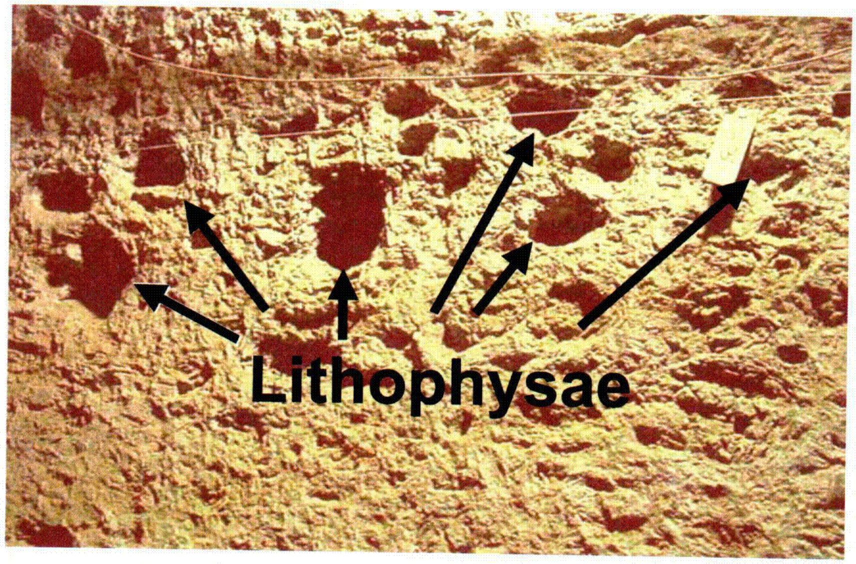
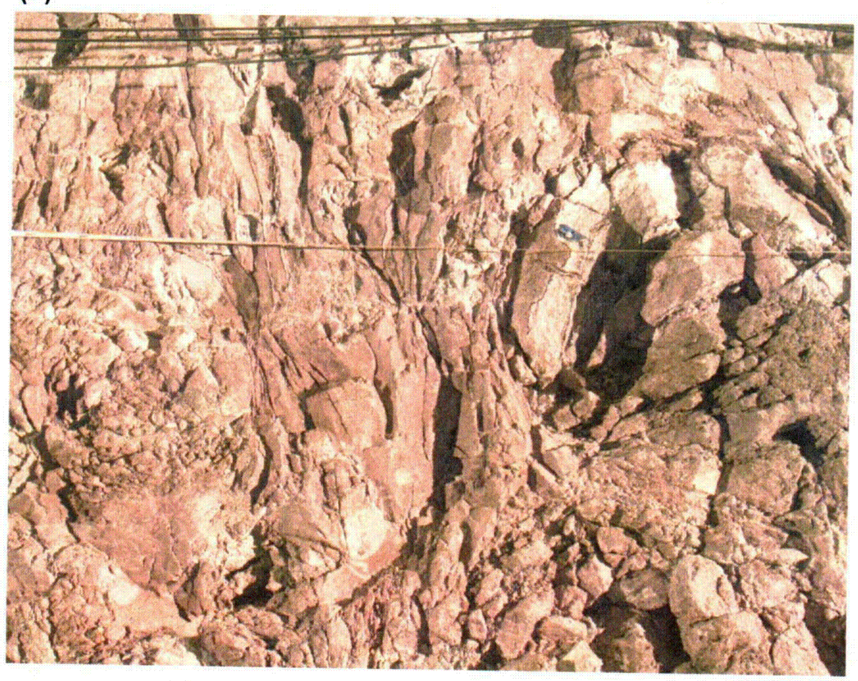
(a)



(b)



00266DC_009.ai

Source: Mongano et al. 1999

NOTES: The Tptpul (a) is characterized by a relatively unfractured matrix between lithophysae whereas the Tptpll (b) is abundant in natural, short length fractures that interconnect lithophysae. Spacing of the fractures is general less than 5 cm.

Figure 10. Comparison of Lithophysae and Fracturing in the Tptpul and Tptpll

3.5.2 Lithophysae

Although the character of the lithophysae varies between the Tptpul and Tptpll as shown in Figure 10, the mineralogy of the matrix material within both of these units is the same as in the nonlithophysal units.

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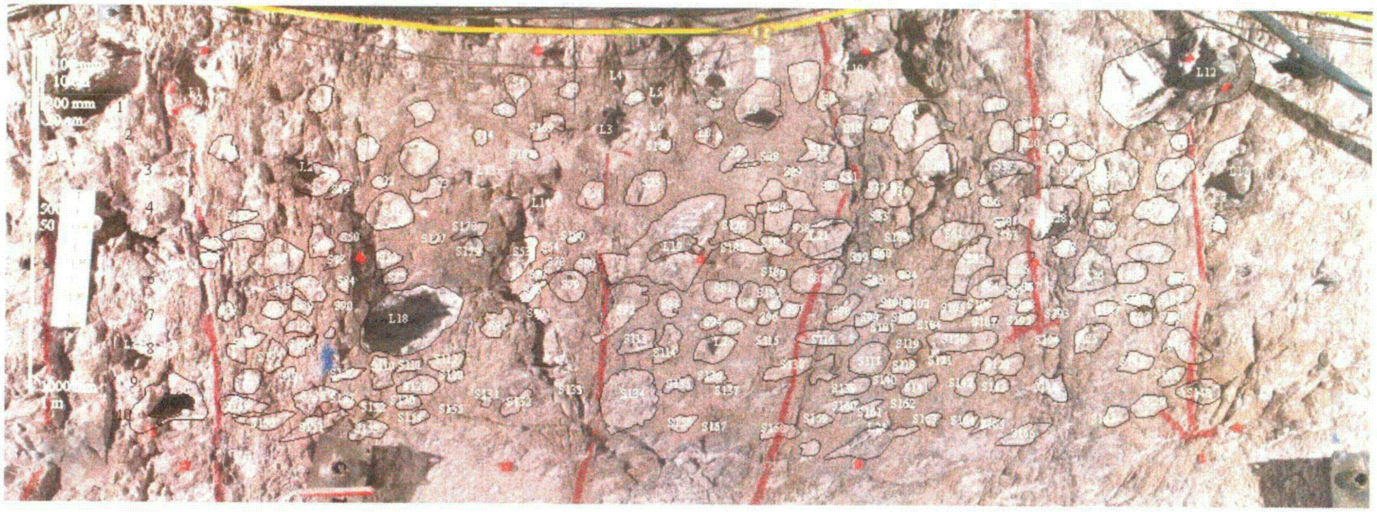
The lithophysae in the Tptpul:

- Tend to be smaller (roughly 1 to 10 cm in diameter)
- Are more uniform in size and distribution within the unit
- Vary in infilling and rim thickness
- Have a volume percentage that varies consistently with stratigraphic position
- Are stratigraphically predictable.

In contrast, the lithophysae in the Tptpll tend to be highly variable in size, from roughly 1 cm to 1.8 m in size. They also:

- Have shapes that are highly variable from smooth and spherical to irregular and sharp boundaries
- Have infilling and rim thickness that vary widely with vertical and horizontal spacing
- Have volume percentages that vary consistently with stratigraphic position
- Are stratigraphically predictable.

Currently, a lithophysal mapping and description project within the Tptpll is nearing completion. This project aims at providing a quantitative assessment of lithophysal porosity, shape, size distribution, alteration and a description of inter-lithophysal fracturing. A total of 18 1×3 m panels have been mapped in detail, and percentages of lithophysae, alteration rims and spots determined. Figure 11 shows a photograph from one of the panels. Photographs are used for classification of the lithophysae, rims and spots and allow determination of the inter-lithophysal fracture density. Current plans call for the results of the lithophysal study to be available in the electronic data management system along with the fracture geometric interpretation in the second quarter of fiscal year 2003, with a Science and Analysis Report to be developed in the first quarter of fiscal year 2004.



00266DC_010.ai

NOTES: The panel shown is 1×3 m. Geometry of each lithophysae, rims and spots are scaled from the photographs and used to determine porosity, size and shape distributions. Lithophysal porosity averages about 20 percent within the Tptpll.

Figure 11. Lithophysal Panel Mapping from the Tptpll

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4. REPOSITORY LOCATION

A repository concept re-evaluation study was recently completed (Board et al. 2002). In this study, the general location of the repository horizon and layout were re-examined in an attempt to minimize performance uncertainties as well as to provide for a flexible or modular layout. Performance uncertainties are minimized through location of the repository within the most heavily characterized geologic region. The purpose of the modular layout is to provide for greater ease in accommodating an incremental approach to exploration and construction as well as accommodation of varying waste types and receipt rates.

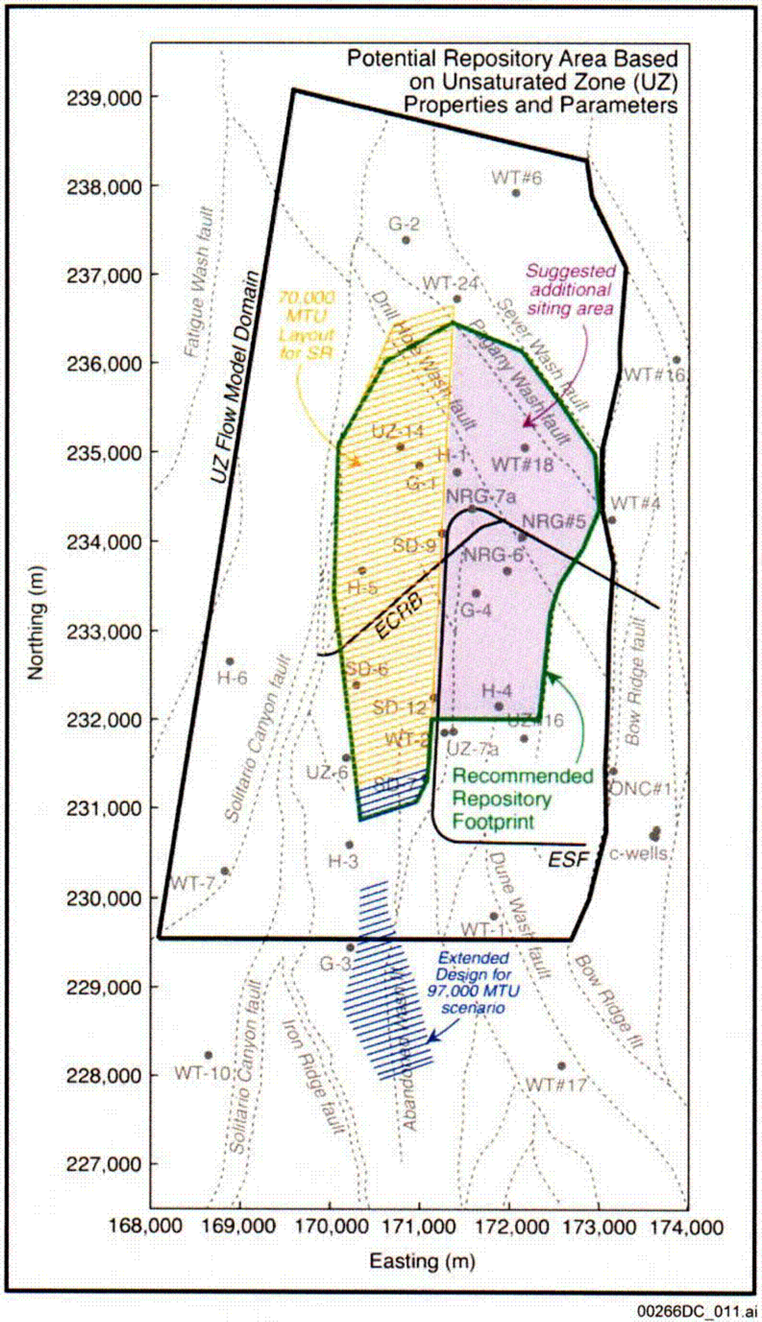
The general footprint within which the repository is to be sited is given in Figure 12. This footprint, determined largely on performance criteria, encompasses most of the Site Recommendation "primary block" and "lower block" regions (DOE 2002). Within this footprint, the repository itself is laid out within the Topopah Spring Formation. The repository layout in plan view is given in Figure 13. The primary difference between the current and Site Recommendation layouts is that the revised configuration is based on a series of smaller panels serviced by surrounding access mains that allow greater flexibility in design and ability to accommodate varying waste receipt rates and thermal profiles. Each panel is developed by first constructing the surrounding access mains. This excavation provides the opportunity for progressively more-intensive exploration and testing of the rock mass as construction proceeds.

The layout consists of five panels, numbered as shown in Figure 13. Panels 1, 2, 3 and 5 all lie in the upper elevation plane (the elevation of the ESF Main lateral. Panel 4 lies approximately 80 m below at the same elevation as the "lower block" of the Site Recommendation layout (the elevation varies from the north to the south end of the repository).

The emplacement drifts are oriented at 72° azimuth for minimization of the formation of removable rock wedges (CRWMS M&O 1999), and have been given nominal lengths of 600 m for ventilation efficiency purposes. The panels are developed by first constructing 7.62 m diameter access mains around the circumference of each panel, followed by development of the 5.5 m diameter emplacement drifts. All emplacement and access drifts are to be driven with tunnel boring machines.

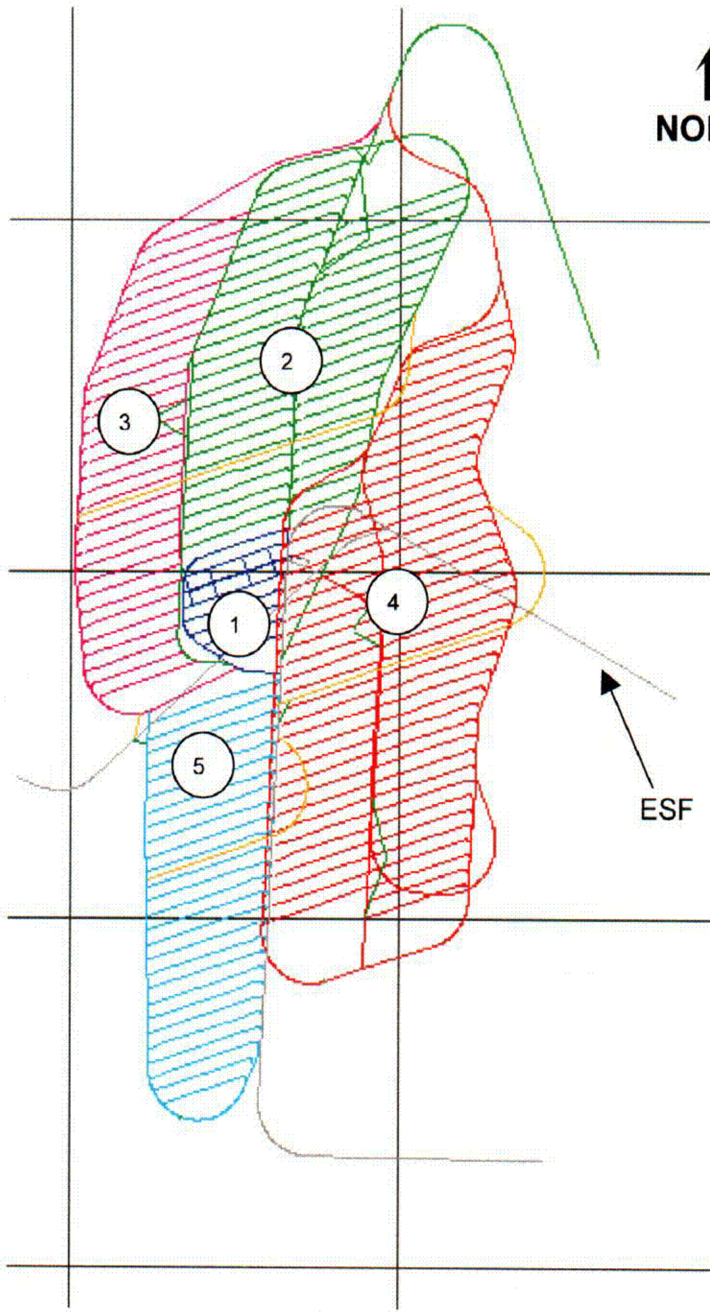
Development of a Performance Confirmation Testing Program is currently underway. This program will provide details on the exploration drilling, geological and geotechnical mapping and in situ testing that will be conducted during construction as well as during the preclosure period. The circumferential development of the mains will allow exploration of the rock mass comprising the panel prior to emplacement drift development.

