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# Geoengineering Properties of Potential Repository Units at Yucca Mountain, Southern Nevada

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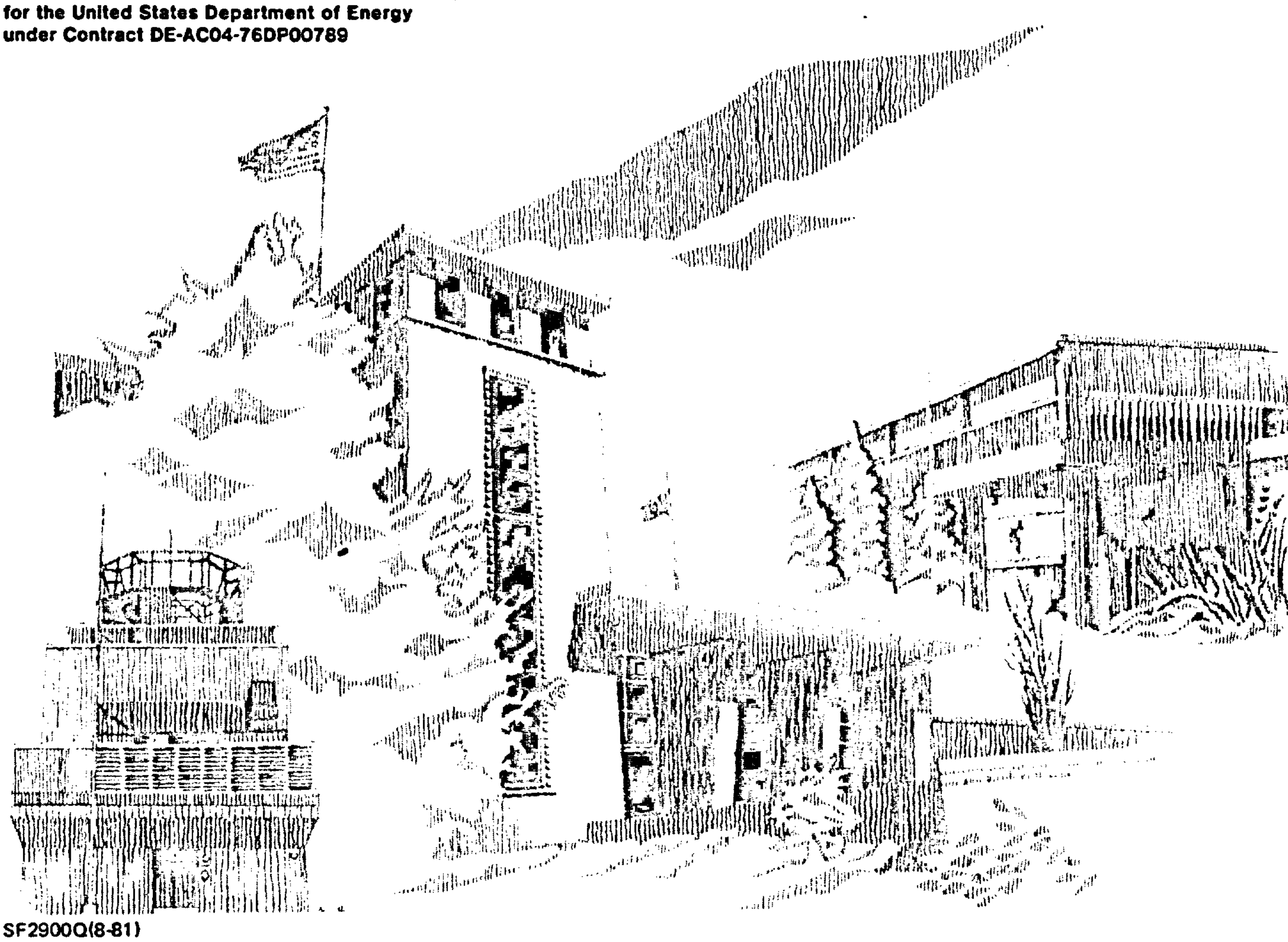

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# GEOENGINEERING PROPERTIES OF POTENTIAL REPOSITORY UNITS AT YUCCA MOUNTAIN, SOUTHERN NEVADA

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ABSTRACT

The Nevada Nuclear Waste Storage Investigations (NNWSI) Project is currently evaluating volcanic tuffs at the Yucca Mountain site, located on and adjacent to the Nevada Test Site, for possible use as a host rock for a radioactive waste repository. The behavior of tuff as an engineering material must be understood to design, license, construct, and operate a repository. Geoengineering evaluations and measurements are being made to develop confidence in both the analysis techniques for thermal, mechanical, and hydrothermal effects and the supporting data base of rock properties. The analysis techniques and the data base are currently used for repository design, waste package design, and performance assessment analyses. This report documents the data base of geoengineering properties used in the analyses that aided the selection of the waste emplacement horizon and in analyses synopsized in the Environmental Assessment Report prepared for the Yucca Mountain site. The strategy used for the development of the data base relies primarily on data obtained in laboratory tests that are then confirmed in field tests. Average thermal and mechanical properties (and their anticipated variations) are presented. Based upon these data, analyses completed to date, and previous excavation experience in tuff, it is anticipated that existing mining technology can be used to develop stable underground openings and that repository operations can be carried out safely.

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## INTRODUCTION

The Nevada Nuclear Waste Storage Investigations (NNWSI) Project is currently evaluating volcanic tuffs on and adjacent to the Nevada Test Site (NTS) for possible use as a host rock for a radioactive waste repository. The NNWSI Project is directed by the Waste Management Project Office (WMPO) of the Department of Energy (DOE) in Las Vegas, Nevada. After completing a screening activity that considered numerous possible repository locations (Sinnock and Fernandez, 1982), the NNWSI Project has focused its attention on evaluating the tuffs beneath Yucca Mountain (see Figure 1) in southeastern Nevada. Based on a unit-evaluation study (Johnstone, Peters, and Gnirk, 1984) of four geologic units potentially useful for waste disposal, the welded tuff identified as the Topopah Spring Member of the Paintbrush Tuff (see stratigraphy in Figure 2) is now considered the reference unit for location of an underground repository.

The behavior of tuff as an engineering material must be understood to design, license, construct, and operate a repository. The uniqueness of a repository design (when compared to mines or tunnels) results mainly from the addition of heat to the rockmass. The heat, produced by the canisters of radioactive waste, changes the temperature field and imposes additional stresses on the rockmass. Geoengineering evaluations are being conducted to develop confidence both in the analysis techniques for thermal, mechanical, and hydrothermal effects and in the supporting data base of rock properties. Both must be sufficient for repository design, waste package design, and performance assessment analyses. This report

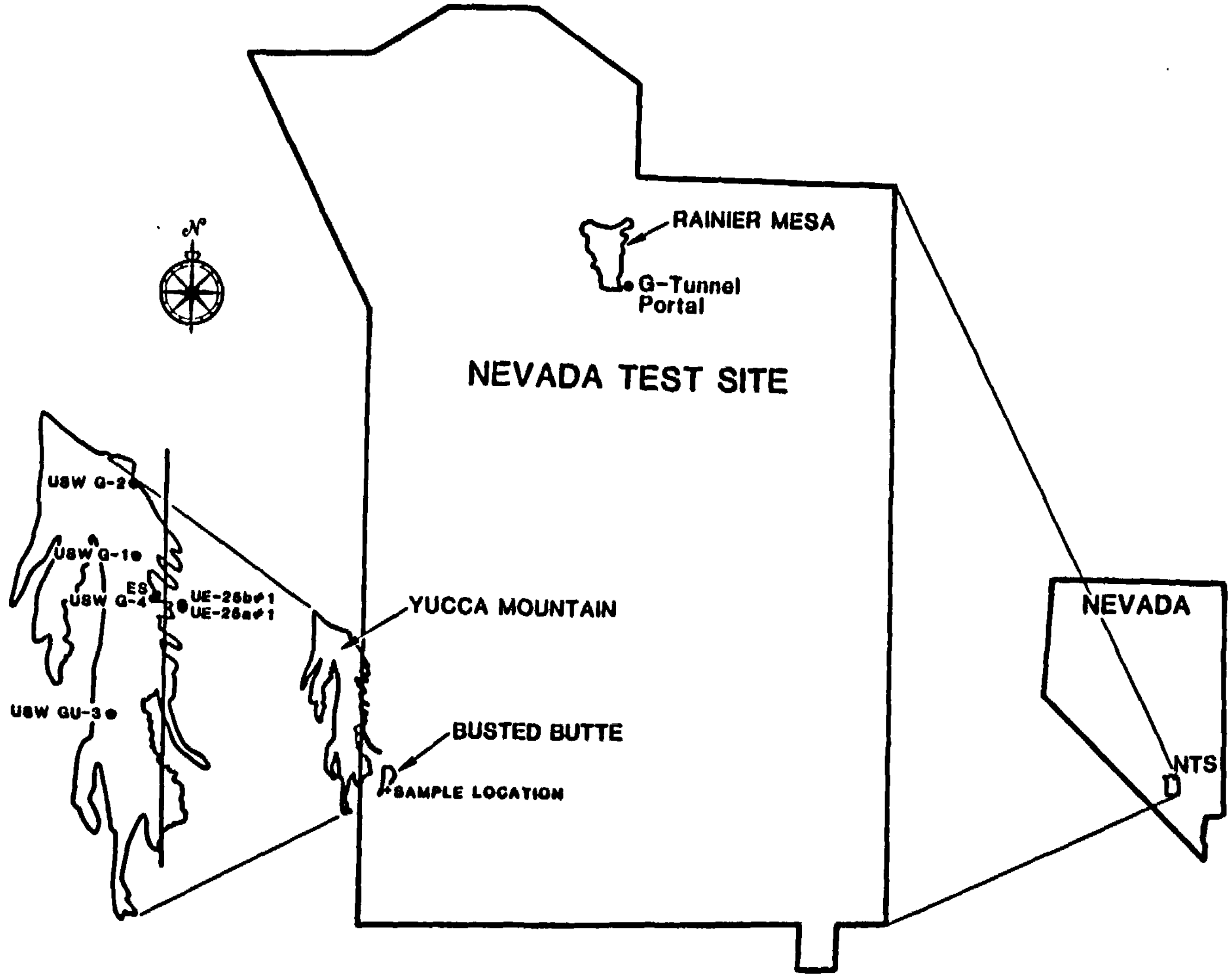


Figure 1. Location Map. Sample Localities Discussed in the Text Include G-Tunnel, Busted Butte, Exploratory Drill Holes (i.e., USW G-1), and the Exploratory Shaft (ES).