The various Topopah Spring sub-zones that are intersected by the drifts are shown in Figure 14. As seen, the emplacement drifts are found primarily within the Tptpll (roughly 72 percent), and the Tptpmn (roughly 20 percent). Emplacement within the Tptpul and Tptpln comprise the remaining roughly 8 percent of the layout.



Source: Board et al. 2002.
NOTES: The repository footprint is outlined in green. The figure also includes geologic structure and location in relation to the Site Recommendation layout.

Figure 12. Repository Siting Footprint



Source: Board et al. 2002.

NOTES: The layout consists of five panels located on two elevations. Only panels 1, 2, 3 and a portion of panel 4 are needed for the 70,000 MTHM layout. See also Figures 12 and 14. The repository waste panel loading sequence is still under consideration. Grid spacing is 2000 meters.

Figure 13. Conceptual Layout of the Repository within the Siting Footprint Boundary

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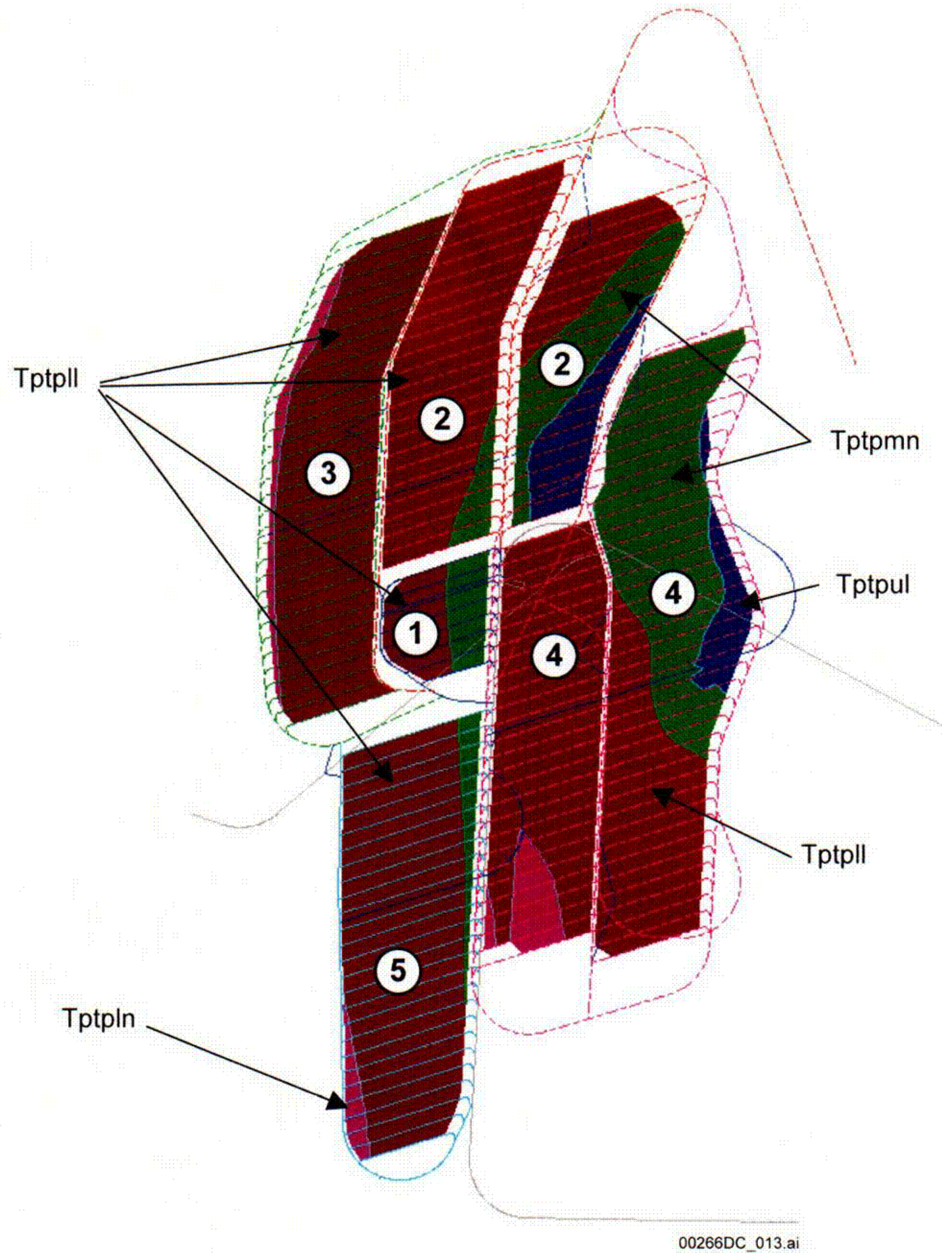


NOTE: Panel 4 to the east is on an elevation approximately 80 m below Panels 1, 2, 3 and 5.

Figure 14. Overlay of the Topopah Spring Geologic Sub-Unit on Repository Layout

5. GEOMECHANICAL ISSUES AND DATA NEEDS FOR USE IN DESIGN AND PERFORMANCE ASSESSMENT STUDIES

5.1 INTRODUCTION

The broad geomechanical KTI agreements that the ORD must resolve are similar in many respects to issues that confront many large underground construction projects. The uniqueness of the present project involves the additional design and performance variables that need to be taken into account, particularly high temperatures and extended periods of time as well as the reliance on numerical models rather than empirical design methods. Resolving these issues will require the following actions:

- Gathering data for estimation of thermomechanical material behavior of the major rock mass geologic units that comprise the repository horizon, and determining how this behavior is affected by environmental conditions (i.e., temperature, moisture) and time

- Estimating the variability of the material behavior as a function of the geologic variability across the site, and examining the impact of uncertainties in rock property measurements and how this uncertainty propagates through the numerical modeling and design calculations

- Determining the preclosure ground support requirements and specifying a support system and maintenance strategy capable of ensuring waste retrieval

- Estimating the stability and possible failure modes of emplacement drifts due to preclosure and postclosure seismic shaking and general thermal and time-related degradation effects.

The above issues result in two major classifications of issues and data needs: those associated with gathering of material properties or geologic data, and those associated with use of numerical modeling for design and performance assessment.

5.2 MATERIALS PROPERTIES AND GEOTECHNICAL CHARACTERIZATION ISSUES

5.2.1 Materials Properties and Geotechnical Characterization Issues/Needs

As described in the previous section, the repository footprint is located approximately 70 percent within the Tptpll and 20 percent within the Tptpmn, with the remaining 10 percent falling inside the Tptpul and Tptpln. The solid groundmass of these sub-units of the Topopah Spring formation have approximately the same mineral composition and texture, but the distinctly different physical structure of the lithophysal and non-lithophysal units leads to different thermal and mechanical response.

The difference in physical character of these sub-units can be reduced to the character of the internal structures within them. The nonlithophysal units are generally hard, strong, fractured rocks with matrix porosities of 10 percent or less (Appendix B). The primary structures in these units are fractures that formed during the cooling process and have undergone little to no postformation shearing. The lithophysal units, on the other hand, have significantly fewer fractures of significant continuous length (i.e., trace length greater than 1 m), but have relatively uniformly distributed porosity in the form of lithophysal cavities. Lithophysal porosity in the Tptpul and Tptpll is on the order of 10 to 30 percent by volume. The groundmass that makes up the rock matrix is heavily fractured with small scale (lengths on the order of 1 cm) inter-lithophysal fractures in the Tptpll, but is relatively unfractured in the Tptpul.

The structural response of the lithophysal and nonlithophysal rock masses is expected to be distinctly different due to these structural differences. The mechanical response of the nonlithophysal units is expected to be governed by the longer cooling fractures whereas the lithophysal cavities and groundmass short trace length fracture density will control the response in the lithophysal units. The cavities in the lithophysal units also have an impact on the thermal properties of the rock mass.

Due to the difference in physical character of the units, different geomechanical issues will dominate for each unit.

5.2.2 Nonlithophysal Units

5.2.2.1 Existing Database

A significant database of thermal and mechanical properties from laboratory and field testing currently exists for the nonlithophysal rocks and fractures. A detailed review of the database is given in Appendix B, and only a brief overview given here. The number of tests for various properties that have been conducted is illustrated in Figure 15 below. As seen in this plot, the base of mechanical information is particularly extensive, including basic uniaxial, triaxial and tensile strength testing, rotary shear testing of fractures and basic physical properties testing.

Hundreds of thermal tests (including tests for thermal capacitance, conductivity, and expansion) have been conducted in the laboratory and at the site for both the lithophysal and nonlithophysal rocks.

The rock properties data base has recently been compiled in a convenient format by test type, and further subdivided as "Q", "non-Q", or "To Be Verified". Statistics of each test type have been determined, and CAD-based geometric plots made of the location of samples with respect to the repository footprint area and geologic unit for visualization purposes. An example of the graphical presentation of these data for the uniaxial compressive strength is given in Figure 16.

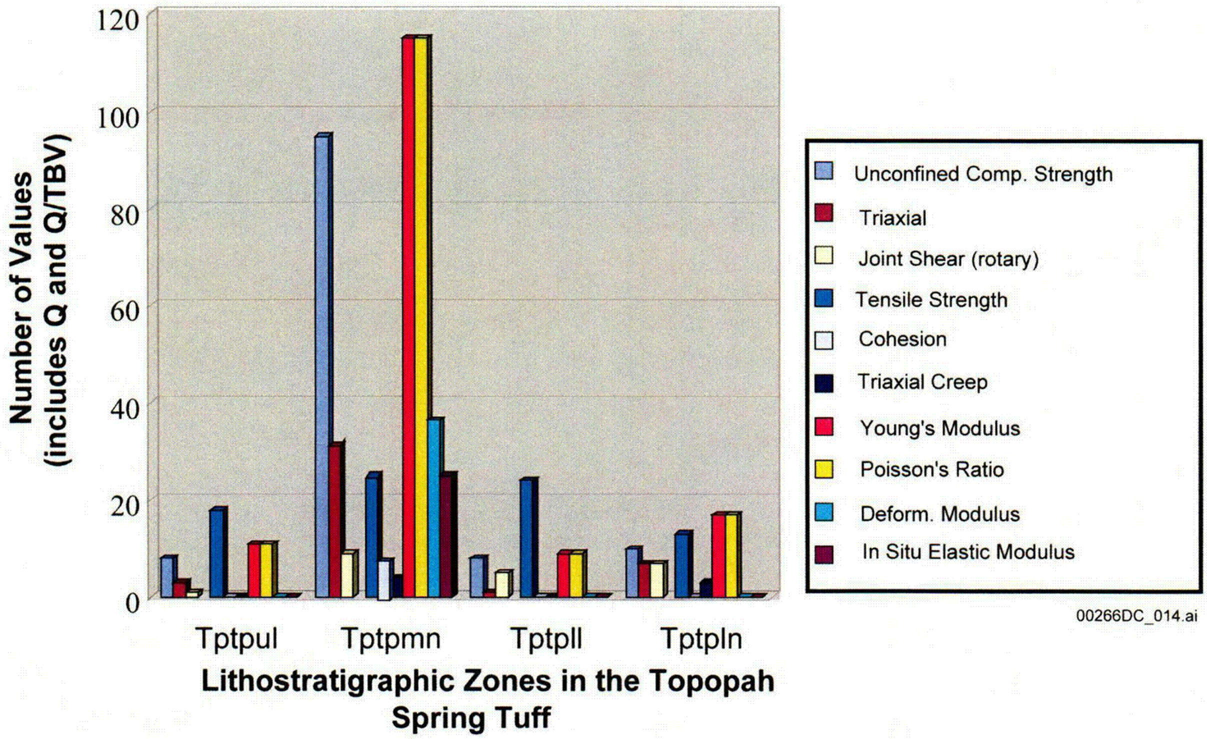
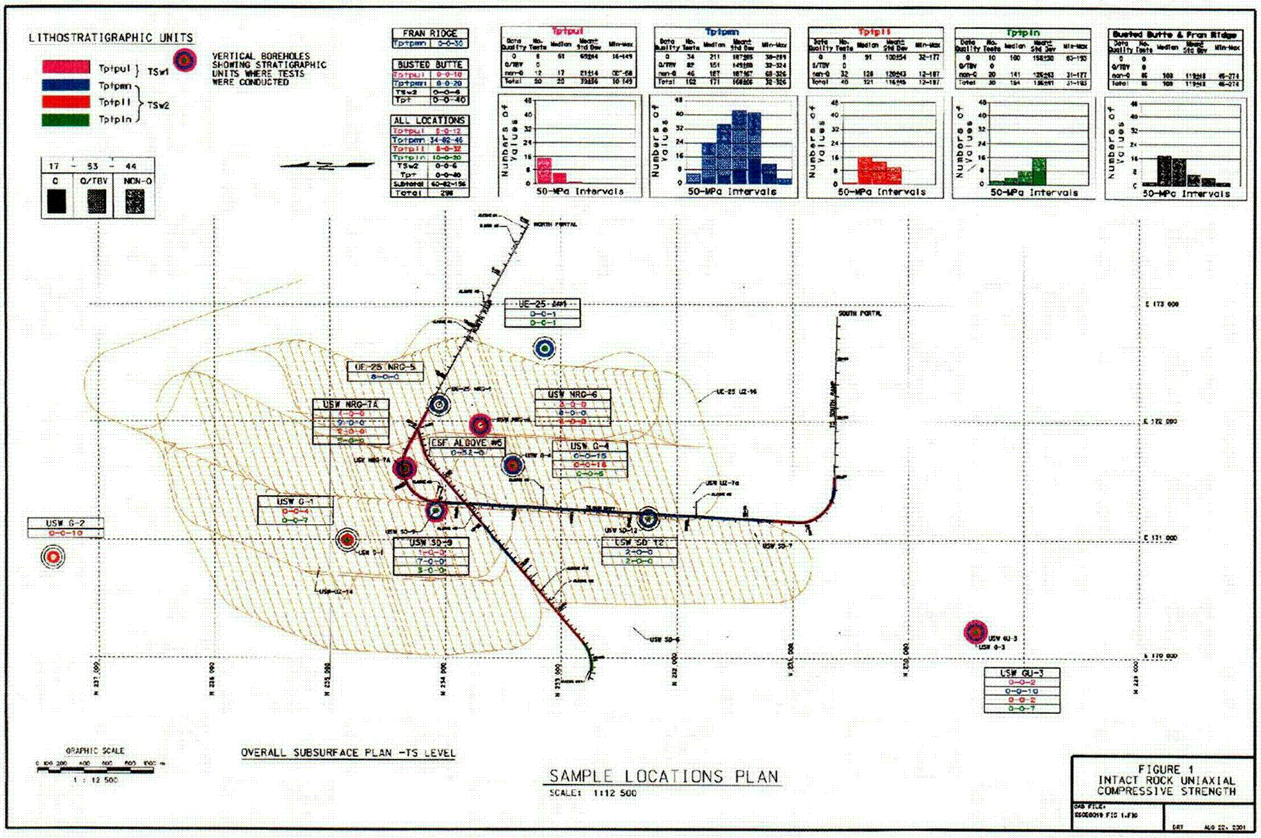


Figure 15. Number of Basic Mechanical Tests Conducted on Various Sub-Zones of the Topopah Spring Tuff as of 2001

In general, the testing on intact nonlithophysal rocks shows that they are hard, strong and brittle rocks with uniaxial compressive strengths averaging around 180 to 220 MPa for 25 mm diameter samples. Underground observations indicate generally excellent mining conditions with minimal ground support. However, this is not always true in localized areas of the Tptpmn that are highly fractured. Since the mining and thermally induced stresses are expected to be relatively small in comparison to the intact block strength, the possible failure response of the openings will likely be controlled by the fracture geometry and properties, and not the intact rock strength. Therefore, the primary conclusions from a review of the Tptpmn database are that:

- A significant and adequate base of intact material properties data exists for the nonlithophysal rocks.
- The geometry and surface properties of fractures will likely control excavation mechanical behavior under excavation, thermal and seismically induced stresses. Additional information is needed on the fracture surface properties to supplement the existing rotary shear test results. Fracture geometry is discussed below.
- There is a need for additional testing for time-dependant strength response (e.g., static fatigue testing).



NOTE: Plan view of the ESF and the ECRB Cross-Drift with an overlay of the former Site Recommendation Repository Primary Block Layout. Summary statistics for each host unit are given at the top of the figure. This type of plot has been developed for all of the rock mechanical and thermal properties as a visualization tool.

Figure 16. Location of Uniaxial Compressive Strength Test Samples

5.2.2.2 Summary – Major Issues for the Nonlithophysal Units

The primary outstanding issues and their related KTI agreements are as follows:

- Need for development of a geometric representation of fracturing based on field database (associated agreements RDTME 3.04, 3.08, 3.10, 3.11, 3.15, 3.16, 3.17, 3.19). A fracture geometry representation is needed as input to discontinuum numerical models of ground support and rockfall. The fracture geometry representation, based on the existing extensive fracture data base, needs to reasonably reproduce the observed fracture geometry data within the ESF and the ECRB Cross-Drift. The model should include, in addition to the statistical variation in dip, dip direction and dip spacing, a representation of the discontinuous nature of the jointing (i.e., the trace length of the fractures and the presence and nature of solid rock “bridges” between joint tracks and joint terminations).

- Need for development of improved estimate of joint strength properties and roughness (dilation angle) (associated agreements: RDTME 3.06, 3.07, 3.17, 3.19, 3.20).

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- Need for development of an improved understanding of the time-dependent fatigue strength of the rock matrix (associated agreements: RDTME 3.07, 3.11, 3.17, 3.19).
- Need for development of an estimate of the time-dependent fatigue strength of the rock joints (associated agreements: RDTME 3.04, 3.11, 3.17, 3.19, 3.20).

The above items deal primarily with the description of the time-dependency of the rock matrix as well as the geometry and properties of rock joints, and how these are represented in numerical models of excavation response to mining effects and thermal and seismic stresses. It is the goal of the project to present a clear picture of the method for inclusion of the geology and its variability directly into the modeling. The proposed method for developing a model of the fracturing is described later.

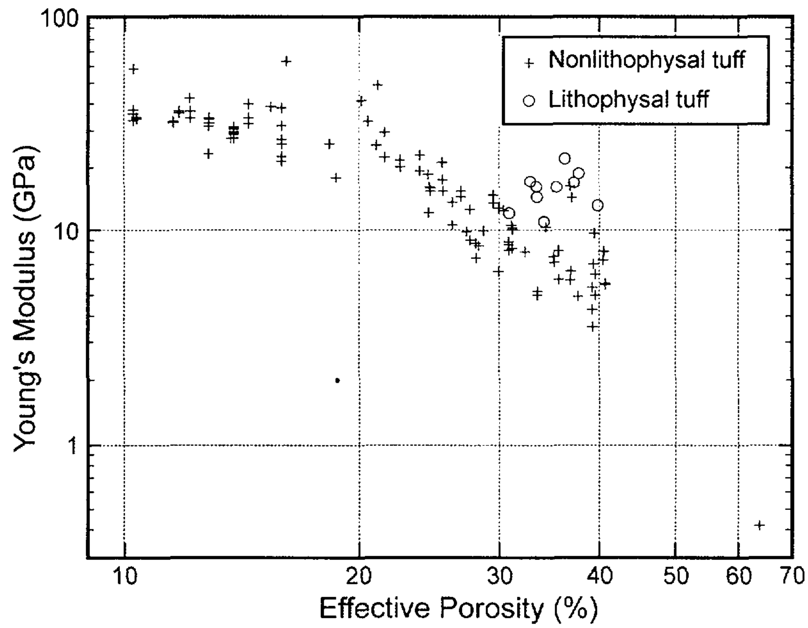
5.2.3 Lithophysal Units

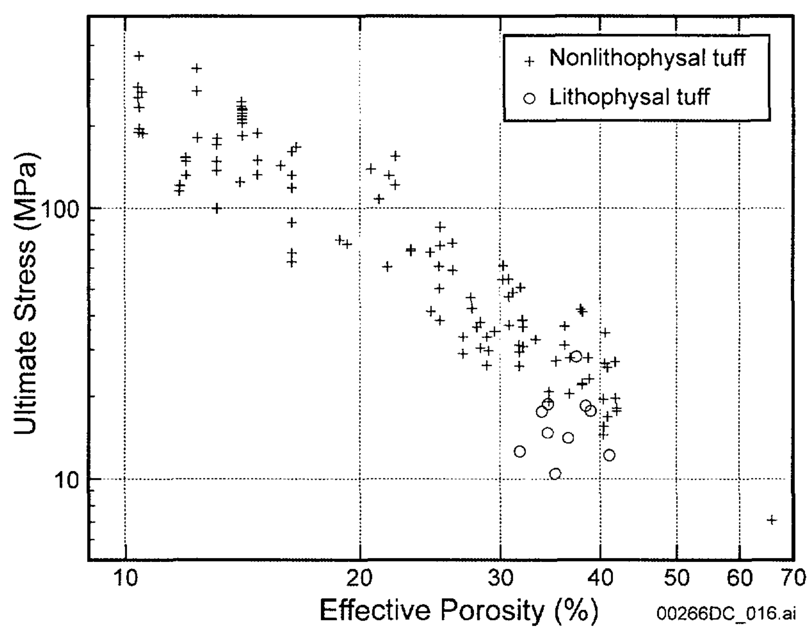
5.2.3.1 Existing Data Base

The current geomechanical data base in the lithophysal units includes primarily index properties, strength and thermal testing on small cores (1 to 2 in. [25 to 50 mm] diameters) from the Tptpul and Tptpll (Appendix B). The mechanical testing data comprising this set are largely uniaxial compression and Brazilian tensile strengths. Triaxial testing is generally not possible due to the difficulty in jacketing samples for confinement.

The testing has shown that a strong relationship exists between compressive strength, modulus and porosity for all tuffs as shown in Figure 17. Here, the mechanical properties database, including tuffs from the Topopah Spring sub-units, as well as other welded and non-welded units, is given in terms of porosity. As noted in Appendix B, there is both porosity and size dependence to the mechanical properties. The porosity dependence is obvious from this figure, but the range of data for a given porosity is partially a function of the size of the sample as shown in Figure 18.

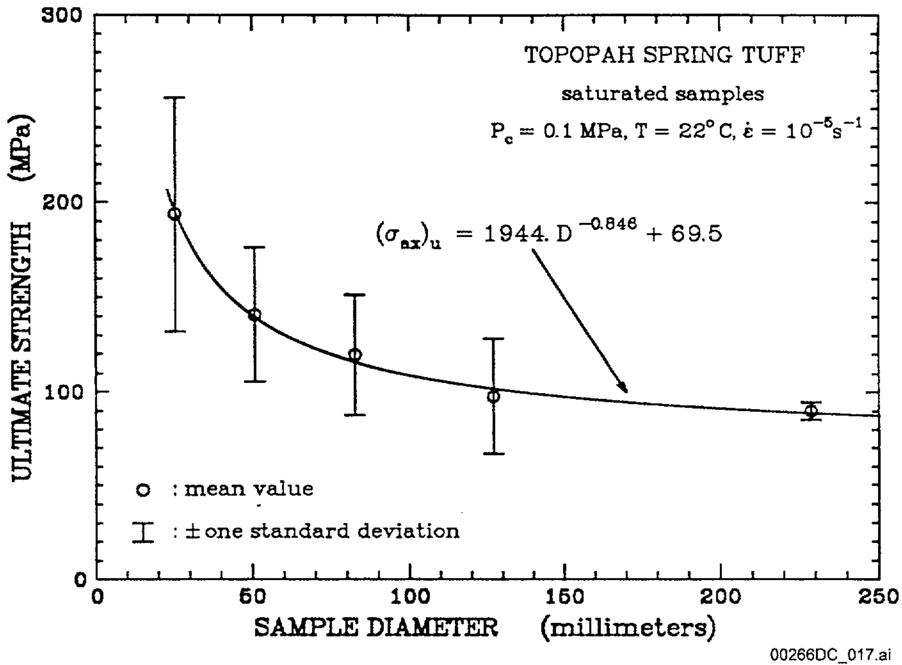
Uniaxial compression tests have been conducted in the Tptpll and Tptpul, primarily on cores with 1 to 2 in. (25 to 50 mm) diameters, but with a few tests on 10.5-in. (267 mm) diameter samples, such as the one in Figure 19. The small diameter cores do not provide representative in situ strengths and moduli since samples of this size do not contain lithophysal cavities. Of greatest interest are the results from strength testing of 10 to 10.5-in. (254 to 267 mm) diameter cores from the Tptpul obtained from Busted Butte (Price et al. 1985). These tests give a better indication of the in situ strength of lithophysal rocks, and show uniaxial compressive strengths (UCS) ranging from 10.3 to 27.8 MPa, with moduli ranging from 10.9 to 21.5 GPa. Figure 20 shows the correlation between the UCS and elastic modulus for these tests. The linear relationship of these properties is probably linked to their dependence on porosity.





Source: Price et al. 1985.

Figure 17. Intact Rock Modulus and Strength as a Function of Effective Porosity



Source: Price 1986.

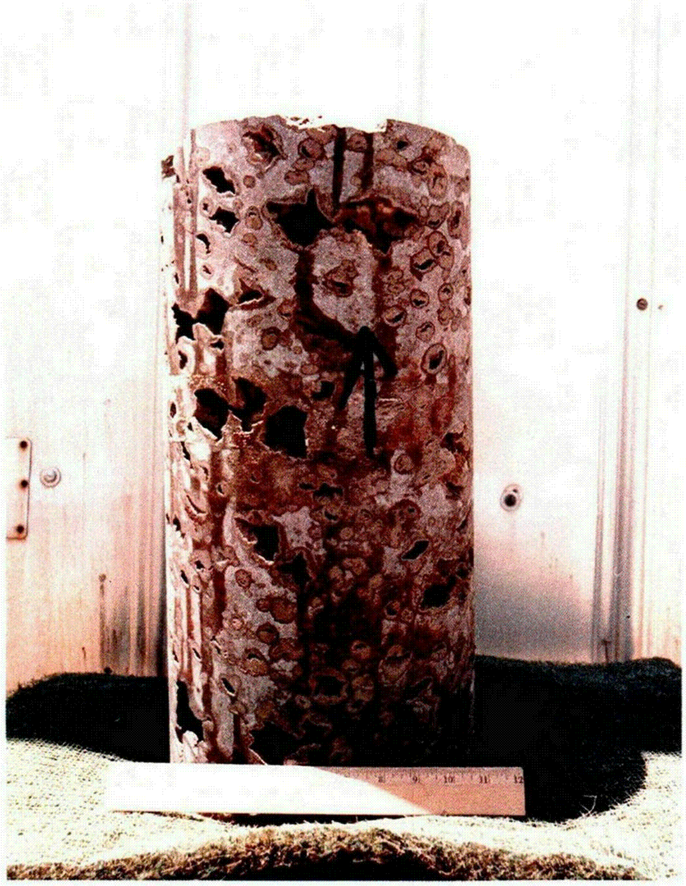
NOTE: P_c = atmospheric confining pressure, T = temperature, $\dot{\varepsilon}$ = strain rate, $(\sigma_{ax})_u$ = ultimate strength (MPa), and D = sample diameter (mm).

Figure 18. Effects of Sample Size on the Uniaxial Compressive Strength of Welded Tuff from the Middle Nonlithophysal Zone (Tptpmn)

A significant base of laboratory-scale thermal properties testing (Appendix B) exists for the lithophysal rocks, including thermal capacitance, thermal conductivity and thermal expansion. As was the case with the mechanical properties testing, the thermal tests have largely been conducted on small diameter cores which do not take into account the presence of the lithophysal porosity. To address this issue, a number of in situ borehole heater tests are either complete or in progress in the Tptpll of the ECRB Cross-Drift for the purposes of measurement of thermal conductivity and thermal capacitance. The tests include:

- Single heater and single instrumentation borehole
- Array of 3 heaters, 3 instrumentation boreholes
- Single heater, 2 instrumentation boreholes.

Tests 1 and 3 are similar in geometry and are used to determine thermal properties using a simple test array. The second test, which includes more heaters, heats a larger rock volume. Results from tests 1 and 3 exhibit a bulk thermal conductivity of about 1.74 W/m°K (BSC 2002, Table 7-9). The porosity at the test locations varied between about 8.1 and 31.5 percent (BSC 2002, Section 7.2.3). The bulk thermal conductivity is about a 15 to 20 percent decrease in value from the nonlithophysal rocks. The analysis of these tests has been used to develop an experimental basis for accounting for the effects of lithophysal porosity on thermal properties of the repository host rocks (BSC 2002).



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Source: Price et al. 1985.

Figure 19. Photograph of a 10.5-in Diameter Core Sample

5.2.3.2 Discussion – Rock Testing Approaches in Lithophysal Rock

The existing data show that porosity appears to be the most significant physical parameter that controls rock mass thermal and mechanical properties in the lithophysal sub-units. The total porosity of the tuffs is made up primarily of matrix porosity and lithophysal porosity. The matrix porosity, which is roughly the same for all of the Topopah Spring sub-units, is essentially grain to grain void space, and is around 10 percent by volume (Appendix B). In the lithophysal rocks, the lithophysal cavities add an additional 10 to 30 percent (approximate) void volume. The lithophysae range in size from a few centimeters up to approximately a meter, resulting in size as well as lithophysal-porosity dependence of rock mass properties. In the following discussions, the term "porosity" refers to total porosity.