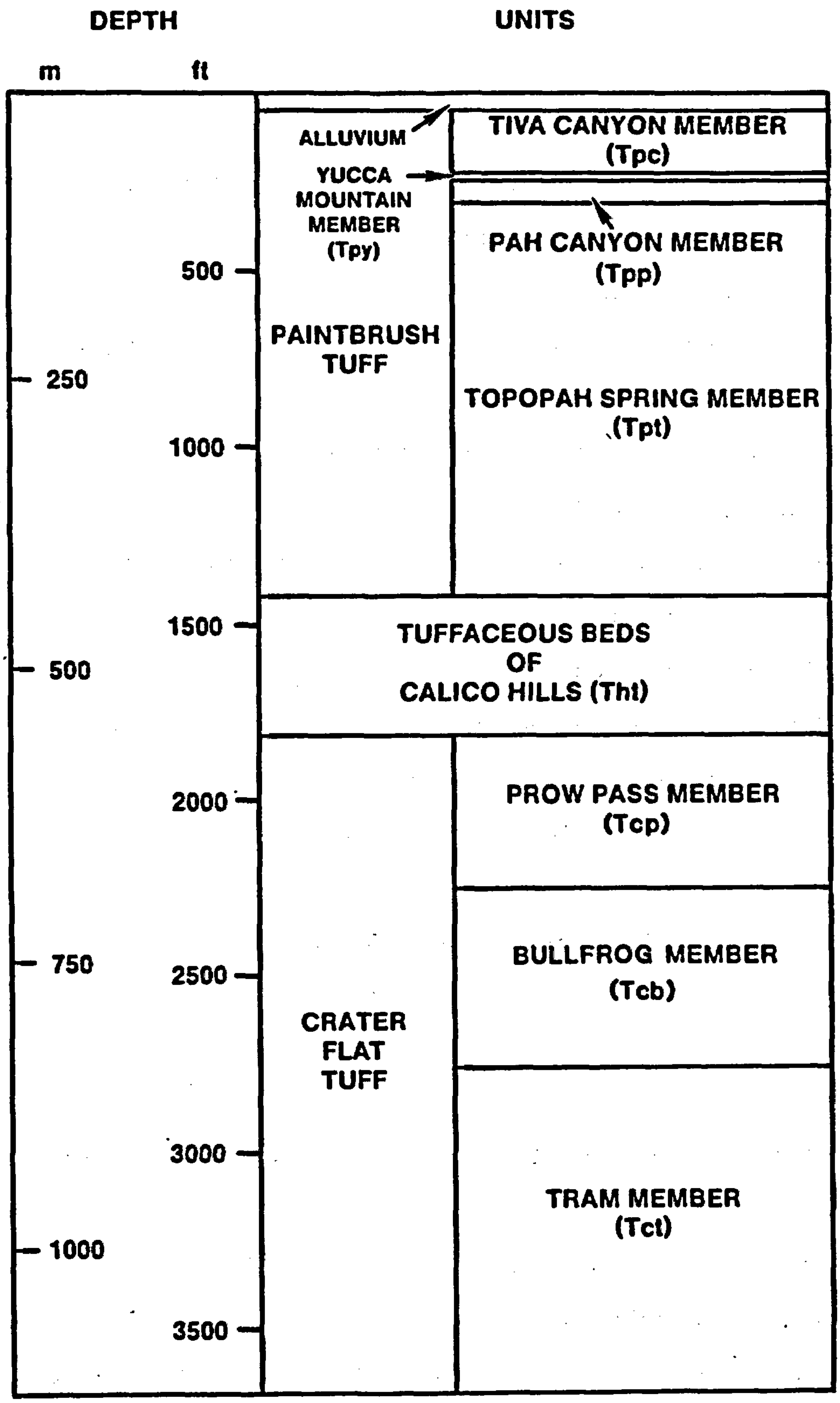


Figure 2 Stratigraphic Units at Yucca Mountain

documents the status of the data base of rock properties that were available for the unit evaluation and analyses supporting the Environmental Assessment Report issued in accordance with the Nuclear Waste Policy Act of 1982.

In order to set the stage for the discussion of specific properties or parameters, the remainder of this Introduction is devoted to:

- Identifying quantities that must be predicted to evaluate thermal, mechanical, and hydrothermal phenomena. Several of the design parameters that will be established and decisions that will be made based in large part upon the predicted quantities will also be identified.
- Identifying specific properties or measured values needed to make or evaluate the required predictions.
- Describing the strategy being used to develop the data base of geotechnical properties.
- Summarizing the sample selection logic and status of the geotechnical measurements activities.

## Predicted Quantities

Detailed analyses of candidate repository and waste package designs relative to thermal, mechanical, and hydrothermal concerns during the emplacement, retrieval, and long-term isolation and containment periods necessitate the prediction of temperatures, stresses, strains, and displacements of the rockmass as well as thermally-induced water flow (quantities and directions).

Predictions of rock temperatures are required for establishing (from a heat transfer viewpoint) the spatial extent of the tuff in the Topopah Spring acceptable for emplacing waste, for establishing the acceptable gross thermal loading within the disposal horizon, and for evaluating the ability of the waste emplacement area and waste package designs to meet very-near-field, near-field, and far-field temperature constraints. Temperature predictions are also an important prerequisite to

- the evaluation of the stability of pillars, waste emplacement holes, and drift intersections,
- a determination of the waste package environment,
- the establishment of ventilation requirements, and
- design trade-off studies such as horizontal versus vertical emplacement, waste package sizing, canister spacing, and drift spacing.

For example, predicted rock temperatures allowed calculations of thermomechanical responses that were used to compare four potential emplacement zones in the unit evaluation activities, contributing to the selection of the Topopah Spring Member as the most appropriate unit for the waste emplacement area.

Stress, strain, and/or displacement predictions are needed for detailed analyses of drift size, shape, spacing, and support requirements and for evaluating emplacement hole stability (including liner requirements, if any). Stress, strain, and/or displacement predictions are also needed for determining the spatial extent of the disposal horizon acceptable for waste emplacement (of particular concern are lithophysae content and gross thermal loading), for evaluating shaft designs with respect to opening stability and liner loading, and for evaluating the amounts and consequences of far-field deformation and subsidence.

Predictions of water migration quantities and mechanisms are important in accurately calculating rock temperatures, in establishing ventilation requirements, and in defining the waste package environment.

### Properties/Parameters Required

Specific tuff properties or in situ parameters that are important to the accurate prediction of temperatures, stresses, strains, displacements, and thermally-induced water movement have been identified. The most important properties and in situ parameters identified to date are the following:

- For temperature predictions:
  - -- thermal conductivity, saturated and dry
  - -- in situ saturation,
  - -- in situ temperature and thermal gradient,
  - -- heat capacity, and
  - -- latent heat of vaporization for tuff pore water.
- For stress, strain, and displacement predictions:
  - -- rock matrix elastic properties (Young's modulus and Poisson's ratio),
  - -- rock matrix thermal expansion,
  - -- rock matrix strength properties (compressive strength, tensile strength, cohesion, and angle of internal friction),
  - -- analogous rockmass elastic and strength properties,

- joint properties (joint cohesion, joint stiffness, coefficient of friction for joint slip initiation), and
- in situ stress state

• For water migration predictions:

- characteristic curves relating hydraulic conductivity and state of rock saturation to pore pressures,
- in situ degree of saturation, and
- rockmass permeability and porosity (including fracture effects).

In tuff materials, these properties often depend on fluid and confining pressure, degree of saturation, time, orientation, or temperature. In addition, several other properties or in situ parameters must be measured. For example, density, porosity, and mineralogical variations from drill hole core as well as borehole logging data must be obtained in order to understand the spatial variability of many of the previously listed parameters. Similarly, empirical approaches to the evaluation of opening stability and support requirements rely upon fracture spacing and condition data, rock quality indices based on core quality, and groundwater flow conditions.

This report does not attempt to discuss each of the required geoengineering parameters. Rather, concentration is on those parameters for which personnel at Sandia National Laboratories (SNL) are obtaining data in support of the NNWSI Project.

## Data Base Strategy

A strategy for the development of the geoengineering properties data base needed for technical decisions has been developed and implemented in the NNWSI Project. The strategy relies primarily upon data obtained from laboratory tests. The relationship of laboratory data to in situ data is evaluated and confirmed in field tests in G-Tunnel, a test facility in Rainier Mesa located on the NTS (Figure 1) and also will be evaluated in tests which will be conducted in the exploratory shaft (ES).

Laboratory data will consist of test results on samples from areas identified in Figure 1:

- boreholes drilled in Yucca Mountain,
- G-Tunnel,
- Topopah Spring Member outcrop at Busted Butte, and
- the ES (including the exploratory lateral boreholes).

Rainier Mesa data are included because the thermal and mechanical properties of the welded and nonwelded tuffs in G-Tunnel are similar to those measured for Yucca Mountain tuffs. Closely spaced samples of both welded and nonwelded tuff were taken to evaluate the effects on tuff response of changes in such variables as fluid and confining pressure, sample orientation, temperature, strain rate, degree of saturation, and joint behavior. By taking very closely spaced samples, the sample-to-sample variability (hence the number of required tests) was minimized. Thus, in a test series designed to identify strain-rate effects, considerations of sample-to-sample variability in grain density or porosity could be neglected in interpreting the data. In addition, the data are presented because they, along with the results of the NNWSI

Project's G-Tunnel experiments, form the basis for early determination of the relationship of intact rock and rockmass properties.

Now that the Topopah Spring Member has been selected as the reference emplacement unit, testing is being completed on samples from the outcrop of the Topopah Spring Member at Busted Butte. Large samples (about 0.5 $m^3$) have been cored (up to 30-cm diameter cores), primarily for measuring the effects of lithophysae on thermal and mechanical properties and for establishing the effect of sample size on the measured strength of the Topopah Spring Member.

Tests will be performed on samples from long horizontal boreholes and from larger cores obtained in the ES. These data will be used to assess effects found to be important in previous tests and to confirm anticipated vertical and lateral variability of the Topopah Spring Member.