Thermal properties of the rock mass can be measured in situ with relatively simple heating experiments as discussed in which the test porosity and saturation levels for the test site are documented carefully prior to testing.

Measurement of mechanical properties is more difficult. Typically, a rock mechanics characterization program aimed at understanding the mechanical constitutive behavior of the rock mass and defining the range of properties is based on a combination of laboratory testing

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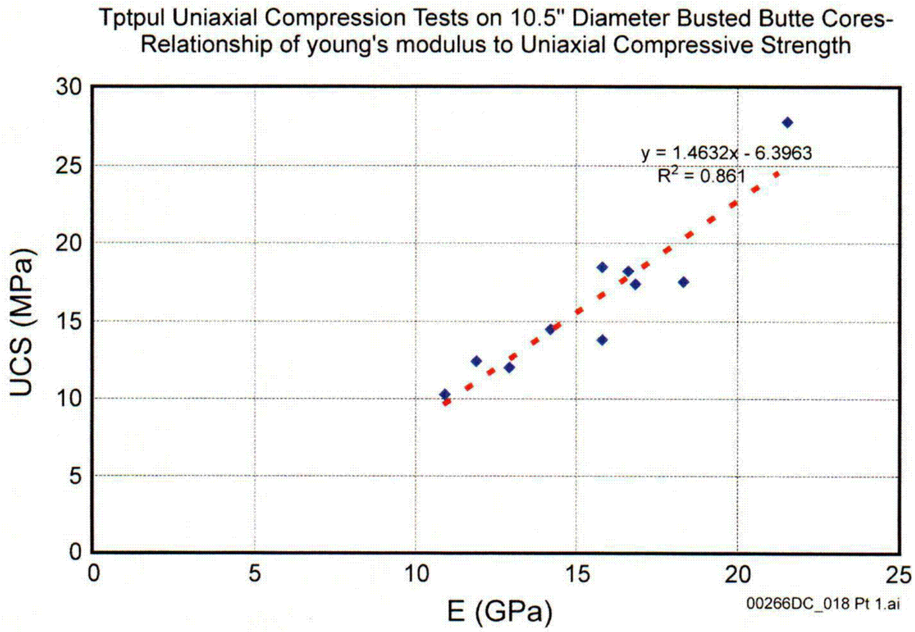
and field rock mass classification. Both of these approaches are problematic in the lithophysal rocks. First, as mentioned above, the rock mass properties are both porosity and size dependent.



Source: Price et al. 1985.

Figure 20. Relationship of Uniaxial Compressive Strength and Young's Modulus for Large Core Testing from the Tptpul, Busted Butte

There are obvious difficulties in sampling and testing material with voids with a size range from a few centimeters to greater than a meter in diameter. Testing of small diameter cores, which make up the entirety of the surface exploration holes, is of limited value as they obviously sample only the solid matrix (the groundmass) and not matrix-plus-void. Large-diameter coring of this material is particularly difficult (although possible) as the core tends to break between lithophysae and along the ubiquitous small-scale fractures in the groundmass. Obtaining standard 2:1 length:diameter ratio samples for 10 to 12 in. (25 to 30 cm) diameter core (i.e., 50 to 60 cm in length) is especially difficult. In situ compression testing on large samples is feasible, but time consuming and costly.

It is obvious from this discussion that a typical form of "statistical" rock testing program, based on testing of many small diameter cores from surface and underground-based drilling for the purpose of exploring the variability of the properties is not possible here.

Although rock mass classification and its use in estimation of rock mass properties is a valuable tool, it must be based on extensive past experience in the same or similar rock types. The existing classification schemes (Barton's Q-classification, Bieniawski's RMR, and Hoek's GSI) do not have case histories for highly porous rocks, or rocks with lithophysal or vesicular cavities. Therefore, the classification schemes typically employed in mining and construction are useful as a means of comparison, but of limited value in the lithophysal units.

In conclusion, thermal and mechanical properties determination of the lithophysal rocks needs to be based on:

- Materials properties testing on samples of lithophysal rocks sufficiently large that they represent the in situ scale
- Observation of the mechanical response of the ESF and the ECRB Cross-Drift.

It is also required that an estimate be made of the variability of the mechanical behavior for the range of lithophysal conditions in the repository block. However, due to the limitations discussed above, only a small number of tests on large cores or in situ samples is possible. A strategy for resolving this issue involving calibration of appropriate numerical models for understanding the basic mechanisms of the rock mass behavior is given in Section 6. Once validated, the intention is to use the model as a "test bed" or numerical tool for assisting in the understanding of the impacts of lithophysae geometry on rock mass properties.

5.2.3.3 Summary - Major Issues for the Lithophysal Rocks

The primary outstanding issues for the lithophysal rocks and their related KTI agreements are as follows:

- Documentation of geometric the variability of lithophysae and small-scale fracturing both vertically and laterally within the lithophysal rocks, particularly the Tptpll, which makes up the bulk of the repository emplacement area (RDTME KTIs 3.04, 3.05, 3.06, 3.08, 3.17)
- Development of additional test data on the thermomechanical properties of the lithophysal rocks, and document the impact of lithophysal porosity and small-scale fracturing on the constitutive behavior and scaling effects (RDTME KTIs 3.04, 3.05, 3.20)
- Determination or estimation of the average and range of block sizes produced as a result of failure of the lower lithophysal unit (RDTME KTIs 3.17)
- Determination of the strength degradation (static fatigue) response of lithophysal rock as a function of loading level. Estimate how this time-dependent degradation impacts possible failure mechanism and extent in the emplacement drifts (RDTME KTIs 3.05, 3.07, 3.11, 3.20).

5.3 NUMERICAL MODELING ISSUES

The design and evaluation of performance of the repository excavations requires examination of loading conditions and time periods unprecedented in common practice. Additionally, there is little contemporary experience in excavation in lithophysal tuffs. For these reasons, there will be a greater reliance than in typical civil construction projects on predictions using numerical modeling methods.

Numerical models for geomechanics purposes fall into several categories: continuum and discontinuum methods, two- or three-dimensional models, methods for inclusion of site-specific geologic conditions into the models, quasi-static or dynamic models, and initial and boundary conditions. Below, the background of the modeling issues raised in the KTI agreements are discussed.

5.3.1 Continuum vs. Discontinuum Methods (Associated RDTME KTIs 3.11, 3.12, 3.20)

In continuum methods, the effect of geologic structure in the rock mass (i.e., fractures or lithophysae) is "lumped" into a thermomechanical constitutive model that represents the overall effect of the structure. In a discontinuum model, the fractures (and possibly lithophysae) are represented explicitly in the model as interfaces or cavities. The difference between these techniques is therefore the level of detail that is necessary in the model to adequately capture the deformation and failure mechanisms.

In the nonlithophysal units, the failure mode of the rock mass is controlled by the fracture distribution and geometry (i.e., wedge-type failures). Predictions will be made of gravitational, thermally and seismically induced rockfall, which is clearly structurally controlled and three-dimensional in nature. Therefore, a three-dimensional discontinuum approach appears warranted in this case. From a ground support design perspective, both continuum and discontinuum models and both two- and three-dimensional approaches have merit. This is particularly true in examination of thermally induced loading scenarios. It is always advisable to begin analyses at the simplest possible level of rock mass geometry – in this case, two dimensional approaches that may be conservative in their structural representation, but allow ease of parametric examination and interpretation. Continuum-based models that use a constitutive model basis for rock mass description (e.g., Mohr-Coulomb) provide good tools for bounding analyses where the rock mass fracture spacing is small relative to the opening diameter.

In the lithophysal rocks, the plan is to perform modeling predictions to estimate the amount of rock that can fall into the tunnel as a function of time-related degradation and strength loss, as well as from thermal loading and seismic shaking. Geologic observation in the existing tunnels indicates that the size of rock particles will be controlled by the spacing of the lithophysae and the spacing of the ubiquitous, short-length inter-lithophysal fracturing. The widely spaced, discontinuous natural fractures in the lithophysal rocks appear to be of secondary importance in this regard. Although geologic and mechanical test data will be used to confirm the estimated block size, practical observation indicates it will be small, and on the order of inches. Therefore, the approach is not to use modeling to determine the size of rock particles, but only the total amount that will dislodge from a given earthquake event. The most reasonable approach to modeling drift degradation in the lithophysal rocks is to use a discontinuum approach. Here, the overall mechanical response of the rock mass is represented using a constitutive model derived from lab and in situ testing, but allows the rock mass to fracture or break apart as the stresses dictate. The approach is described in detail later.

5.3.2 Two vs. Three Dimensions, Isotropic vs. Anisotropic Models (Associated RDTME KTI 3.10)

Due to fracturing, the response of non-lithophysal rocks are assumed to be anisotropic and three-dimensional in nature. In the lithophysal units, the large-scale fracturing appears to be less important than the impact of lithophysae and small-scale inter-lithophysal fracturing on rock mass strength. Since the lithophysae are laterally consistent within a sub-unit and roughly uniformly distributed through the rock mass, it is reasonable to assume that a mechanical constitutive model, dependent on porosity and matrix strength properties, can capture the general failure mechanisms. There is no reason to assume that the mechanical response is anisotropic since the porosity is distributed uniformly. In other words, the orientation of the opening would appear to be of lesser importance to its mechanical response. Additionally, the lithophysal cavity radius is much smaller than the radius of the opening, and therefore, as long as the properties are determined for size greater than a few lithophysae diameters, a two-dimensional approach would appear adequate.

5.3.3 Geologic "Realism" in Numerical Models (Associated RDTME KTIs 3.04, 3.05, 3.08, 3.10, 3.15, 3.16, 3.17, 3.19, 3.20)

Implicit in the above discussion is the need for a clear methodology for incorporating geologic reality into the numerical models. The proposed approach incorporates two types of mechanical representations based on rock type: a discrete, fracture-based discontinuum approach for modeling emplacement drifts in the fractured, nonlithophysal rocks, and an isotropic constitutive representation for modeling the deformation and failure of lithophysal rocks. The success of both of these approaches is dependent on the ability to demonstrate that the basic representations and rock mass properties have been developed from the geologic mapping and geotechnical characterization as well as field test data.

For example, the three-dimensional discontinuum models of the Tptpmn need to have joint geometries that have been directly derived from field mapping and geotechnical studies, and that sufficient representations are modeled to reflect the statistical variability of the joint orientation, length, and spacing. In a similar fashion, the mechanical constitutive model used to represent the Tptpll and Tptpul needs to be based on compression testing at a large enough scale so that the effect of the lithophysae are adequately accounted for. Additionally, the resulting rock mass property (i.e., strength and deformability) ranges need to be related to the porosity, size and distribution of lithophysae as determined from geologic mapping. Methodologies to ensure geologic "realism" are discussed in Section 6 of this report.

5.3.4 Quasi-Static vs. Dynamic Models (Associated RDTME KTIs 3.12, 3.13, 3.19)

The failure response of the rock mass to dynamic loading is of potential importance to performance assessment at Yucca Mountain. Two numerical approaches are often used to represent this type of problem: quasi-static and fully dynamic models. Since the wavelength of the earthquake ground motions in question are much greater in length than the dimension of the opening (the tunnel is 5.5 meters wide, while an earthquake wavelength would be hundreds of meters in length), the dynamic load is often represented as an equivalent static load, taking into account the ground acceleration of the motion. It is felt that this approach is inadequate for examination of rockfall since it does not account for the translational motion of the tunnel, the transient stress concentrations and complex load path and inertial loading that a tunnel can undergo during high acceleration, long duration earthquakes. The ORD is therefore developing fully dynamic large displacement models for rockfall examination. However, in preclosure time periods, where the accelerations are small, use of equivalent static models may be sufficient for ground support analyses. Therefore, flexibility will be maintained in choice of modeling approach for ground support studies.

5.3.5 Initial and Boundary Conditions (Associated RDTME KTIs 3.13)

The repository excavations are initially loaded by the in situ gravitational stresses. At Yucca Mountain, the vertical, gravitational stress is the maximum component, while the principal horizontal components vary somewhat, depending on the topography. On average, the major horizontal components at 300 m depth are approximately $0.62\sigma_v$ (NE–SW) and $0.36\sigma_v$ (NW-SE), where σ_v is the vertical component, which is approximately 0.024 MPa/m depth.

The repository will undergo thermal loading in which the rock mass temperature will peak within a few hundred years after closure (depending on heat loading and ventilation time), followed by a long cool-down phase. The heating will induce rock mass expansion that will result in increased horizontal stresses at the repository level. This will increase the tangential stresses around the opening that could result in shear failure near the free surface. During cool-down, these thermally induced stresses will decay, with the effect of possible "loosening" of the rock mass. The magnitude of the temperature and stress changes will depend on the thermal loading scenario. Currently, the project is examining a range of thermal loading options. A series of three-dimensional models that include the mountain topography have been run to determine the regional temperature and stress changes as a function of the thermal operating mode.

5.4 CONCLUSIONS

This section of the report has provided a discussion of the basic, overriding issues/information needs that have led to the explicit RDTME KTI agreements. These information needs are as follows:

A. Geological and geotechnical characterization

   1. Development of a data base of rock fracture characteristics and lithophysal content and their variability over the repository host horizon sub-units.

B. Materials Properties Measurement

   1. Nonlithophysal rocks

      a. Development of a representation of the geometry and strength characteristics of fractures and the blocks they form

      b. Development of an enhanced database of the strength properties of joints through direct shear testing. Supplement this laboratory database with analysis of existing field index properties for development of an empirical shear model of the various joint sets

c. Measurement of static fatigue properties of non-lithophysal rock and investigation of the static fatigue response of rock fractures typical of the Tptpmn.

2. Lithophysal rocks

a. Development of thermal and mechanical constitutive models and rock mass properties for lithophysal rocks that accounts for the size, shape, distribution and variability of lithophysae and inter-lithophysal fracturing

b. Investigation of the static fatigue response of lithophysal rocks under long-term mining and thermally induced stresses.

D. Numerical Modeling

1. Determine proper modeling technique for examination of thermomechanical rock mass response under quasi-static and dynamic loading. Investigate continuum vs. discontinuum methods of analysis for ground support and rockfall simulation.

2. Verify proper choice of model dimensions, initial and boundary conditions. This includes accounting for thermally induced stresses and their impact on drift and seismic stability, and the use of site-specific ground motions for earthquake analysis

3. Perform sensitivity studies of tunnel stability and ground support under gravitational, thermal, and seismic loading in the preclosure and postclosure periods.