An important aspect of the laboratory testing is obtaining confidence in the quality of the data being used to make design analyses and performance assessments. Quality assurance procedures (QAPs) have therefore been prepared for all of the more routine (nondevelopmental) tests. Procedures have been written, approved, followed, and audited for thermal expansion, thermal conductivity, bulk and grain density, and uniaxial and triaxial compression testing. Where applicable, ASTM Standard Test Procedures (see Table 1) have been compared to QAPs. In several areas (particularly sample handling techniques, natural-state saturation effects, and instrumentation for lateral displacement measurements), more stringent requirements than those in the ASTM procedures are being used. These requirements are evident from the data sheets and experiment procedures provided in the QAPs. In developmental

TABLE 1

APPLICABLE ASTM TEST PROCEDURES

| Measurements | Test Procedure* |
|---|---|
| Uniaxial Compressive Strength | ASTM-D-2938-79 |
| Triaxial Compressive Strength | ASTM-D-2664-80 |
| Tensile Strength (Brazilian Test) | ASTM-D-3967-81 |
| Elastic Properties (Static) | ASTM-D-3148-80 |
| Elastic Properties (Dynamic) | ASTM-D-2845-69 (reapp. 1976) |
| Thermal Conductivity | ASTM-C-202-71 (reapp. 1977) |
| Thermal Expansion | ASTM-E-228-71 (reapp. 1979) |
| Specific Heat | ASTM-C-351-61 (reapp. 1973) |
| Bulk Density | ASTM-C-97-47 (reapp. 1977) |
| - Paraffin-coated specimens | ASTM-C-118-71 |
| Grain Density - Water pycnometer | ASTM-C-135-66 |
| - Helium pycnometer | ASTM-C-604-79 |

*Complete citations are provided in the references at the end of this report.

tests, such as those for the measurement of either time-dependent thermal expansion coefficients or joint slip, documentation of the test procedures is provided as an important product of the testing.

A second part of the data base development is the field testing program currently under way in welded and nonwelded tuff in G-Tunnel. Underground openings in the G-Tunnel facility have been developed as part of the NNWSI Project rock mechanics program in both welded and nonwelded tuff. The data from the experiments and observations in the welded Grouse Canyon Member in G-Tunnel are especially valuable to the current design evaluation of the emplacement horizon in the Topopah Spring Member because

- bulk, thermal, and mechanical properties of both Members are similar,*
- the overburden loadings (about 425 m in depth) and opening dimensions (up to a 5-m span) are similar,
- fracture characteristics are similar, and
- the degrees of saturation (0.8 to 0.95) are similar.

Site-specific field data (thermal conductivity, elastic moduli, strength, support requirements, drift and borehole stability, joint motion, and water migration) obtained in G-Tunnel will be used to support site evaluations and the conceptual designs of both the waste emplacement area and the waste package. The G-Tunnel tests will also allow development of measurement techniques and instrumentation evaluations before testing in the ES begins.

*Lithophysae are, however, not present in the Grouse Canyon Member welded tuff in G-Tunnel; a detailed comparison of properties is presented later in this report.

Finally, the last part of the data base development approach is the field observations made during construction of and testing in the ES. These tests will increase confidence in the design of the emplacement area by providing both a direct measurement of rockmass properties and an opportunity to evaluate the thermal and structural codes used in the prediction of the coupled behavior that results from mechanical and thermal loadings. The specific tests are currently being planned and evaluated.

Data gathering and interpretation activities are planned to provide recommended values for material properties on which to base the decisions that must be made throughout the design of the emplacement area. In the future, these data will reflect steadily increasing levels of site- and horizon-specific information. To an increasing degree, data will be obtained directly from the rockmass instead of inferring rockmass data from laboratory measurements on cores.

As an example of the implementation of the data base development approach, consider the timing and contribution of various laboratory and field tests to the development of recommended values for the elastic properties of the host rock (see Figure 3). The data base reported here consists only of laboratory tests on samples from holes UE-25a#1, USW G-1, and USW G-2 and from Rainier Mesa and initial field test results from G-Tunnel. Activities are being completed that add results from laboratory tests of samples from USW GU-3 and USW G-4 and from outcrops of tuff containing lithophysae. Future input will include additional interpreted data from field tests conducted in G-Tunnel and from laboratory tests on cores obtained by lateral drilling in the ES. The

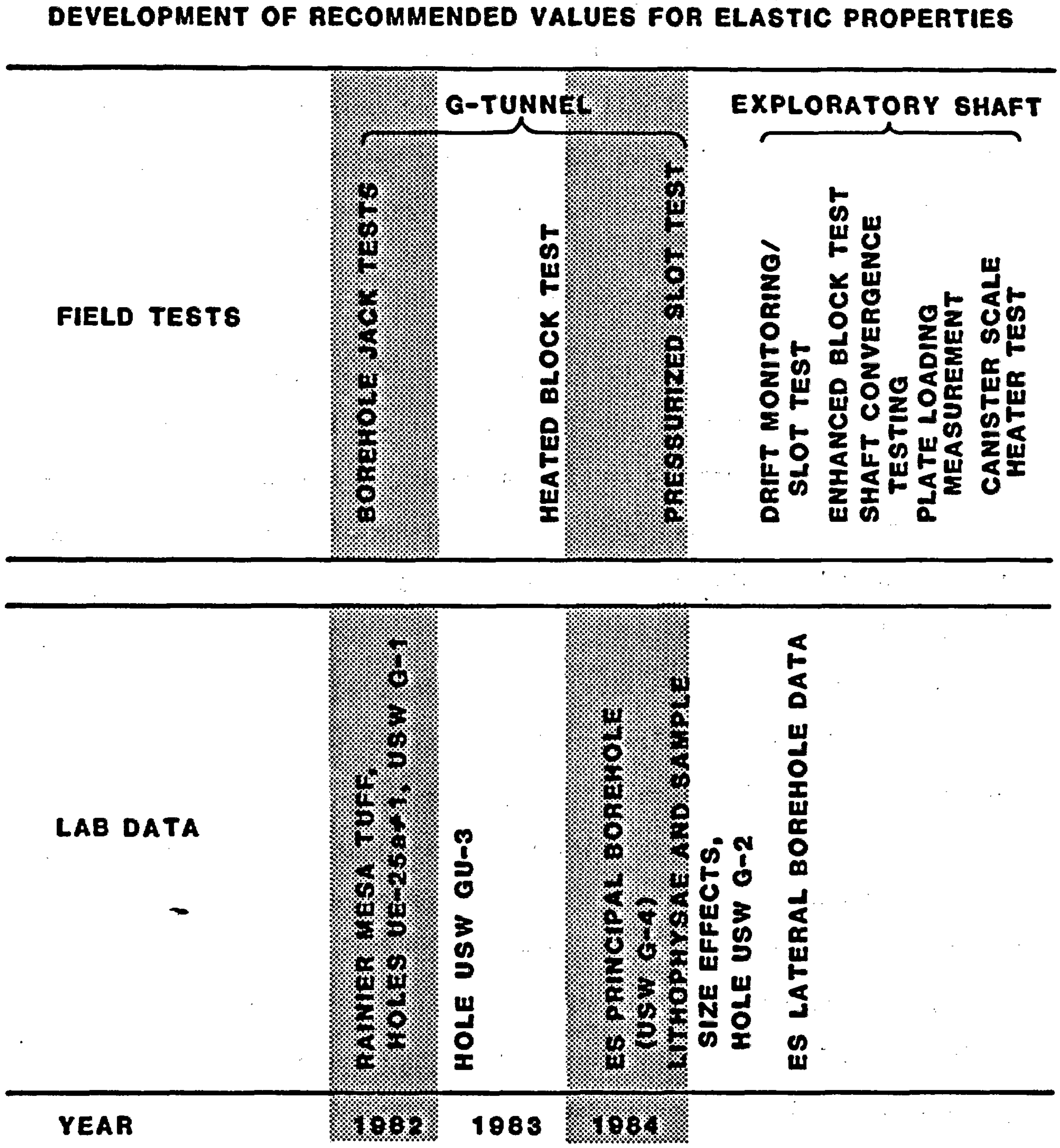


Figure 3 Data Base Development for Rockmass Elastic Properties

interim products of this work will be recommended rockmass properties based on data available at the time the design need is expressed. The final product of this work will be recommended rockmass properties (and their uncertainties) that have been confirmed by in situ tests and observations made in the emplacement horizon during ES testing.

## Sample Selection Logic

The procedures and logic used in sample selection for laboratory testing of cores from Yucca Mountain are important in assessing how well the data base represents the in situ material. In the NNWSI Project, this logic has evolved with time. Both the inherent sampling limitations (procedural and lithological) and the progression of the logic are described below.

Because the primary objective of every cored hole at Yucca Mountain has been to determine the stratigraphic relationships within the cored interval, sections of core near stratigraphic contacts were unavailable for thermomechanical testing. This procedural limitation has little impact on testing of relatively thick units, such as the lower devitrified portion of the Topopah Spring Member, but could affect testing in thinner layers. Lithologic limitations caused by fracture spacing and lithophysal content result from the concern that core samples selected for testing be representative of the interval from which they are taken. To determine thermal and mechanical properties, sample lengths of 5.1 cm or greater are needed. Therefore, tested samples can, at best, be representative of that material which is recovered from coring operations in pieces at least 5.1 cm in length. In addition, the size of the lithophysae causes core to break into small pieces in portions of the Topopah Spring Member. Cores containing lithophysae can only be obtained if the lithophysae are small; therefore, it cannot be guaranteed that samples of lithophysal tuff collected during drilling are representative of in situ material.

The laboratory testing program was initiated in 1979. Rather than obtaining samples from evenly spaced vertical intervals, emphasis was placed on tests on core samples taken from below the water table (particularly from the Bullfrog Member) in UE-25a#1 and on limited samples from other units.

During the testing of samples from USW G-1 (mid-1981 through mid-1982) and the initial tests made using USW G-2, USW G-3, and USW GU-3 core, two important events took place. First, the concept of a functional stratigraphy was developed. Each zone in the functional stratigraphy represents an interval for which average thermal and mechanical properties (and their anticipated variations) are defined. Zone boundaries reflect regions in which potentially significant changes in thermal and mechanical properties are anticipated. These boundaries do not always reflect the changes in formal stratigraphic divisions defined in geologic studies. Bulk property data obtained from samples taken at evenly spaced intervals are needed for definition of boundaries between the functional zones. Second, the tuffs in the zone above the static water level began to receive serious consideration for waste disposal. At this stage, sample selection requirements were based on two assumptions.

- Given sufficient thermomechanical measurements and bulk property data from evenly spaced samples, it is possible to predict with sufficient accuracy the thermomechanical properties of layered tuff units.
- The properties of anomalous zones, the presence of which is indicated by bulk property measurements, can be predicted adequately from the correlation curves.

As a result, the completeness of the sampling and the evenness of the sampling intervals, especially with respect to bulk properties, are much better in USW G-1 and subsequent drill holes. Sample depths and intervals at which bulk property samples were to be collected were specified in drilling criteria that were established for each drill hole before drilling began. Any bias has been toward maintaining an even spacing of samples rather than toward selection of the best material in each interval.

## Current Data Base

The current data base consists primarily of measurements on cores with relatively small diameters. Thermal and mechanical properties have been defined for the four units (Topopah Spring Member, Tuffaceous Beds of Calico Hills, Bullfrog Member, and Tram Member) initially considered for waste emplacement in Yucca Mountain. The data base consists of approximately 75 thermal conductivity tests, 95 thermal expansion tests, 35 mineralogical/petrological analyses, and 120 unconfined and 50 pressure-dependent mechanical properties tests. Most of the data are from UE-25a#1 and USW G-1; in some cases, samples from USW G-2 and Rainier Mesa have been included.

Interpretations of the thermal and mechanical properties and their statistical variation have relied heavily on the use of the bulk properties data and mineralogical analyses to establish correlation. These data, coupled with observations of core quality and G-Tunnel opening stability and support requirements, were the basis for thermal and mechanical evaluations in the unit evaluation analyses and for analyses cited in the Environmental Assessment Report. The unit evaluation analyses led to the conclusion that stable openings could be developed in all four potential disposal units. This conclusion contributed to the selection of the Topopah Spring Member as the preferable unit.

Data-gathering efforts have now been directed primarily at evaluating the behavior of the Topopah Spring Member, primarily emphasizing lateral variability, lithophysal effects, joint properties and temperature, pressure, and sample size effects on compressive strength and elastic moduli. An updated version of the properties discussed in this report will be prepared for inclusion in the Site Characterization Plan if the Yucca Mountain site is approved for site characterization.

## SECTION 1. MECHANICAL PROPERTIES OF INTACT ROCK

Intact, unfractured, homogeneous rock can be considered to be a continuum. Data on the intact rock mechanical properties of the volcanic tuffs in Yucca Mountain are required: (1) For direct use in analysis and design of mined openings, shafts, and boreholes; (2) To determine the spatial distribution of rock properties in the Yucca Mountain tuffs; and (3) To predict (in conjunction with fracture effects) rockmass or in situ mechanical properties. The values obtained from mechanical testing of samples from each of the four initial candidate emplacement horizons (the Topopah Spring Member of the Paintbrush Tuff, the Tuffaceous Beds of Calico Hills, the Bullfrog Member of the Crater Flat Tuff, and the Tram Member of the Crater Flat Tuff) are presented in this section. These data have been used in disposal unit evaluation studies (Johnstone, Peters, and Gnirk, 1984) and in analyses that are reported in the Preliminary Repository Concepts Report (PRCR) (Jackson, 1984).

### Definition of Terms

#### Elastic Constants

In the design, modeling, and analysis of openings, elastic constants are required to predict how rock surrounding the subsurface openings may elastically deform after excavation and emplacement of wastes. Young's modulus and Poisson's ratio are used to characterize the elastic deformation (strain) of rock under load (stress). Young's modulus is defined as the slope of the linear portion of the longitudinal (axial) stress strain curve. Poisson's ratio is the ratio of lateral (transverse) strain to longitudinal strain. Both of these elastic constants are measured in uniaxial or triaxial compressive tests or in tensile tests. In addition, for an isotropic material, any of the other elastic constants (e.g., shear modulus or bulk modulus) can be calculated directly from Young's modulus and Poisson's ratio.

Strength

Compressive and tensile strengths are measures of the ability of rock to resist failure when subjected to externally applied compressive and tensile forces, respectively. Uniaxial compression tests (i.e., laterally unconfined) yield the unconfined compressive strength and are the most common method for determining strengths of intact laboratory test specimens. Confined compressive strength and Mohr Coulomb parameters (the angle of internal friction and cohesion) are determined in tests run in triaxial compression. The tensile strength of a rock sample may be determined by simple extension to failure in a uniaxial tension test. Because this test is difficult to perform, indirect means of testing have been devised. One such test, the Brazilian tensile test, has been found to provide a reasonable measure of the tensile strength (Mellor and Hawkes, 1971).

Each of the above-mentioned strength parameters is utilized in analysis and modeling of in situ rock strength and stability for design of subsurface openings. The strength parameters are required to assess whether in situ stress conditions, as modified by excavation and thermal loading, will cause instability in the vicinity of underground openings.

The strength and stress/strain characteristics of intact samples represent the upper-limit values of the strength and stiffness of the in situ rockmass. The reductions in strength and stiffness reflected in the actual values for the rockmass are functions of the frequency and nature of existing discontinuities.

Physical Properties and Mineralogy

The physical properties of rock include grain density, bulk density, porosity, and water content. The physical properties and mineralogy of rock specimens are used in the characterization and analysis of field and laboratory strength and stress/strain test results.

## Equipment and Procedures, Limitations, and Error Analysis

Detailed results of laboratory mechanical tests on samples from drill holes in Yucca Mountain are contained in numerous reports (Olsson and Jones, 1980; Blacic et al., 1982; Olsson, 1982; Price and Jones, 1982; Price, Jones, and Nimick, 1982; Price and Nimick, 1982; and Price, 1983). The reports also include detailed discussions of sample treatment, equipment, experimental procedures, and calibrations.

The large majority of samples tested were right circular cylinders with diameters of 2.54 cm and a length-to-diameter ratio of approximately 2:1. The specimen size allowed the number of samples available for testing to be maximized to compensate for the limited amount and size (approximately 6 cm in diameter) of raw core material. In the large majority of samples, grain and flaw (pore) sizes were less than one-tenth of the diameter of the sample, thus minimizing the effects of grain and pore size on the bulk mechanical properties. Using the 2:1

length-to-diameter ratio, end effects (i.e., interaction of the sample and loading piston) attenuate within the sample such that strain measurements near the midsection of the sample are unaffected. The 2:1 ratio also minimizes the production of bending moments, which occur more frequently when higher ratios are used. In addition, the 2:1 ratio is commonly used in mechanical tests on other rocks; thus, its use allows the results of tests on tuff to be compared to those for other rock types.

Calibrations of force and displacement gages before each experimental series have shown that errors in these measurements are in all cases less than three percent. Any major differences in mechanical properties exhibited in adjacent tuff samples must, therefore, be a result of sample variability (mineralogy, porosity, grain density, etc.) or test conditions.

## Mechanical Properties of Other Potential Repository Host Rocks

A list of mechanical property ranges for three other rock types which are also being considered as repository host rocks is presented in Table 2. Corresponding ranges of properties for tuffs are 11.7 to 176.6 MPa for unconfined compressive strength, 2.5 to 40.8 GPa for Young's modulus, and 0.03 to 0.38 for Poisson's ratio (Price, 1983).

TABLE 2

RANGE OF MECHANICAL PROPERTIES OF OTHER POTENTIAL REPOSITORY HOST ROCKS

| Rock Type | Unconfined Compressive Strength (MPa) | Young's Modulus (GPa) | Poisson's Ratio | Reference |
|---|---|---|---|---|
| Basalt | 22.1-359.0 | 19.6-183.0 | 0.09-0.35 | Carmichael, 1982 |
| Granite | 107.0-229.0 | 15.7-87.6 | 0.19-0.30 | Carmichael, 1982 |
| Rock Salt | 19.4-27.7 | 28.3-39.2 | 0.23-0.39 | Price et al., 1981 |

## Mechanical Properties of Tuff

Detailed results of individual laboratory mechanical property tests on samples both from drill holes in Yucca Mountain and from G-Tunnel at Rainier Mesa are contained in numerous reports (Olsson and Jones, 1980; Blacic et al., 1982; Olsson, 1982; Price and Jones, 1982; Price, Jones and Nimick, 1982; and Price, 1983). These references contain data from about 120 unconfined compression tests, 20 indirect tensile tests, and 50 triaxial compression tests. Where possible, statistical evaluations of the data have been made. In addition, the results of all compression experiments performed to date in Yucca Mountain tuff have been compiled (Price, 1983).

Test results are summarized below for the elastic properties and the compressive and tensile strengths of Yucca Mountain tuffs. The current status of evaluations of the effects of water saturation, confining and fluid pressure, elevated temperature, time-dependent behavior, lithophysae, mechanical anisotropy, and sample size are described.

## Elastic Properties

Young's modulus and Poisson's ratio data have been collected for Yucca Mountain tuffs for use in structural response modeling of the emplacement drifts, emplacement boreholes, and shafts. Data are all from experiments run on fully saturated samples at atmospheric pressure (unconfined), a nominal strain rate of $10^{-5}$ $s^{-1}$, and ambient temperature.

Statistical analyses to determine the correlation among the elastic properties and porosity, grain density, and mineralogy have been performed to assess the possibility of extending such a relationship to other tuffs on which mechanical testing has not been performed. Data for the analyses were taken from unconfined tests on samples of the Tuffaceous Beds of Callico Hills and the Bullfrog and Tram Members. Test results from the Topopah Spring Member were not available at the time that the analyses were performed, but the results appear to be consistent with the statistical fits discussed by Price (1983) and summarized later in this report.

The data on elastic properties, porosity, and grain density were fitted by two models.

MODEL 1. $\log Y = B_0 + B_1 \log X$,

where $X$ = effective porosity <u>or</u> grain density,

$Y$ = Young's modulus <u>or</u> Poisson's ratio,

and $B_0$, $B_1$ = fitting parameters;

MODEL 2. $\log Y = B_0 + B_1 \log X_1 + B_2 \log X_2$,

where $X_1$ = effective porosity,

$X_2$ = grain density,

$Y$ = Young's modulus or Poisson's ratio,

and $B_0$, $B_1$, $B_2$ = fitting parameters.

The results of the analyses are summarized in Table 3. The fitting parameters were obtained using results from tests performed at SNL. The fits were calculated using an effective porosity defined as the actual porosity plus the volume of clay estimated to be present in each sample. Because clay is a relatively compliant material, it was considered appropriate to include its volume in the effective porosity. Furthermore, the statistical analyses indicated that better correlation was achieved by including clay in the effective porosity (Price, 1983).

The statistical evaluation indicates that the Young's modulus values can be predicted on the basis of the effective porosity of the samples, while Poisson's ratio values correlate better using both the effective porosity and the grain density. The data used for the analysis of Young's modulus and the best-fit line for the data are shown in Figure 4. None of the data used in the statistical evaluation has been obtained from welded tuff samples with less than twenty percent effective porosity. Future tests concentrating on samples from the target emplacement zone in the Topopah Spring Member in USW GU-3 and USW G-4 should therefore significantly increase confidence regarding the response of the low-porosity material and the ability of the statistical correlations to predict the response.