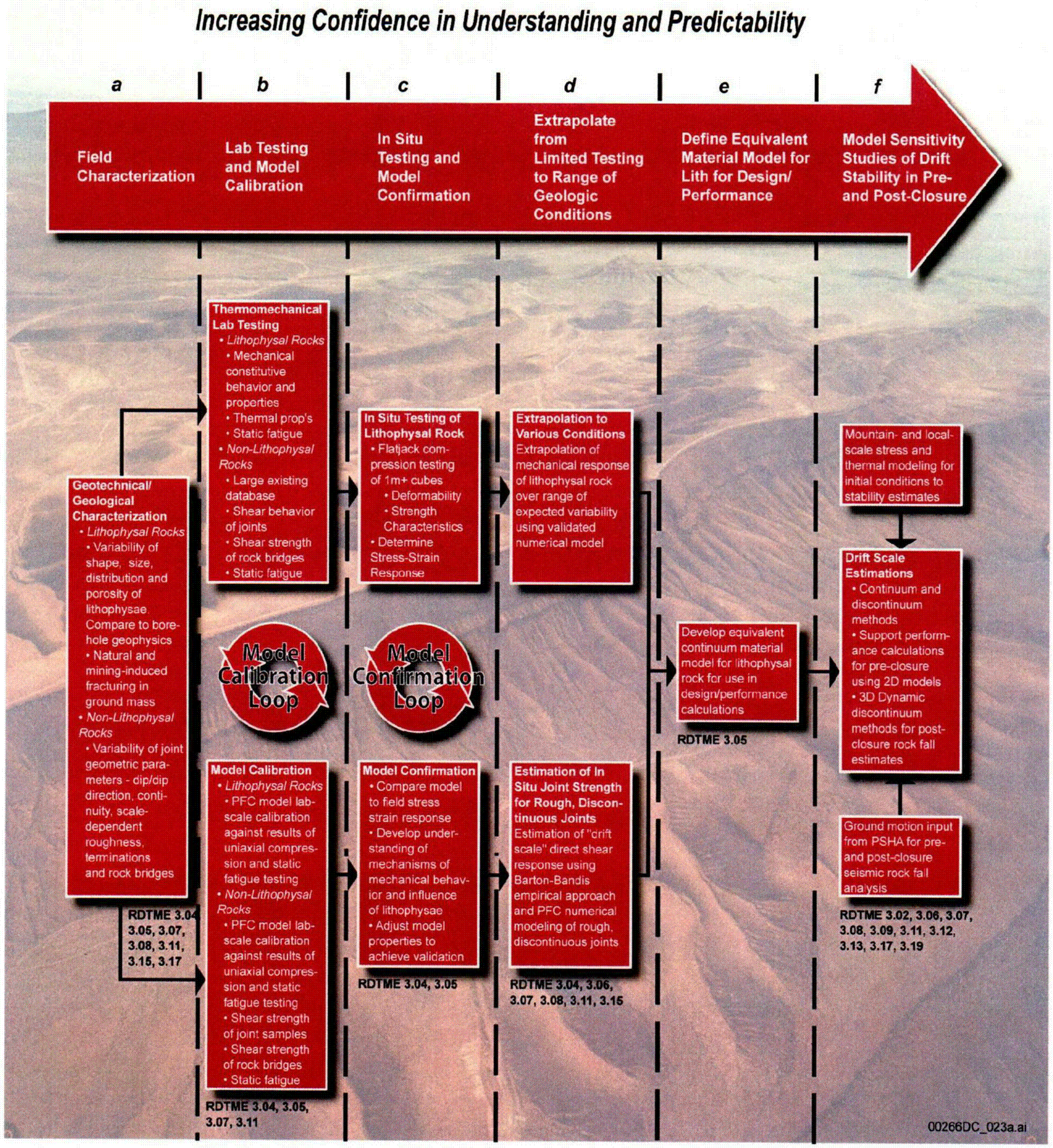
6. APPROACH TO RESOLVING THE AGREEMENTS

The overall approach to resolution of the information needs described in Section 5 and the RDTME agreements is given in Figure 21. The process involves a program of field and laboratory testing, coupled with numerical studies, aimed at providing additional information on the rock mass geology and structure, and their property variations for use as input to numerical sensitivity studies of excavation stability under gravitational, thermal and seismic loading. Integral to this process is development of a detailed and transparent geological and geotechnical basis for the development of the site-specific rock-mass models. The KTI agreements that are addressed at each stage in this process are given in the figure.

The process is composed of six basic program work elements, a through f, given from left to right in this figure. The approach initially involves development of a detailed understanding of the thermomechanical properties and variability of lithophysal and non-lithophysal rocks, and development of validated numerical models that can be used for design and performance assessment (elements a-e). The outcome of this process are material models and properties and their ranges that can be used as input to sensitivity studies. The design and performance assessment modeling (element f) is aimed at estimating tunnel stability in the preclosure and postclosure time frames. In the preclosure time frame, the primary issue is the specification of ground support methods, and in the postclosure, estimation of drift degradation from either thermal or seismic loading, or time-dependent response of the rock mass. The basic program elements are as follows:

a. Field Geotechnical Characterization–Includes further analysis of the extensive, existing rock mass geological and geotechnical characterization data from the ESF and the ECRB Cross-Drift (as well as surface outcrops and boreholes) to estimate the geometrical variability of rock mass structure. This analysis provides the basic rock mass structural input to the modeling and analysis activities.

b. Laboratory Testing and Model Calibration–Perform laboratory testing of large diameter (12 in. [30.5 cm]) lithophysal cores for determination of mechanical and thermal properties as a function of porosity, temperature and saturation level. The results from the laboratory testing are used for estimating rock mass properties, but also provide data for initial testing and calibration of numerical models capable of representing the basic mechanisms of the deformability and yield of lithophysal rocks. A number of numerical approaches will be used for analysis of the lithophysal laboratory and field data. PFC, which uses a "micromechanical" discontinuum approach for representing rock is one approach that will be used for this purpose. This program has the capability of modeling lithophysae, inter-lithophysal fracturing, and complex failure mechanisms. Additionally, it is planned plan to calibrate the FLAC (continuum) (FLAC V3.5, 10167-3.5-00 V 3.5) and UDEC (discontinuum) programs as alternatives to the more conventional means of representing the mechanical behavior of the lithophysal rocks. Additional laboratory testing is planned to determine the shear properties of joints and the time-dependent, static fatigue properties of lithophysal and nonlithophysal rocks.



NOTE: Process starts with compilation and analysis of basic geotechnical mapping, followed by laboratory and field testing and model validation to develop rock mass property estimates for design and performance sensitivity studies.

Figure 21. General Approach to Resolution of the RDTME KTI Agreements

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c. In Situ Testing and Model Confirmation–In situ mechanical and thermal testing of lithophysal rocks to determine the size effect (porosity and fracture) on rock mass constitutive behavior. These tests will further be used for validation of the numerical model at increasing size scales. The outcome here is expected to be a model that can be used with confidence for extrapolating the mechanical response of lithophysal rocks.

d. Extrapolate from Limited Testing to Range of Geologic Conditions–Extrapolation of the properties of lithophysal rocks to the varying conditions of porosity, lithophysal shape, size distribution and spacing, and inter-lithophysal fracture density on mechanical properties. It is impractical to perform a statistically large number of in situ tests to determine strength properties. The goal of this project element is to provide a means by which the effect of lithophysal rock mass variability can be estimated. The results of static fatigue testing will also be included in the model for time-dependent strength representation.

e. Define Equivalent Material Model for Lith for Design/Performance–Here, the constitutive models and the numerical approaches in which they are embedded will be finalized for sensitivity studies. The rock property ranges defined for each geologic unit will need to reflect the impact of the variability of the geologic structure within the particular rock strata. The range of properties also need to reflect the uncertainty in the parameters. The uncertainty will be a function of the scope of rock testing for each unit. The intact rock property data base for the non-lithophysal rocks is large and thus the range of uncertainty in these parameters is more easily defined and evaluated. The properties of the lithophysal rock, on the other hand, are both size and lithophysal porosity-dependent. These dependencies require large scale testing methods, which limits the number and extent of testing, and thus increases the level of uncertainty. Uncertainties will be dealt with in detail in the Design Parameters Analysis Report (scheduled for completion in FY 2003). Additionally, the uncertainty in lithophysal rock properties will be addressed through use of large scale lab and in situ mechanical testing, numerical simulation of lithophysal effects using the PFC program, and numerical sensitivity studies using a wide range of input material properties to verify the sensitivity of the rock mass response to uncertainty in input properties.

f. Model Sensitivity Studies of Drift Stability in Preclosure and Postclosure–Sensitivity studies of excavation stability under gravitational, thermal and seismic loads in the preclosure and postclosure time frames. Here, numerical model sensitivity studies are performed using the range and distribution of rock mass properties determined from the previous project elements. The deformation and yield of the openings in preclosure time will be used to define ground support requirements and methods. A ground support observation and maintenance program for the preclosure period will be developed. The models will also be used to examine time-related degradation and seismic stability for site-specific ground motions at various annual exceedance frequencies.

6.1 PROGRAM ELEMENT A – GEOTECHNICAL AND GEOLOGICAL CHARACTERIZATION OF THE TOPOPAH SPRING FORMATION

6.1.1 Introduction

As reviewed earlier, a very large base of geological and geotechnical data exists from the ESF and the ECRB Cross-Drift facilities. These data include:

- Fracture mapping from full periphery maps and detailed line surveys in which any fracture with a trace length greater than 1 m that crosses a tape line at the tunnel springline has been mapped. Data collected from the detailed line surveys include dip, dip direction, fracture trace length, spacing and position (offset of fracture centroid from the line survey position), and small and large scale roughness, using the U.S. Bureau of Reclamation (USBR) roughness scale. Barton's "Q" classification for the rock mass and joints were also recorded in conjunction with this work.

- Lithophysae mapping and description has been performed as part of the lithophysae study as reviewed earlier. This study provides data on the variability of porosity, size and shape of lithophysae and their distribution within the Tptpll.

- Inter-lithophysal fracture density is available from the detailed lithophysal panel maps constructed within the ECRB Cross-Drift across the Tptpll and from the "small-scale" fracture mapping study.

These data are currently being used for three purposes associated with RDTME KTI resolution:

- Development of representative fracture geometry and characteristics within a rock volume that reasonably represents the variability of those fractures with trace lengths of 1 m or more. This work is being performed for the Tptpmn, Tptpll and Tptpul.

- Development of an estimate of the range and variability of lithophysae shapes, sizes, and porosity within the Tptpll.

- Development of an estimate of the small-scale fracture fabric, density, and length within the Tptpll.

The results of the work described below will be described in a Science and Analysis Report, authored by USBR and U. S. Geological Survey staff, covering the geometric characteristics of fractures and lithophysae, to be released in January 2004. Data from this study will also be described and used in the revision of *Drift Degradation Analyses* (BSC 2001) to be completed in FY 2003.

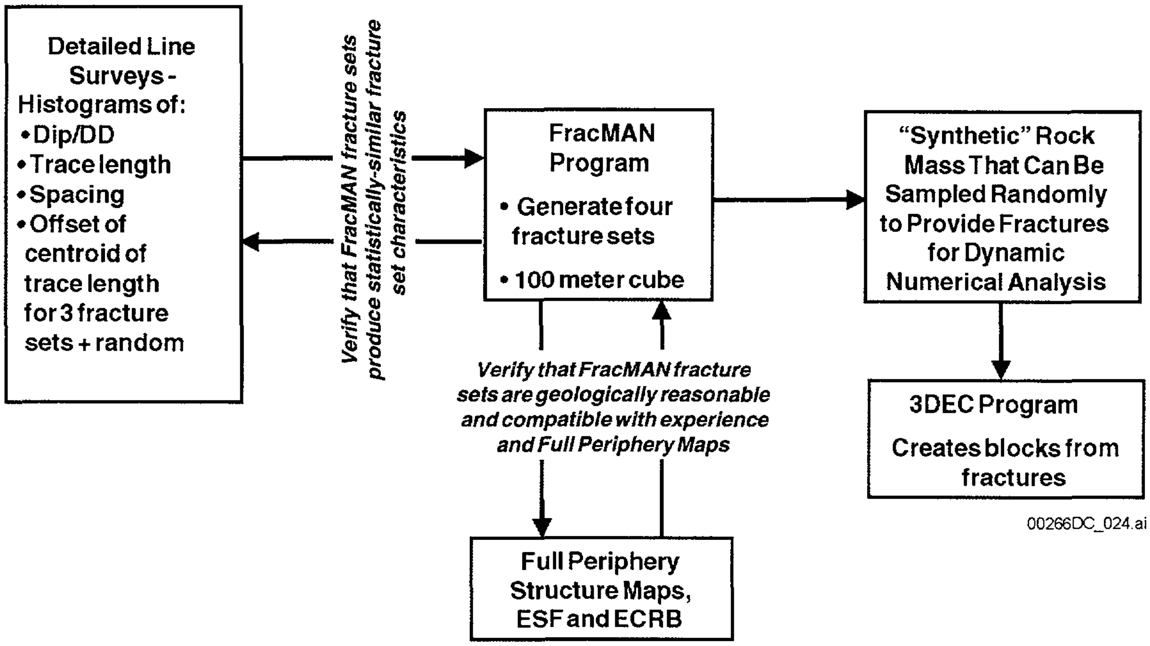
6.1.2 Generation of a Representative Fracture Volume for Ground Support and Rockfall Studies

6.1.2.1 Fracture Data Base and the FracMAN Program

Seismic analyses in the nonlithophysal rocks will be performed using a three-dimensional discontinuum modeling approach since it is assumed that its stability response will be controlled by the fractures. Therefore, a fracture model that reasonably represents the field geometry of the fractures and the rock blocks is essential. The FracMAN program is used here for generation of fracture patterns in three dimensions for use as input to the discontinuum modeling (Figure 22). FracMAN is a special-purpose fracture modeling tool that was developed for creation of synthetic fracture representations for use in hydrologic modeling, reservoir engineering and rock mechanics applications.

The detailed line survey data base is first subdivided by rock unit–the Tptpmn, Tptpul, Tptpll and Tptpln. The approach here is to use the detailed line survey statistics (i.e., dip, dip direction, fracture trace length, spacing and position [offset of the fracture centroid from the detailed line survey line]) to generate a statistically equivalent set of fractures in a volume of rock that can be sampled for the numerical modeling. The fracture set descriptive data are generally described by FracMAN as a form of power law (the proper form of law is determined initially). The fractures are then distributed within the volume assuming a Poisson process. A cubic volume is generated that has sufficient edge length to allow a large number of randomly located tunnels and the volume surrounding them to be developed for the ground support or seismic sensitivity simulations. The total number of tunnels and their associated rock volumes will be determined iteratively as the variability in rockfall introduced by the fracture geometry becomes apparent.

FracMAN has numerous capabilities that can be used to verify the generated fracture geometry. These include the ability to create detailed fracture statistics that can be compared to those from the actual detailed line surveys to make certain the populations have similar geometric and statistical characteristics. Also, synthetic full periphery maps can be created from the FracMAN results for a comparison to actual tunnel observations to make certain that the results make practical geological sense. Numerous index values related to fracture density and fracture surface area for the overall volume for each joint set can also be made within FracMAN to establish that the correct numbers, spacings and lengths of fractures are being generated. The generation of the fractures is somewhat of an iterative process, particularly establishing the fracture length (or radius, since the base case assumes circular disks to describe the fractures) and spacing. Due to the finite continuity of the fractures, the trace length distributions derived from the detailed line surveys are used as an initial guide to selection of fracture length. The length is iteratively adjusted to achieve a reasonable estimate to the in situ trace length distribution as seen from the detailed line surveys and on the full periphery maps. Since the detailed line survey values may show bias against structures whose dip is subparallel to the tunnel, correction factors are necessary. Mauldon corrections, which accommodate the finite size/persistence of the fractures, will be used instead of Terzaghi corrections that assume infinite persistence.



NOTE: The FracMAN program is used to create input to the 3DEC program.