TABLE 3

MODEL FITS TO SELECTED MECHANICAL PROPERTIES DATA FROM YUCCA MOUNTAIN TUFFS

| X $(n, \rho_g)$ | Model (1,2) | $B_0$ | $B_1$ | $B_2$ | Standard Error of Y | Index of Determination $R^2$ |
|---|---|---|---|---|---|---|
| | | | Young's Modulus (GPa) | | | |
| n | 1 | 3.641 | -1.800 | - | 0.124 | 0.676 |
| | | | Poisson's Ratio | | | |
| n, g | 2 | -3.932 | 0.676 | 5.560 | 0.169 | 0.229 |
| | | | Unconfined Compressive Strength (MPa) | | | |
| n | 1 | 4.103 | -1.724 | - | 0.155 | 0.553 |

Model 1 $\log Y = B_0 + B_1 \log X_1$
Model 2 $\log Y = B_0 + B_1 \log X_1 + B_2 \log X_2$

$X_1 = n =$ effective porosity (%)
$X_2 = \rho_g =$ grain density (g/cm$^3$)

(Source: Price, 1983)

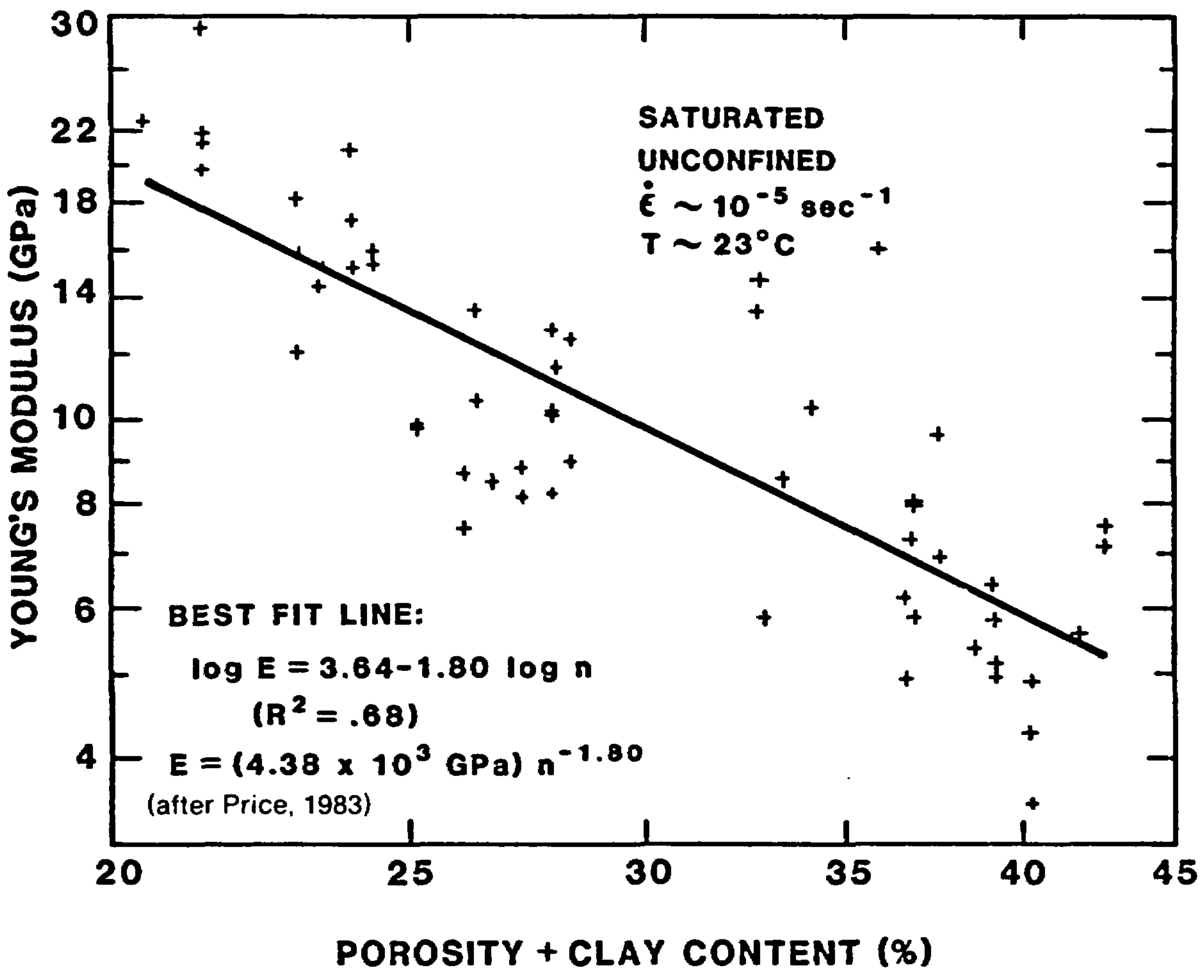


Figure 4 Young's Modulus as a Function of Effective Porosity

One preliminary study (Olsson and Jones, 1980) has shown that the elastic moduli of the tuff are anisotropic. Study results indicate a correlation between degree of welding (i.e., amount of porosity) and degree of anisotropy. Although welded tuff is stiffest in the direction perpendicular to bedding (approximately vertical), the nonwelded tuff is stiffest in the direction parallel to bedding (approximately horizontal). A discussion of tests planned to further investigate anisotropic elastic response and strength anisotropy in Topopah Spring Member is presented later in the report.

Compressive Strength

Ultimate stress values have been documented (Olsson and Jones, 1980; Olsson, 1982; Price and Jones, 1982; Price, Jones, and Nimick, 1982; Price and Nimick, 1982; and Price, 1983) for a wide range of tuff samples from Yucca Mountain. The same sets of unconfined, constant strain rate, ambient temperature experiments discussed above were also studied to determine whether the uniaxial strength could be related to the effective porosity or grain density. Both the logarithmic models and the sources of data are identical to those described in the preceding section. The resultant model parameters are given in Table 3. The results show that changes in compressive strength between samples can be correlated with changes in effective porosity. The fit to the data is statistically significant, with a relatively low standard error. The data and the best-fit line are shown in Figure 5.

Effect of Water Saturation. Because water has been found to reduce the strength of most silicic rocks, a series of drained uniaxial compression tests was run to quantify such a reduction in tuff (Olsson

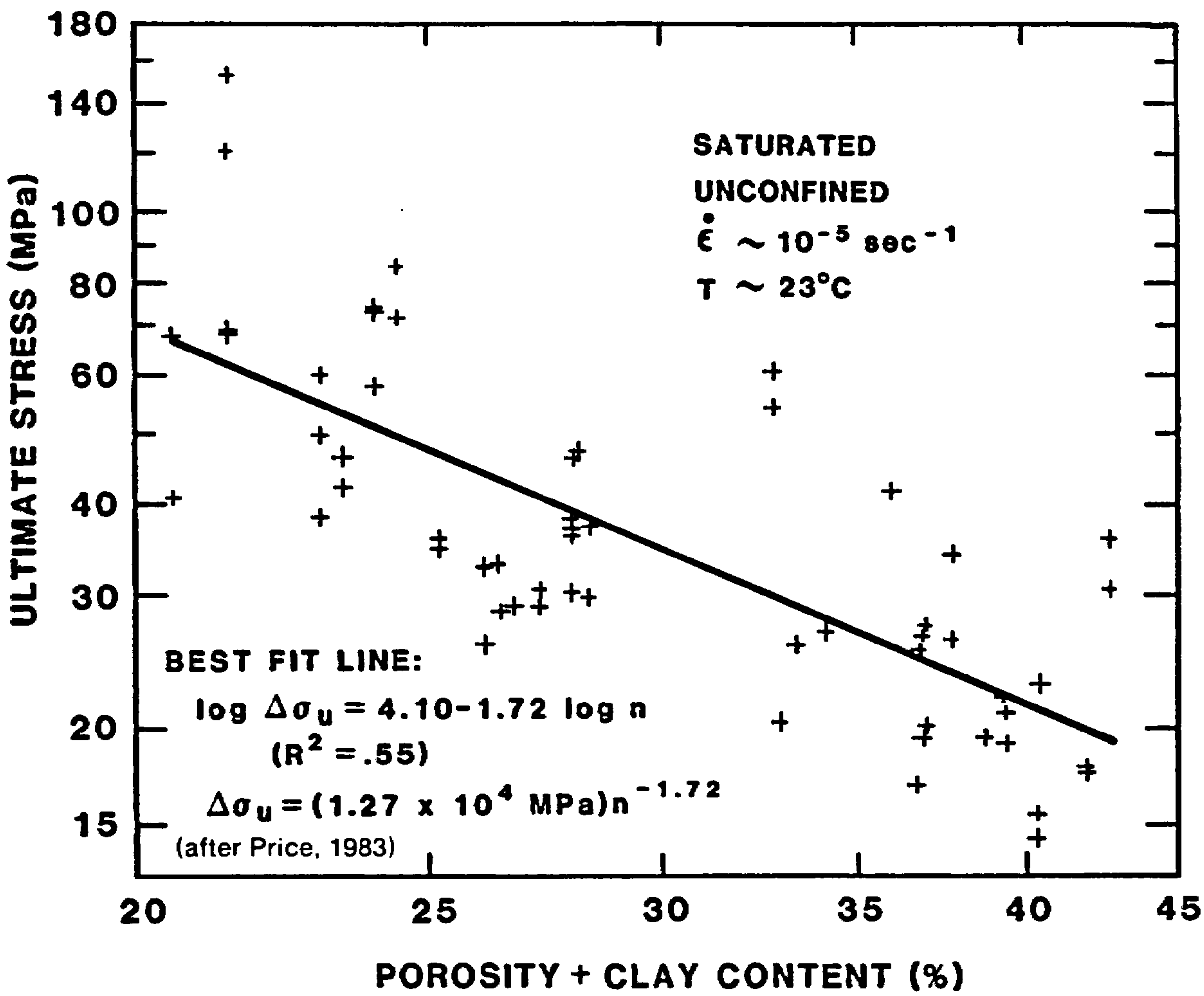


Figure 5 Unconfined Compressive Strength as a Function of Effective Porosity

and Jones, 1980). Closely spaced samples were obtained from the Grouse Canyon Member (a formation similar to the Topopah Spring Member at Yucca Mountain) exposed in G-Tunnel. Eighteen water-saturated and oven-dried samples were deformed at atmospheric pressure, room temperature, and nominal strain rates of $10^{-2}$, $10^{-4}$, and $10^{-6}$ $s^{-1}$. The results are presented in Figure 6. At each strain rate, the resulting data reveal that the average strengths of the saturated specimens are approximately thirty percent lower than the average strengths of the corresponding dry samples. Four experiments were run on samples of the Tuffaceous Beds of Calico Hills (Price and Jones, 1982) at approximately the same test conditions (unconfined, strain rate $10^{-5}$ $s^{-1}$, room temperature). In this study, two test specimens were fully saturated and two were room-dry. The average sample's strength decreased approximately 23 percent when the samples were water-saturated rather than air-dried. These results are similar to those from the Grouse Canyon Member study.

The results summarized in the preceding paragraph indicate that water-saturated tuff is expected to have a lower compressive strength than is tuff in which the saturation is less than 1.0. Using strengths measured on saturated samples as input to calculations in support of the design process thus should add a degree of conservatism to the process. A quantitative estimate of this conservatism is not possible because the saturation state will vary during the history of a repository.

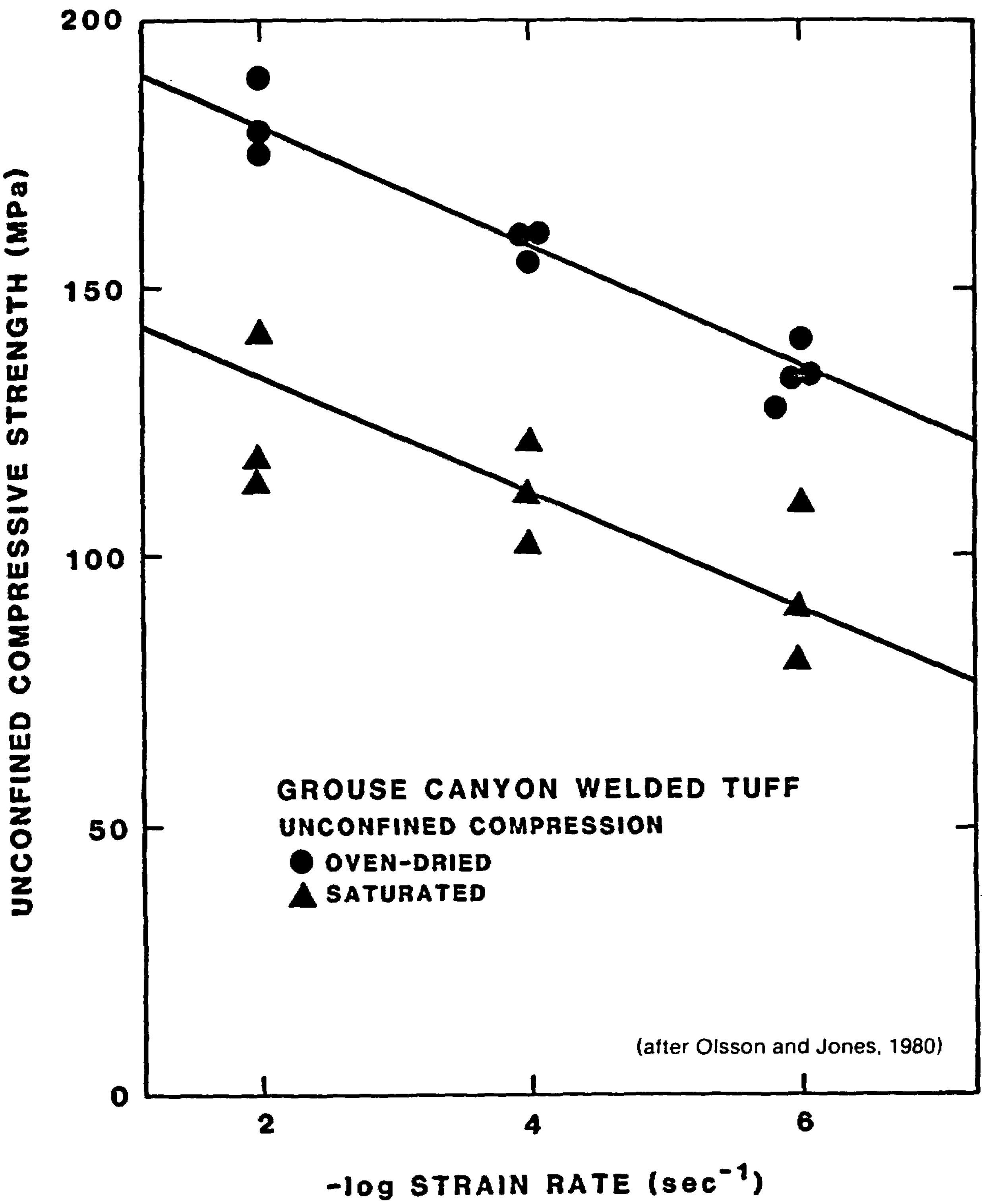


Figure 6 Effect of Saturation on Unconfined Compressive Strength

<u>Effects of Confining and Fluid Pressure</u>. Numerical analyses of the structural stability of mined openings, boreholes, and shafts require the use of failure criteria for the rock. The Coulomb failure criterion has been selected to represent the failure of the tuff matrix:

$$\tau = C_o + \sigma \tan \varphi$$

where

$\tau$ = shear stress on the failure plane at the onset of failure,

$\sigma$ = normal stress on the failure plane at the onset of failure,

$C_o$ = cohesion, and

$\varphi$ = angle of internal friction.

Uniaxial and triaxial compression tests are used to determine these parameters.

Thirteen sets of triaxial compression tests on 51 tuff samples have been run (Olsson and Jones, 1980; Olsson, 1982; Price and Jones, 1982; Price, Nimick, and Zirzow, 1982). Five of these test sets have been run with room-dry samples. The experimental results have been fit using the Coulomb criterion. The data illustrate a relatively small range of cohesion values (10.2 to 17.5 MPa) and a large range of friction angles (25.0 to 67.0°). Three sets of fully saturated samples from the Tuffaceous Beds of Calico Hills were deformed, but with pore fluid constrained to remain in the samples during the course of the tests. The resulting ranges and magnitudes of Coulomb parameters are quite small, with cohesion and friction angles ranging from 9.7 to 13.2 MPa and 4.8° to 7.8°, respectively. The three remaining test series were performed saturated and drained, with two sets at ambient temperature and one set at 200°C.

Data on the effects of confining pressure are recognized as being both limited in quantity (thirteen sets of data covering five units) and covering a wide range of experimental conditions. In general, both the cohesion and the friction angle are inversely related to sample porosity. Therefore, changes in the porosity of tuff samples can be used to estimate the anticipated range of cohesion and friction angle expected in the tuffs from Yucca Mountain. Additional testing is being focused on evaluating the cohesion and friction angles for the Topopah Spring Member.

To date, only one series of tests has investigated the effects of pore fluid pressure on the strength of tuffs from Yucca Mountain. Olsson (1982) reports results for samples of the Bullfrog Member deformed at 200°C and a nominal strain rate of $10^{-4}$ $s^{-1}$. Four samples were tested in a dry state at confining pressures of 5, 10, and 20 MPa. Three samples were saturated and tested at effective pressures (confining pressure minus pore fluid pressure) of 5, 12.5, and 20 MPa. Although data are available from only these seven tests, the results indicate that the concept of effective stress developed for other porous rocks (Handin et al., 1963) may also hold for tuff.

Effects of Elevated Temperature. The strength of most engineering materials (metals, plastics, concretes, rocks) decreases with an increase in temperature. Limited experimental data on tuff at elevated temperatures are available (Olsson and Jones, 1980; Olsson, 1982; Price, 1983). Data from the fifteen tests completed to date are inconclusive in quantifying strength changes. Variations in not only temperature but also other test conditions (pressure, strain rate, and confining pressure) and intrinsic rock properties (density and porosity) are present. A test series on samples from the Topopah Spring Member has been initiated to evaluate the strength of samples at 23, 100 and 200°C.

Time-Dependent Behavior. Three series of experiments on site-specific tuffs (Price and Jones, 1982; Price and Nimick, 1982, Price, Nimick, and Zirzow, 1982) and two series on Rainier Mesa tuffs (Olsson and Jones, 1980) have been performed to examine strain rate effects. Three of the test series have resulted in average strength decreases of three to six percent for every factor-of-10 decrease in strain rate. The sequence of experiments on the Topopah Spring Member resulted in virtually no rate effect on strength. However, this result may reflect the physical and mineralogical variability of the samples tested. Because of a lack of adjacent samples, the core used was from an interval ranging from 371.3 to 390.0 m in depth (USW G-1) and therefore probably had a range of physical and mineralogical characteristics.

To predict nonlinear time-dependent rock behavior, a preliminary model (Costin, 1983) has been developed based on the assumption that time- and stress-dependent microcrack growth is responsible for the deformation observed in mechanical tests on low-porosity (less than fifteen percent) welded tuffs. The evolution of microcrack density is estimated by extrapolating the experimentally determined behavior of single cracks to that of a random ensemble of microcracks. Stress corrosion is assumed to be the dominant mechanism of time-dependent crack growth. The model therefore assumes an initial population of microcracks that has been modified by the stress history.

As a test of the model's capability, model simulations of uniaxial compression tests were performed at various strain rates over the range $10^{-1}$ to $10^{-10}$ $s^{-1}$. The material parameters of the model were chosen to match those of the previously tested Grouse Canyon Member (Olsson and Jones, 1980). The results of the model simulation are compared to the mechanical data in Figure 7.

For strain rates between $10^{-2}$ and $10^{-6}$ $s^{-1}$, the model predictions show a reasonable agreement with the limited experimental data available. At lower strain rates, the model predicts that the strength decrease with strain rate is much less than a linear extrapolation from the experimental data would indicate. Since in situ strain rates are expected to be lower than the lowest experimental strain rate, determination of the most realistic trend in strength decrease is important in order to perform realistic calculations during the design process. Additional testing is planned to acquire data to determine whether the linear or the nonlinear model is a better representation of actual conditions.