Figure 22. Methodology for Generation and Verification of Fracture Geometries in Nonlithophysal Rocks

6.1.2.2 Treatment of the "Intensely-Fractured Zone" Within the Tptpmn

Within the Tptpmn, the region termed the "intensely-fractured zone" (encountered from Station 42+50 to 52+50 along the ESF Main Drift) is an area of intense fracture frequency (fracture spacing of approximately 0.25 m or less) which is uncharacteristic of the remainder of the Tptpmn. These fractures, which are high-angle and sub-parallel to Set 1, create thin, platy blocks. The origins of this zone, which lies along the Ghost Dance fault, is uncertain, and could be either related to the shear on this structure, or to the presence of a lithophysal-rich subzone within the Tptpmn. In any case, the lateral extent of this zone is not known, but it is not seen in the ECRB Cross-Drift, surface-based boreholes or surface outcroppings. This zone lies adjacent to Panel 5 (the possible expansion panel in Figure 14), and to the south of the area proposed to meet the 70,000 MTHM requirements (Panels 1 to 4). Therefore, the extent to which this zone actually impacts the base repository emplacement drifts is unknown at present, but is probably not particularly significant. The block sizes created in this zone are clear in the tunnel itself, where the intense fracturing results in small (about 0.25 m or less) block dimensions. Since this zone clearly represents a separate fracture population from the general Tptpmn, it will therefore be treated separately from the population used for the FracMAN and 3DEC rockfall analyses. At the current time, the plan is to empirically estimate the rock block size that can be created from this zone by examining the fracture spacings. The amount of rock that can fall due to seismic loading will be estimated from three-dimensional models in a conservative fashion.

6.1.2.3 Lithophysae Characteristics

The panel mapping within the ECRB will be used to generate the following information:

- Lithophysal porosity as a function of depth within the Tptpll
- Description of alteration rims and spots and their contribution to porosity
- Variability of lithophysal shape and size
- Distribution of lithophysae within the rock mass and the thickening "webbing" between lithophysae.

These data will provide the basis for estimating variability of porosity and its impact on the distribution of thermal and mechanical properties within the Tptpll.

6.2 PROGRAM ELEMENTS B–E–SUPPLEMENTAL MATERIAL PROPERTIES TESTING AND NUMERICAL MODEL VALIDATION

6.2.1 Introduction

As discussed previously, KTI resolution requires developing a detailed understanding of the thermal and mechanical constitutive behavior of lithophysal rocks. The approach shown in Figure 22 involves use of laboratory and in situ testing to calibrate and validate a numerical model that can be used to understand the basic mechanisms of behavior of the lithophysal rocks, and as a test-bed for estimating rock mass properties through numerical extrapolation.

6.2.2 Laboratory Testing

A laboratory testing program has been designed to provide mechanical and thermal properties, primarily on lithophysal rocks. Additionally, long-term static fatigue of lithophysal and nonlithophysal rocks will be determined. The proposed testing can be subdivided into four areas:

- Compression testing of lithophysal rocks
- Thermal testing of lithophysal rocks (thermal expansion)
- Static fatigue testing of lithophysal and nonlithophysal rocks
- Direct shear of fractures from nonlithophysal and lithophysal rocks.

Due to the lithophysal porosity and size-dependence, it is necessary to test large sample sizes. Therefore, 12 in. (30.5 cm) diameter cores, containing approximately 5 or more lithophysae across a given sample diameter, are used for testing purposes. Table 3 reviews the primary test types and the environmental conditions to be applied. The majority of the compression and thermal testing will be completed at Sandia National Laboratories, while the joint direct shear and static fatigue testing will be accomplished at the USBR laboratories in Denver. The USBR has the capability to conduct shear tests on large diameter cores, and has extensive thermal creep testing facilities.

Coring of the Tptpll is difficult due to the presence of larger lithophysae and inter-lithophysal fracturing, making it quite difficult to obtain standard 2:1 length:diameter ratio samples. Lithophysal rock testing will therefore be centered on tests of the more easily cored Tptpul with a fewer number of Tptpll tests. In situ testing of the Tptpll will be necessary to determine the differences in behavior of these two lithophysal units. Additionally, the compression testing of lithophysal rocks will necessarily be in uniaxial compression due to difficulties in jacketing samples for triaxial compression.

6.2.3 In Situ Compression Testing

Due to the size dependence of the rock mass properties in lithophysal rocks and the difficulties in coring of the Tptpll, some in situ compression tests driven to rock mass failure will be necessary. A number of different in situ testing techniques were considered in the planning stages. In particular, in choosing the proper testing technique, it is necessary that the test not only obtain a measure of the deformation modulus of the lithophysal rocks, but that it also obtain data on the rock mass strength. These objectives can most easily be accomplished by conducting "slot" tests. The slot test involves cutting long, thin, parallel slots approximately 1 m apart in the wall or floor of the drift to create a "sample" whose length is greater than its width and is attached on three sides and free on three sides (Figure 23). Load is applied to the parallel slots through use of aluminum or steel flatjack bladders that are inflated in the slots, compressing the sample. Instrumentation for monitoring the deformation of the block is typically installed from the block surface as well as through boreholes drilled into the block. The flatjacks are capable of applying pressures up to about 30 to 40 MPa. To ensure that failure is achieved, a larger (approximately 12 in. [30.5 cm]) central hole can be drilled into the block to provide a means of achieving higher stresses and failure, as well as providing easier access for instrumentation and viewing inside the block.

Table 3. Testing Parameters and Conditions

Test Type	Parameters and Environmental Conditions
Uniaxial Compressive Strength Unconfined Modulus	Temperature to roughly 200°C Saturation – room dry and saturated Spatial Variability/porosity variation
Thermal Expansion	Spatial Variability/porosity variation
Joint Shear Strength	Normal stress Variability – Various joint sets from nonlithophysal rocks
Uniaxial compression-Static Fatigue Strength (time to failure)	Function of applied stress (50 to 90 percent peak strength)

It is proposed that three tests be conducted that span the best to poorest quality of the lithophysal rocks (Figure 24). To this end, the first test would be conducted in the uppermost portion of the Tptpll which, in general, has the poorest geotechnical quality of the various repository rocks. This upper 10 m or so of the Tptpll is characterized by large, irregular lithophysae and intense inter-lithophysal fracturing. The second test is planned for what may be considered the highest quality lithophysal rock located within the Tptpul, in uniformly sized and distributed, small (less than 10 cm diameter) lithophysae, with minimal inter-lithophysal fracturing. The third test is to be located within the central area of the Tptpll, characteristic of the bulk of the emplacement areas of the repository.

The basic testing strategy is to load the rock mass in a series of load cycles at increasing peak pressure levels. The deformation modulus of the rock mass is determined on loading, with a measure of the "intact" rock block modulus determined on unloading. The central hole allows both access for internal measurement as well as providing stress concentrations sufficient for failing the rock. It is planned to hold the load at constant pressure at each of the load peaks to examine time-dependent deformation of the rock mass. If time-dependence is present, the load will be held until steady conditions are reached. In at least one of the latter two tests, borehole heaters will be used to raise the temperature of the block to approximately 100°C to examine thermal expansion and temperature effects on deformation modulus and time-dependency.

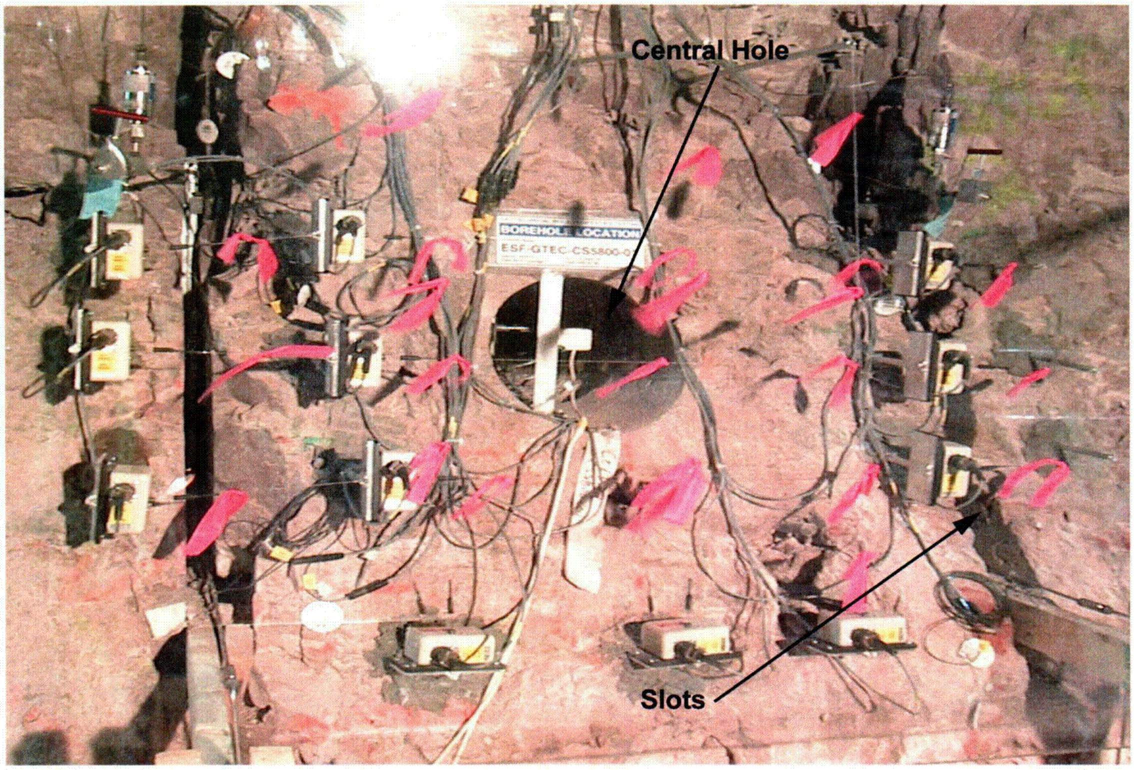
At the completion of the test, the applied stresses will be raised to fail the rock in compression (i.e., shear). The failure mechanism will be observed on the block surface as well as in the central hole. A thorough video taping and geological mapping will be made of the surface, slots and central hole of the test before and after the testing.

Back-analysis of ongoing thermal conductivity tests as well as additional tests in the Tptpll are anticipated. Additional tests will include monitoring of pretest and posttest saturation conditions. The goal of this work is to produce a relationship of thermal conductivity to porosity and saturation for lithophysal rocks. The current approach uses a three-dimensional cubic model of the lithophysal rock mass for assessing the thermal conductivity. Rock mass conductivity is calculated based on the matrix thermal conductivity, the matrix saturation, and lithophysal porosity. A volume averaging procedure discussed in *Thermal Conductivity of the Potential Repository Horizon Model Report* (BSC 2002) is used to estimate the rock mass thermal conductivity from these parameters. The analytical model of porosity dependence is examined in light of the field tests described in Section 5 of this report. Further work will include extrapolation of the thermal conductivity based on lithophysal porosity.

6.2.4 Model Calibration and Determination of a Rock Mass Mechanical Constitutive Model for Lithophysal Rocks

The basic strategy for laboratory and field testing discussed above provides data from large cores and field sites at a number of locations within the ESF and the ECRB Cross-Drift. Due to the limited areas where samples can be taken, and to the general effort and cost necessary to prepare and conduct such large-scale tests, it is impractical to conduct a typical "statistically based" testing approach. As discussed previously, in the nonlithophysal rocks, the intact rock strength is significantly higher than the anticipated induced stresses. Non-linearity occurs due to the presence of the jointing along which slip and separation can occur. Typically, the blocks are represented as elastic materials and the joints as interfaces corresponding to a Mohr-Coulomb slip condition. Modeling of the nonlithophysal rocks can be represented using a discontinuum model in which the joints are given proper friction, cohesion and dilation angle.

This approach is reasonable for the nonlithophysal material, but cannot reliably be used for the lithophysal rocks due to the unknown impact of lithophysae and fractured matrix material on the shear failure criteria and possible volumetric compaction response. The only recourse in determining material response is to perform testing of samples large enough to encompass the non-linearities.



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NOTE: Width of the test sample is approximately 1 m. Surface deformation instruments shown.

Figure 23. Slot Test Combining Parallel Slots and a Central Drilled Hole

To overcome the testing limitations, several modeling approaches will be calibrated as an integral part of the lab and field testing program. Ultimately, the goal is to understand and reproduce the basic deformation and failure mechanisms of the lithophysal material so that the models can be used for extrapolation purposes (i.e., they can be used to examine the impact of parameters such as lithophysal porosity, shape, size, and distribution on rock mass design properties). In this manner, the models can be used as "test-beds" (i.e., numerical laboratories) for supplementing the testing program. For this approach to be feasible, models with the capability of representing the basic failure and deformation mechanisms must be used.

6.2.4.1 "Micromechanical" Modeling Using the PFC Approach

It is proposed here to use the "micromechanical" PFC program for calibration/verification against test results, beginning with the laboratory scale testing. The model can be used to simulate the lab testing stress paths, while predicting the stress and strain results. Detailed comparison to the laboratory test results and observations will be made and a constitutive model developed.

Why is use of this modeling approach suggested? This approach is used as it allows straightforward representation of holes in a matrix, and complex failure mechanisms of the webbing between holes without resorting to simplifying assumptions such as lumping holes and solid into an "equivalent" continuum material. It is felt that, without significantly greater amounts of test data upon which to build a constitutive model, a direct physical representation of the impact of void space is needed. The PFC program (Figure 25) represents rock as a number of small spherical grains that are bonded together at their contacts with a shear and tensile strength, as well as a grain to grain friction angle after the "contact bond" has been broken. If cementing exists between grains, it can be represented with a "parallel bond" that provides a rotational resistance as well. The deformability of the contacts between particles is represented by normal and shear stiffness at the contact point. Porosity is developed naturally in the model by control of the shape and size of void space between chains of bonded grains. Thus, the input assumptions necessary for the model are very simple: contact strength and stiffness. Constitutive behavior may develop naturally based on porosity and the few input properties. Calibration of the model against laboratory testing is necessary via sensitivity studies in which the contact strength and stiffness values are varied. A range of contact property values that reproduce the range of lithophysal rock properties will be developed and verified against lab and field test results.

An example of this approach on the existing laboratory testing of the solid samples of Tptpmn and Tptpul is given here. Figure 26 shows a PFC model of a uniaxial compression test of nonlithophysal rock that has been calibrated to produce the same modulus and strength properties as typical 1-in. diameter Tptpmn samples (about 200 MPa compressive strength). The PFC sample is compressed by a velocity applied to the "sample" ends, as is the case in a laboratory. A picture of the sample in postpeak failure is superimposed by the stress-strain curve. The "calibration" is achieved by simply setting the contact stiffnesses and strength properties so that a match is achieved between test and model. The PFC model is able to spontaneously produce a macroscopic shear failure mechanism composed of coalescing tensile fractures that is quite realistic in comparison to typical laboratory behavior. Without changing the calibrated bond properties, porosity is then added to the PFC model by removing particles to form circular cavities. In this case, a total void porosity of approximately 20 percent is developed more-or-less uniformly across the sample (Figure 27). Compression of this sample leads to a completely different internal failure and deformation mechanism. The cavities provide internal holes that promote extensional fracture development between them, leading to a macroscopic shear failure mechanism that occurs at much lower peak stresses. In this case, a reduction in the uniaxial compressive strength of over 5 times results, even though the particle bond strength is the same as in the previous, nonlithophysal example. An actual test on a sample of Tptpul is shown in this figure, with similar results. Obviously, detailed examination of PFC strength and stiffness parameters will need to be examined for both Tptpul and Tptpll "samples" to reproduce the range of strength and moduli observed in the laboratory data, but even at the simplest level, this approach appears to yield considerable promise in understanding how porosity and inter-lithophysal fracturing impacts rock properties.

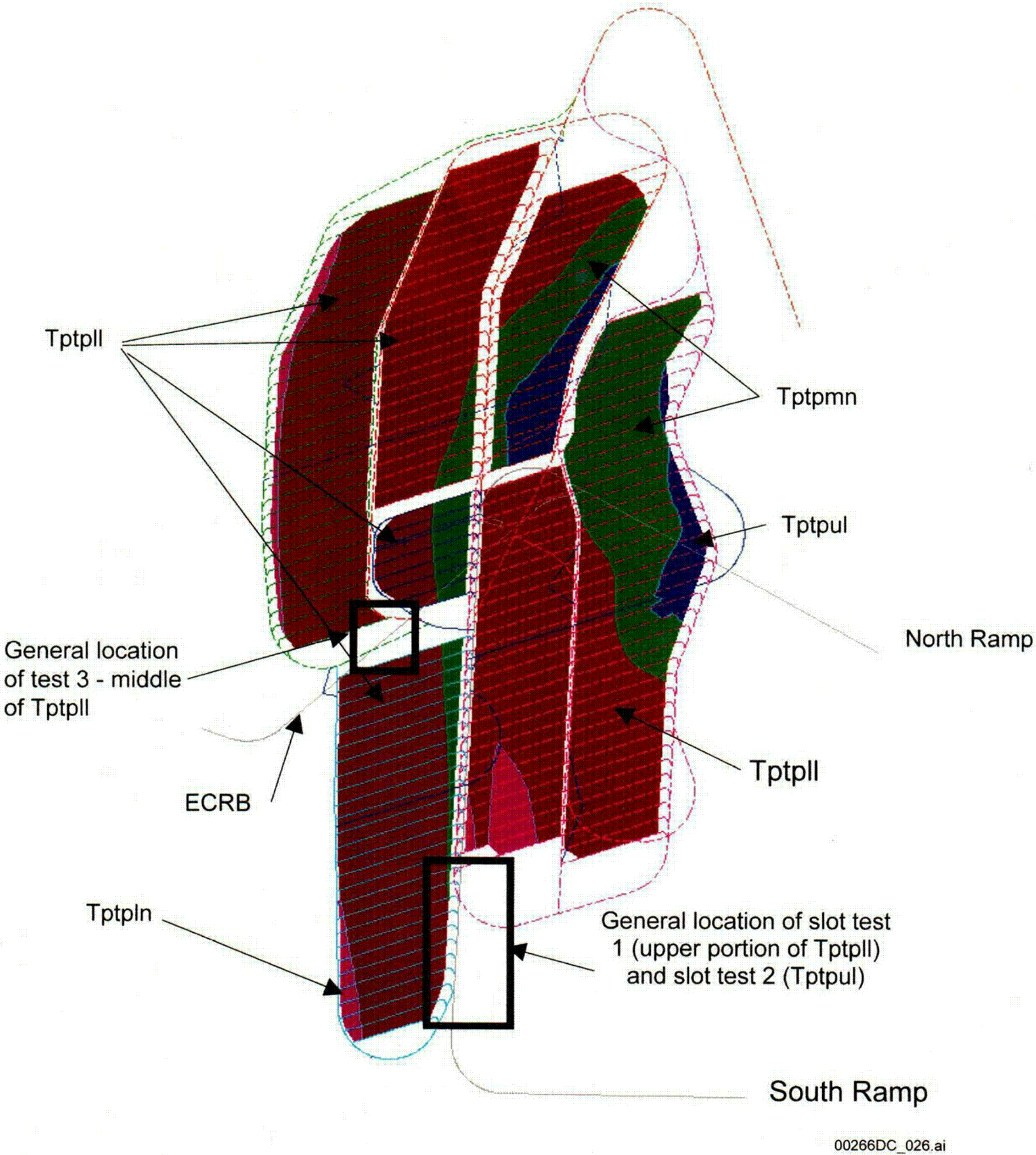
After calibration is achieved at the laboratory scale, validation will be explored through comparison to the in situ slot tests. The in situ testing will be conducted in the Tptpul and Tptpll, so comparison of size effect and rock quality (in the form of inter-lithophysal fracturing) will be possible. The ultimate goal is to develop a validated model for a range of rock types and qualities that can reproduce the general deformability and failure mechanisms for lithophysal rocks. Although only the PFC model is discussed here, it is probable that other modeling approaches, including the UDEC and FLAC programs will be used for comparison to lab and field data. A more traditional approach, which is fitting of standard material models, such as elastic-perfectly plastic models with shear and volumetric failure envelopes will be used to supplement the PFC modeling.

6.2.4.2 Extrapolation of Lithophysal Material Behavior Using Numerical Model

Assuming validation, the PFC model (as well as others, if necessary) will be used as a numerical "laboratory" for extrapolation to obtain estimates of lithophysal rock mass properties and response mechanisms. Studies will be performed to examine mechanical response for the range of lithophysal porosity, sizes, shapes and distribution as determined from the lithophysal mapping study described in Section 6.1. Figure 28 shows a schematic of what these studies hope to accomplish. The uniaxial compressive strength (as an example) is shown plotted against porosity for all welded and non-welded tuffs. The existing large-scale tests from Busted Butte Tptpul samples area shown as open circles. This data base will be supplemented with the new laboratory and in situ tests on lithophysal rocks, further extending the knowledge of size effect/porosity on properties. The validated PFC model will then be used to examine the property range variations based on the estimated range of variability of lithophysal porosity, shape, and size as determined from the geologic mapping studies.

6.2.4.3 Long-term Strength Degradation

An additional issue that will need to be addressed is the long-term strength degradation of the lithophysal rocks. A number of samples of non-lithophysal tuff will be subjected to static fatigue testing. This testing will involve producing many cores from closely spaced blocks of material obtained in either the ECRB or ESF. A number of samples will be tested to determine their UCS. These data will provide an average value of the UCS for the ensuing static fatigue tests. A number of samples will then be loaded in uniaxial compression to a target stress that will range from about 70 to 95 percent of the average UCS value. These samples will be held at constant stress until the sample fails. This may require times from a few seconds to months. The time-to-failure at that load level will be plotted against the relative stress level and a relationship established between the ratio of stress to strength and time-to-failure (e.g., Figure 29, Lajtai et al. 1987). For typical hard rocks, significant time-dependence does not occur until stress levels of approximately 80 percent of the uniaxial compressive strength are achieved.



NOTE: Approximate locations of the slot testing are shown.

Figure 24. Repository Layout with Overlay of the Topopah Spring Sub-Unit

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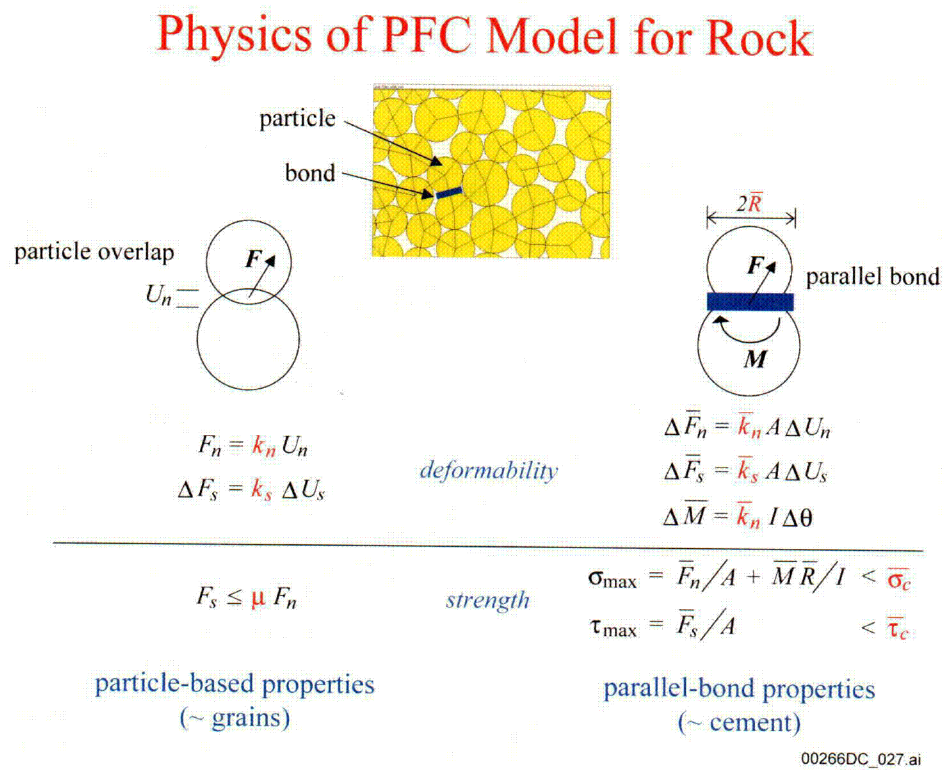

NOTE: The rock mass is composed of a large number of bonded circular (two-dimensional) or spherical (three-dimensional) particles. Porosity is developed naturally in the model by creation of pore space. The elastic moduli of the system are governed by contact shear and normal stiffness. The strength of the particle bonds is governed by a shear and tensile strength. Once a bond is broken, intergranular friction governs the shear strength of the material. Two types of bonds are possible: a simple contact bond and a "parallel" bond that represents intergranular cement and accounts for rotational resistance.

Symbols:

F_n = normal contact force
k_n = normal stiffness
U_n = relative normal displacement
ΔF_s = shear contact force increment
k_s = shear stiffness
ΔU_s = relative shear displacement increment
$\Delta \bar{F}_n$ = axial-directed force increment for bond
$\bar{k}_n$ = bond normal stiffness
A = area of bond cross-section
ΔU_n = relative normal displacement increment
$\Delta \bar{F}_s$ = shear-directed force increment for bond
$\bar{k}_s$ = bond shear stiffness
ΔU_s = relative shear displacement increment

$\Delta \bar{M}$ = bending moment increment for bond
I = moment of inertia of the bond cross-section
$\Delta\theta$ = increment of rotational angle
F_s = shear contact force
μ = contact friction coefficient
σ_{max} = maximum tensile stress acting on the bond periphery
τ_{max} = maximum shear stress acting on the bond periphery
$\bar{R}$ = particle radius
$\bar{F}_n$ = axial-directed force for bond
$\bar{F}_s$ = shear-directed force for bond

Figure 25. Physical Basis of the PFC Modeling Approach

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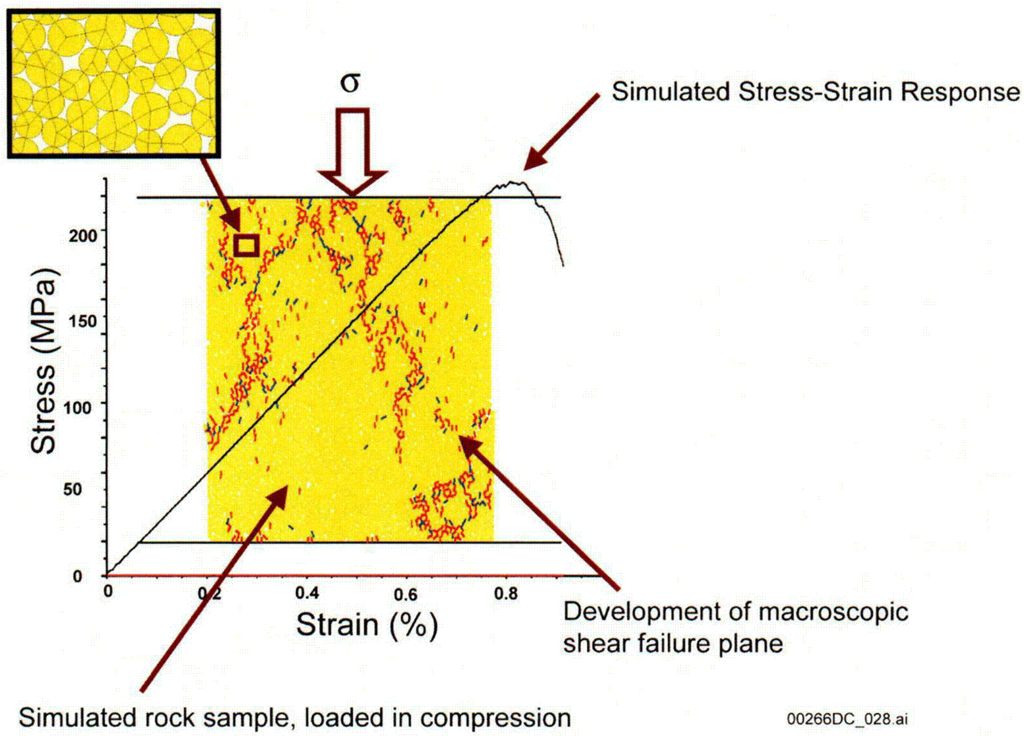
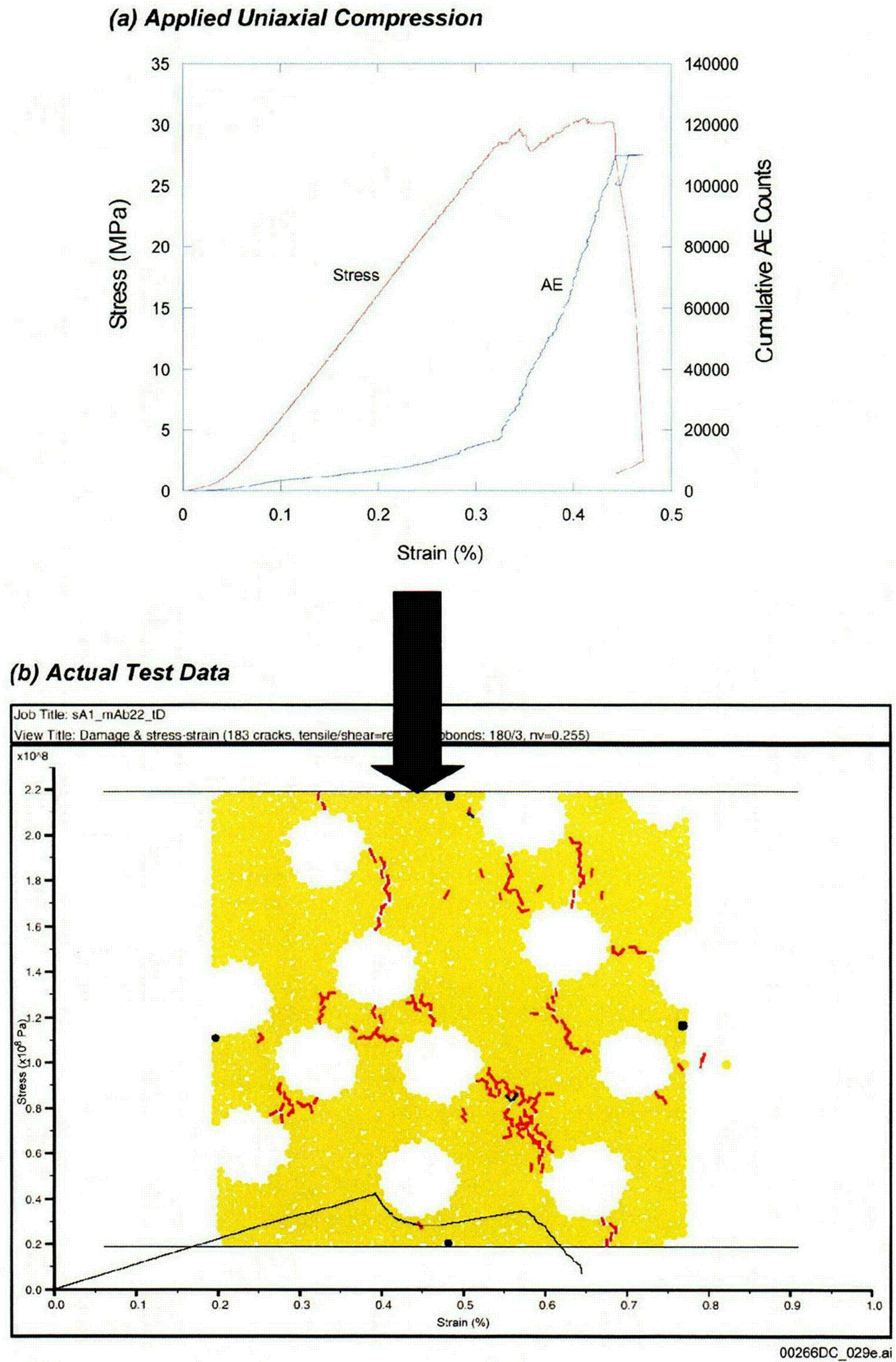
This testing will supply needed information on non-lithophysal rocks, but will also be used as the basis for estimating time-dependency in the lithophysal rocks as well. Why do we not simply conduct a similar testing program for lithophysal rocks? Due to the general difficulty in obtaining significant numbers of large diameter samples, and due to the inherent variability of the strength due to local sample porosity, it is difficult to accurately judge the compressive strength of any individual lithophysal sample. Therefore, the "target" stress levels for every sample will vary and one would never be certain of the relationship between time-to-failure and stress to strength ratio, as the strength would be unknown. To overcome this difficulty, we make use of the understanding that the matrix material of the lithophysal and non-lithophysal rocks is the same, and therefore the non-lithophysal static fatigue testing applies to the lithophysal matrix as well. The PFC program provides a platform by which the impact of static fatigue can be accounted for. The particle bonding strength of the matrix material can be adjusted to account for the time-to-failure derived from the laboratory testing in a manner consistent with a fracture-mechanics-based stress corrosion mechanism. The PFC model without lithophysal cavities is calibrated against the static fatigue behavior of non-lithophysal core samples. Then, lithophysae are added to the PFC model and numerical "lab tests" are performed. The model will account correctly for the stress concentration effect of the lithophysae, and allow numerical construction of time-to-failure plots for lithophysal rocks. A parametric study will allow the impact of porosity on time-to-failure in the same manner as a laboratory program if it were possible to control porosity from sample to sample. A level of validation of this approach will be achieved by PFC back-analysis of a limited number of progressive loading fatigue tests conducted on large lithophysal samples at the USBR laboratories in Denver. A series of approximately 10 uniaxial compression tests will be conducted on 6- to 12-in. (15.2- to 30.5-cm) diameter cores of lithophysal rock. The samples will be stressed to increasing levels of the axial load, which will be held constant while the axial strain is monitored. The load will be increased in increments until the samples indicate strain and failure. The stress level, sample porosity and time-to-failure will be recorded. This test is not a static fatigue test in the strict sense in that the complex load path could induce damage in the sample that could impact its time-to-failure. However, the test data can be used as a means of validation of the PFC model.