The possibility of creep closure of openings in the Topopah Spring Member can also be examined using information obtained for other rock types at the pressures and temperatures expected to occur in situ. Because creep closure depends on temperature and shear (deviatoric) stresses, preliminary calculations of the thermomechanical behavior of the Topopah Spring Member near the prospective repository site (Johnstone, Peters, and Gnirk, 1984) were examined to determine predicted maximum temperatures (on the order of 250°C) and maximum deviatoric stresses (approximately 30 MPa). At this temperature, which is less than

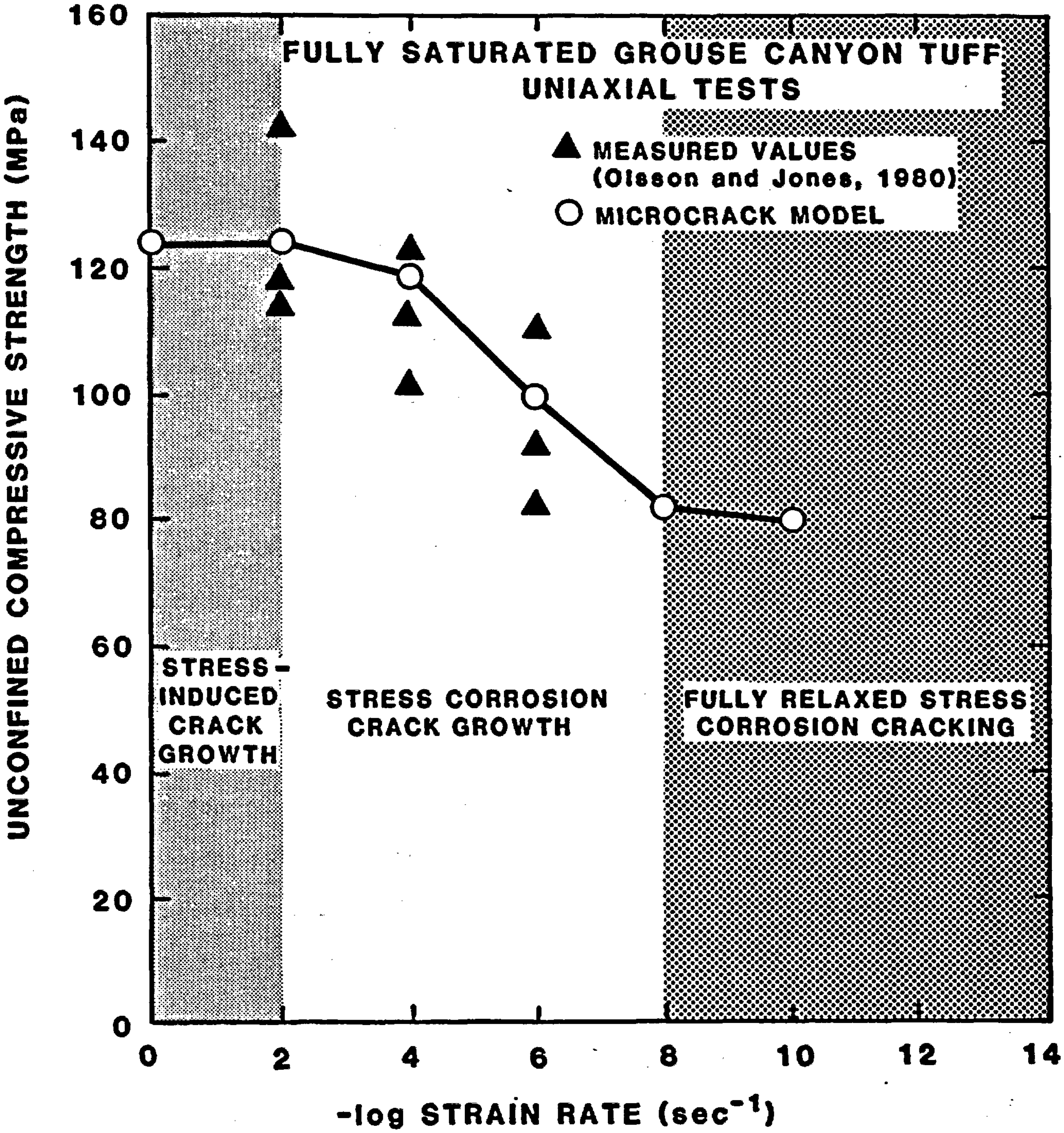


Figure 7 Compressive Strength as a Function of Strain Rate for Microcrack Model for Saturated Grouse Canyon Member

one-third of the melting temperature of most rock-forming silicates, the silicates are brittle, and creep can occur only at stresses greater than about one-half their short-term breaking strength (Handin and Carter, 1981). The predicted maximum stress is, however, only on the order of one-third of the short-term breaking strength, clearly below the threshold beyond which significant creep deformation can occur even over geologic time (Griggs, 1939). Consequently, based on these conditions, a preliminary conclusion has been drawn that the Topopah Spring Member is a brittle, essentially elastic solid in which creep deformations can be ignored. This conclusion, if correct, would support the non-linear model of time-dependent tuff deformation.

Effects of Lithophysae. The effects of lithophysal cavities (voids formed by vapor-phase activity during the cooling of a thick ash-flow tuff) on strength are important in determining the thickness of the Topopah Spring Member that is acceptable for waste emplacement. Of the four repository horizons studied in Yucca Mountain, only portions of the Topopah Spring Member have been observed to contain abundant lithophysae. Samples containing significant lithophysae have not yet been deformed in mechanical tests. A test series on samples containing small cavities has been planned. This series will test ten samples that are 0.27 m in diameter in uniaxial compression. The samples are being obtained from the outcrop of Topopah Spring Member at Busted Butte (Figure 1). Confirmation testing on large samples from the ES is planned. Lithophysae are expected to decrease the strength of the tuff in a manner similar to that created by the effects of smaller pore spaces reported earlier.

Anisotropy. To date, all mechanical experiments have been performed on samples in which the loading axes are parallel to the original coring direction (i.e., approximately vertical and therefore approximately perpendicular to the bedding). To determine whether mechanical anisotropy should be investigated in detail, a test series is planned on adjacent samples oriented parallel to, perpendicular to, and at three intermediate orientations to the core axis. A test series on samples of the Topopah Spring Member taken from the outcrop at Busted Butte will be conducted to quantify the degree of anisotropy of the elastic and strength properties.

Sample Size Effects. All tests completed to date have been performed on samples that have a diameter of 2.5 cm and a length of 5.0 cm. Because of defects (inhomogeneities and fractures) inherent in the rock samples, size effects are anticipated in both the strength and deformation behavior of the tuff. Sample size effects are expected to result in measurement of lower rock strengths and moduli for the larger samples (Bieniawski and Van Heerden, 1975). A series of 24 unconfined compression tests will be performed on samples with diameters of 2.5, 5, 8.7, and 12.5 cm to quantify the sample size effects in the Topopah Spring Member and to determine whether additional laboratory measurements on large samples are warranted.

Tensile Strength

Tensile strengths were calculated from Brazilian (indirect tensile) tests on twenty samples from all four lithologic units (Blacic et al., 1982). The relationship between tensile strength and porosity is approximately linear, as shown in Figure 8. This functional relationship

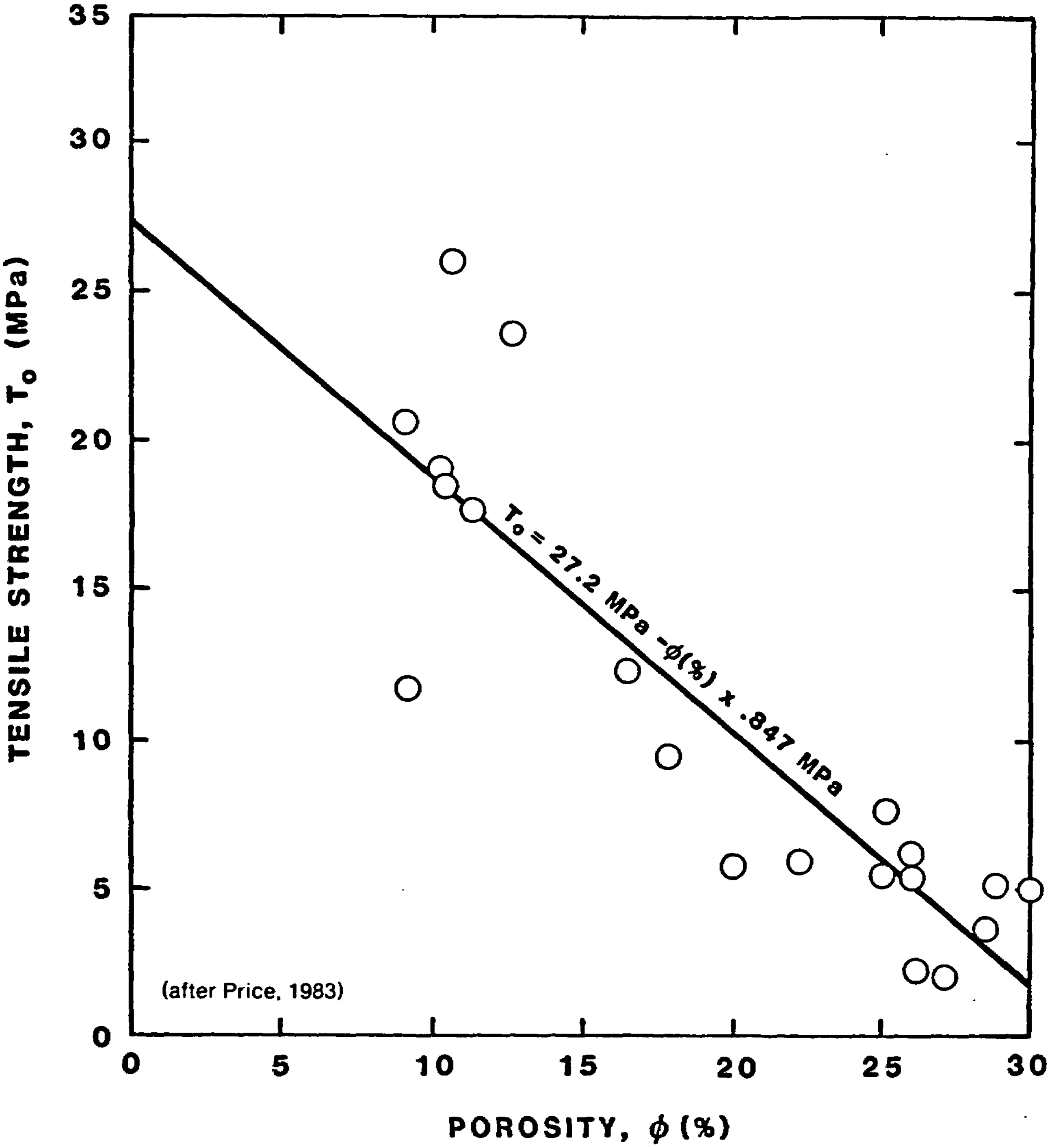


Figure 8 Tensile Strength of Yucca Mountain Tuff as a Function of Porosity

may be used for first-order approximations of the tensile strength of any tuff from Yucca Mountain for which physical properties have been determined. Additional tests are planned to measure the tensile strength of the Topopah Spring Member.