NOTE: Model is calibrated to achieve typical Tptpmn modulus and peak strength from uniaxial compression testing. The PFC model is compressed axially by applying a velocity to the ends of the "sample". Here, the postpeak condition is shown with particle bonds failing primarily in tension to form macroscopic shear fracture planes through the sample.

Figure 26. Example of a PFC Model Calibration



NOTE: Figure 27a shows uniaxial compression of the Tptpul, while 27b shows actual test data. The PFC model represents lithophysae as physical circular voids in the sample (here at 26 percent porosity). Failure mechanism is by tensile splitting of the webbing between voids, resulting in a macroscopic shear failure plane through the sample. Modulus and failure strength is similar in model and actual sample.

Figure 27. PFC Model of Uniaxial Compression

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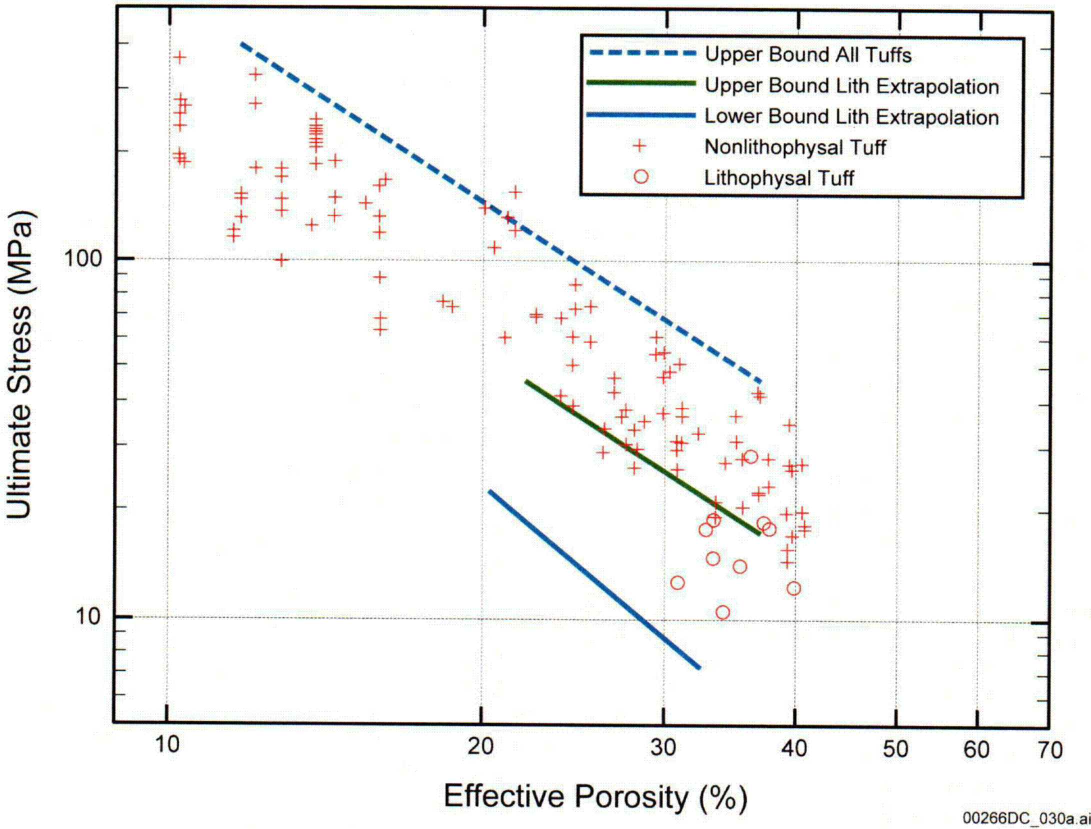

Source: Modified from Price et al. 1985.

NOTE: The current lab and field tests are shown schematically here, with ultimate upper and lower bounds defined for all lithophysal rocks using the validated numerical model.

Figure 28. Extrapolation Strategy to Define the Range in Design and Performance Properties for Lithophysal Rocks

An example of inclusion of time-related degradation in the PFC model is given by Potyondy and Cundall (2001). They conducted a back-analysis of time-dependent fatigue failure of granite from the Underground Research Laboratory (URL) in Canada using a stress-corrosion criteria embodied within the basic bonding strength logic of the PFC program. Basic laboratory uniaxial compression testing of granite was conducted in a fashion similar to that proposed here. The time to failure for samples loaded at 70 to 80 percent of peak strength was determined (Figure 29). The data was used to develop a time-dependent bond strength in the PFC program that was calibrated to reproduce the lab fatigue failure response. It was then applied to simulate the observed time-dependent development of stress-induced "notch" formation in the URL tunnels. Figure 30 is a composite picture showing the PFC model and field observations after 2 months time. The fracturing associated with the notch formation could be observed physically, but was more accurately defined during and after mining of the tunnels by using very sensitive acoustic emission monitoring (Young and Collins 1997). Good agreement in the prediction of time-dependent formation of the notch was found using the model. More importantly, the PFC model has provided a better understanding of the mechanisms of the yielding process and thus gives greater confidence in predictability. This methodology has been developed to examine the potential for time-related instabilities that could be encountered in a granite repository.

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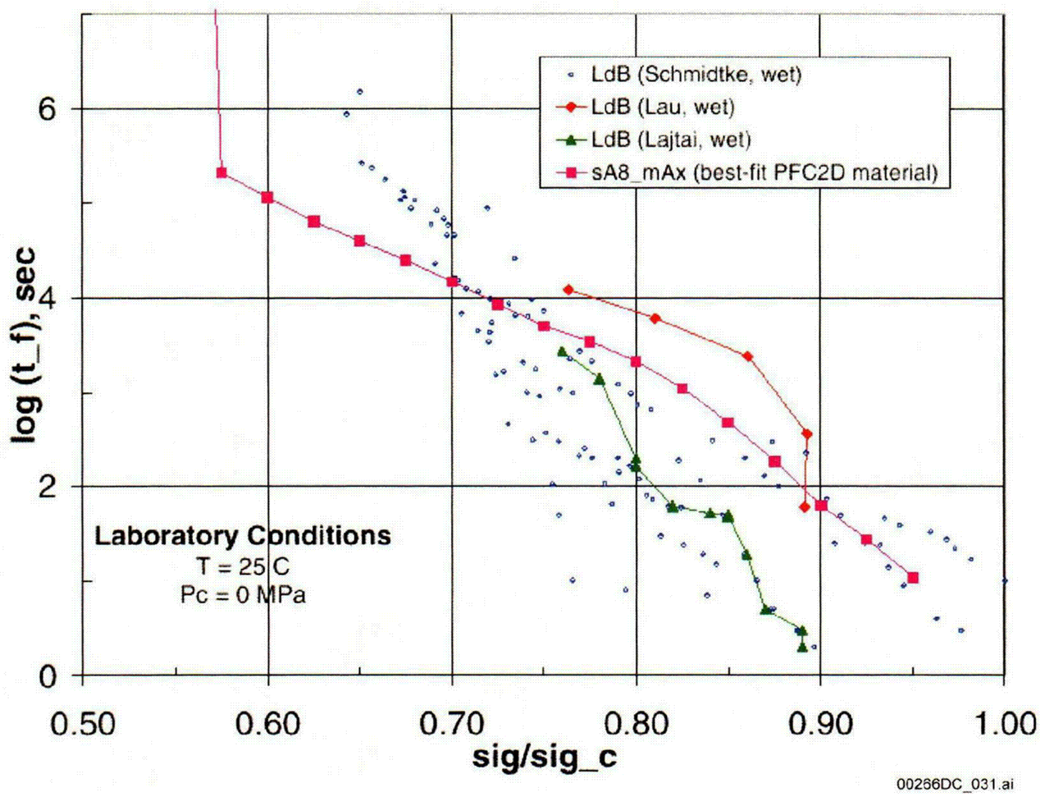
The PFC model (and others, as appropriate) will be used to investigate the effect of the time-dependent failure response (static fatigue) for emplacement tunnels in the Tptpll based on the time-to-failure estimates derived from the above procedure. The models will be used to predict the progression of failure and possible raveling of rock particles to the ultimate equilibrium position of the tunnels, and the static load this applies to the drip shield.



NOTE: Figure shows the static-fatigue curve (log time to failure) vs. stress level for Lac du Bonnet Granite in unconfined compression and best-fit PFC model predictions based on a bond strength stress-corrosion model.

Figure 29. Static-Fatigue Curve vs. Stress Level for Lac du Bonnet Granite

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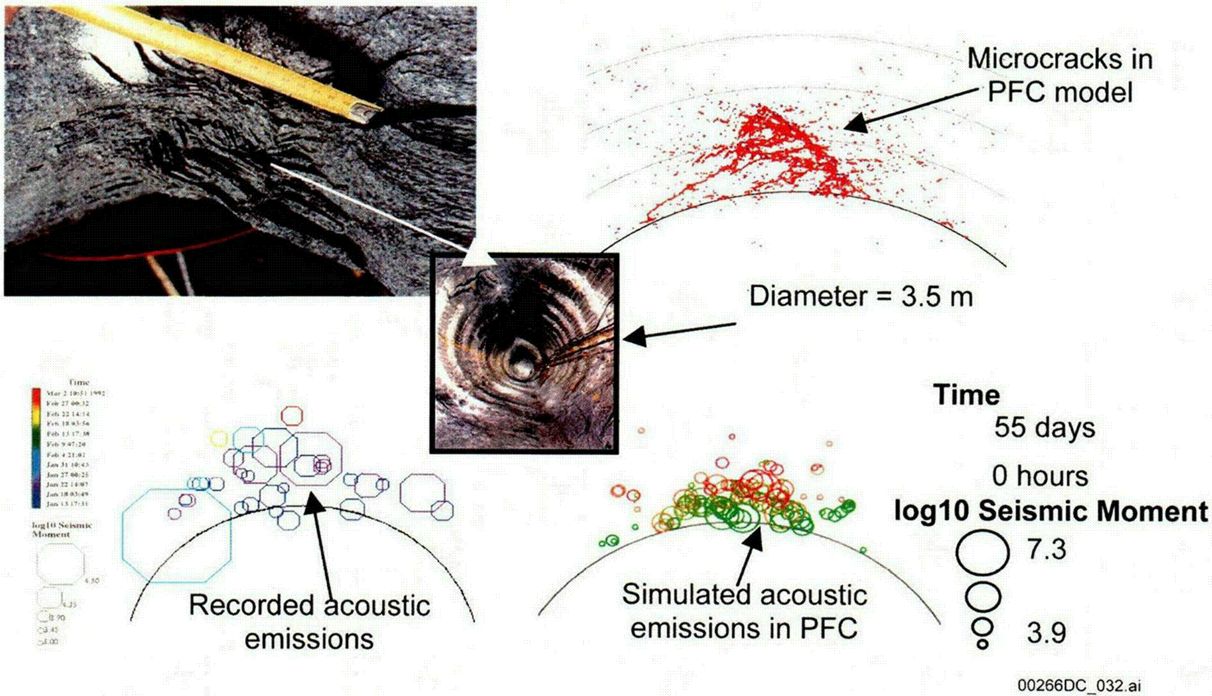

Source: Potyondy and Cundall 2001.

NOTE: Microcracks have formed in a fine resolution in the PFC model. Physical observation of the notching (upper left), and acoustic emission monitoring (lower left) and seismicity source locations "recorded" in the PFC coarse model (lower right).

Figure 30. Comparison of URL Mine-By Tunnel Time-Dependent Notch Formation with PFC Excavation-Scale Model with Bond Strength Governed by Time Dependent Degradation of Rock Strength Governed by Stress Corrosion (Upper Right) after 2 Months

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