## SECTION 2. MECHANICAL PROPERTIES OF DISCONTINUITIES

Discontinuities such as joints, faults, and bedding planes cause the mechanical response of the rockmass to be different from that of the unfractured intact rock. In general, the strength and deformation modulus of the rockmass will be lower than that of the matrix material. In conventional mine design approaches, the effects of fractures are approximated by assuming that the effective rockmass strength is some selected percentage (based on experience in similar rocks) of the strength measured for intact material. More detailed stress analyses use frictional properties of joints (cohesion and coefficient of friction), orientation, and spacing to determine if slip can occur along the discontinuities and to evaluate the impact of the slip on support requirements or usability of the opening. The unique aspect of repository analyses and testing is that temperature-induced changes in the joint properties need to be bounded in order to evaluate the stability of openings at the temperature expected to be found in the rock before repository closure. Analyses to bound the possible conditions in the tuff will be made to determine whether it is likely that regions will be encountered in which significant support will be required to maintain a stable opening. The data obtained from laboratory tests on jointed tuff, which form the basis of current detailed stress analyses, are discussed below.

Laboratory-derived mechanical properties of joints are believed to be representative of mechanical properties of faults and bedding planes (Barton, 1973; Byerlee, 1978). Therefore, current investigations are concentrating on the properties of joints. Initial tests have been conducted using simulated joints (precut) in about sixty samples of both welded and nonwelded tuffs to determine the coefficient of friction of the joints and to compare the results to those for other rock types. A few additional tests are being conducted on samples with both natural and, in some cases, simulated joints. The data discussed below constitute an initial data base for conceptual design and performance assessment modeling studies. The applicability of these data will ultimately be determined by comparison to data from large-scale in situ tests.

## Definition of Terms

The shear strength of joints, bedding planes, and other discontinuities is a measure of the ability of the discontinuities to resist externally applied shearing forces. Compressive normal stress can be transmitted across a joint, but the amount of shear stress transmitted will depend on the inherent shear strength (cohesion) and the frictional properties of the joint and/or joint infilling. The shear strength ($\tau$) of jointed rock fits the relation $\tau = C + \sigma \tan \varphi$ where C is the cohesion, $\varphi$ is the friction angle, $\tan \varphi$ is the coefficient of friction, and $\sigma$ is the applied normal stress. The shear strength parameters C and $\varphi$ are required to assess whether in situ stress conditions, modified by excavation and thermal stresses, will cause instability or sliding along joints, bedding planes, and faults within the excavated rockmass. Insufficient shear resistance along unfavorably oriented discontinuities can be a major cause of instability in drifts and other subsurface openings.

## Equipment and Procedures, Limitations, and Error Analysis

In the laboratory tests performed on joints (natural and sawcut), specimens were deformed in triaxial compression at confining pressures to 40 MPa, axial displacement rates from $10^{-2}$ to $10^{-6}$ cm/s, and temperatures to $200^{o}$ C (Olsson and Jones, 1980; Teufel 1981). Because neither the American Society for Testing and Materials (ASTM) nor the International Society of Rock Mechanics (ISRM) has published standard procedures for jointed rock testing, these reports include detailed discussions of the test apparatus, instrumentation, sample preparation techniques, and test procedures.

## Mechanical Properties of Discontinuities-General

The magnitude of shear stress that can be transmitted across a joint depends on the cohesion and the frictional properties of the joint and/or joint infilling. Shear strength parameters for discontinuities in similar rock types have been reviewed and summarized to allow comparison to tuff properties presented in the remainder of this section.

The coefficient of friction is generally independent of rock type and increases only with increasing surface roughness (Barton, 1973). The effect of surface roughness, found to be important only at low normal stresses, is a result of the interlocking of asperities along the sliding surface. Quasi-static experiments on a variety of jointed rock types exhibiting extreme variations in surface roughness have shown that the coefficient of friction can vary from 0.4 to 10 at normal stresses less than 10 MPa (Barton, 1973). At higher normal stresses, surface roughness becomes less significant because asperities are sheared off and incorporated into gouge along the sliding surface. Quasi-static test measurements of coefficients of friction for joints of differing surface roughness in a wide variety of rock types have been compiled (Byerlee, 1978). These studies indicate a coefficient of friction range of 0.4 to 1.0 at normal stresses greater than 10 MPa. The results of an experimental study (Teufel, 1981) on simulated joints in welded tuff are consistent with Byerlee's compilation in that the normal stresses across the joints were 8 to 70 MPa, and all measured values of the coefficient of friction were less than 1.0.

The cohesion of jointed rock does not show strong dependence on rock type or surface roughness (Byerlee, 1978), and generally the cohesion is less than 4 MPa. For jointed/welded tuff with smooth joint surfaces, cohesion was found to be less than 1 MPa (Teufel, 1981).

## Mechanical Properties of Discontinuities in Tuff

Existing mechanical properties data on discontinuities in tuff are generally limited to studies of simulated joints (Olsson and Jones, 1980; Teufel, 1981). In these studies, simulated joints were precut in samples of the Grouse Canyon Member from Rainier Mesa and of the Prow Pass Member from Yucca Mountain. Results are included here because these samples are physically and mechanically similar to welded portions of the Topopah Spring, Bullfrog, and Tram Members at Yucca Mountain. A summary of mechanical test results on discontinuities in tuff is presented in the following paragraphs.

At present, no data have been measured to quantify the normal stiffness of joints in tuff. Tests are in progress to obtain these data.

Mechanical Properties of Simulated Joints

The shear strength in triaxial compression of a simulated joint in welded Grouse Canyon Member as a function of confining pressure, displacement rate, temperature, and water saturation has been determined by Teufel (1981). The Grouse Canyon Member in Rainier Mesa has mechanical properties similar to those of the Topopah Spring Member in Yucca Mountain. Joints were simulated by using a right circular cylinder with a polished precut inclined at 35° to the cylinder (load) axis. Tests were conducted at ambient temperature and at confining pressures from 5 to 40 MPa, axial displacement rates from $10^{-2}$ to $10^{-6}$ cm/s, under both dry and fully saturated conditions.

The shear strength of a simulated joint in welded tuff fits the linear relation $\tau = c + \sigma \tan\varphi$. The coefficient of friction at the initiation of slip was found to be independent of the normal stress, with a value of 0.64 at a displacement rate of $10^{-4}$ cm/s (Figure 9). Similar results ($\tan\varphi = 0.59$) were obtained for partially welded tuff (Prow Pass Member) at a displacement rate of $10^{-3}$ cm/s (Olsson and Jones, 1980) (Figure 10). The independence of the coefficient of friction with respect to the confining pressure and the corresponding normal stress across the sliding surface is consistent with rock-friction literature as reviewed by Byerlee (1978).

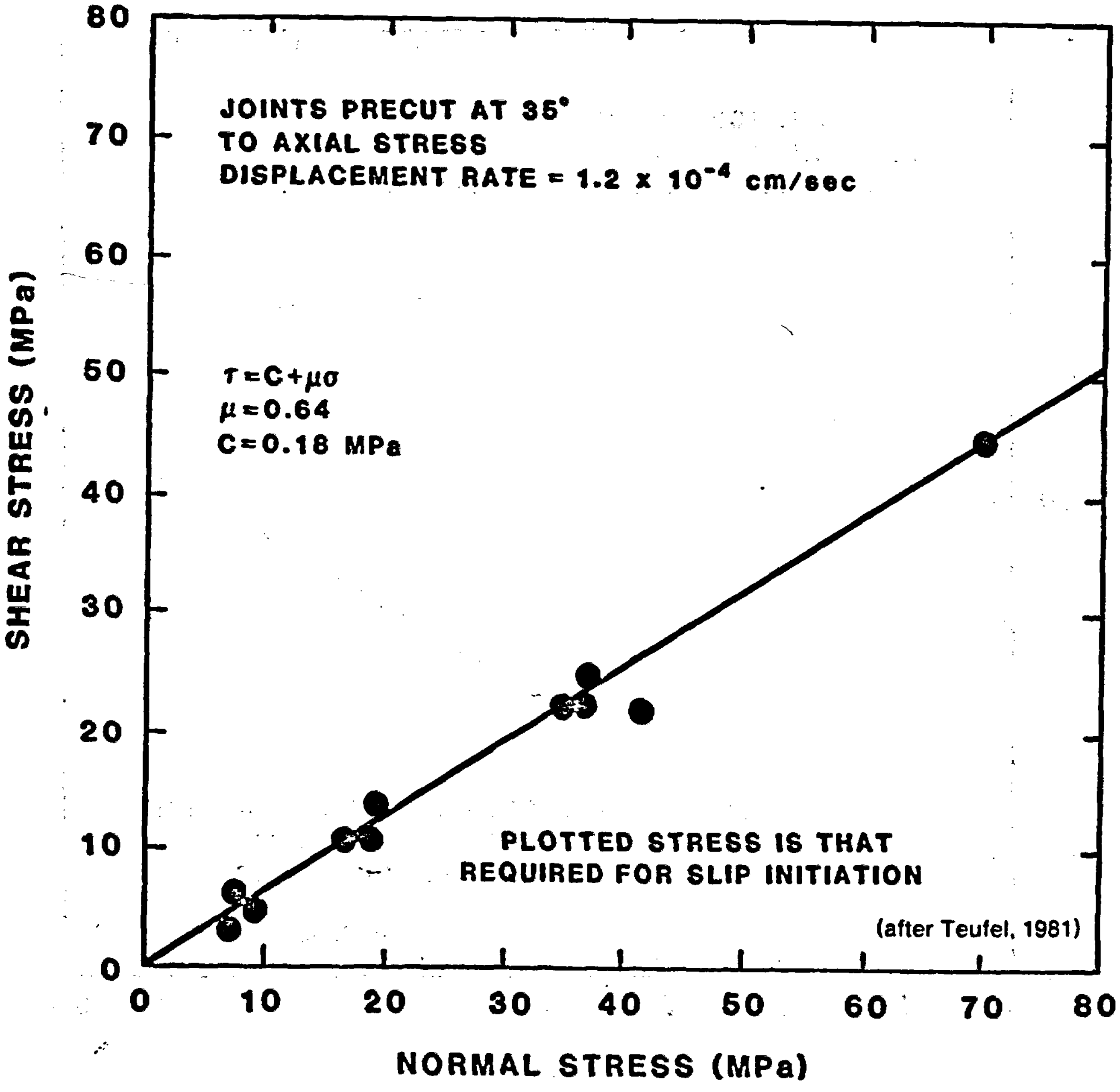


Figure 9 Shear Stress-Normal Stress Relation at Slip Initiation for Air-Dried, Precut Joints in Grouse Canyon Member Welded Tuff

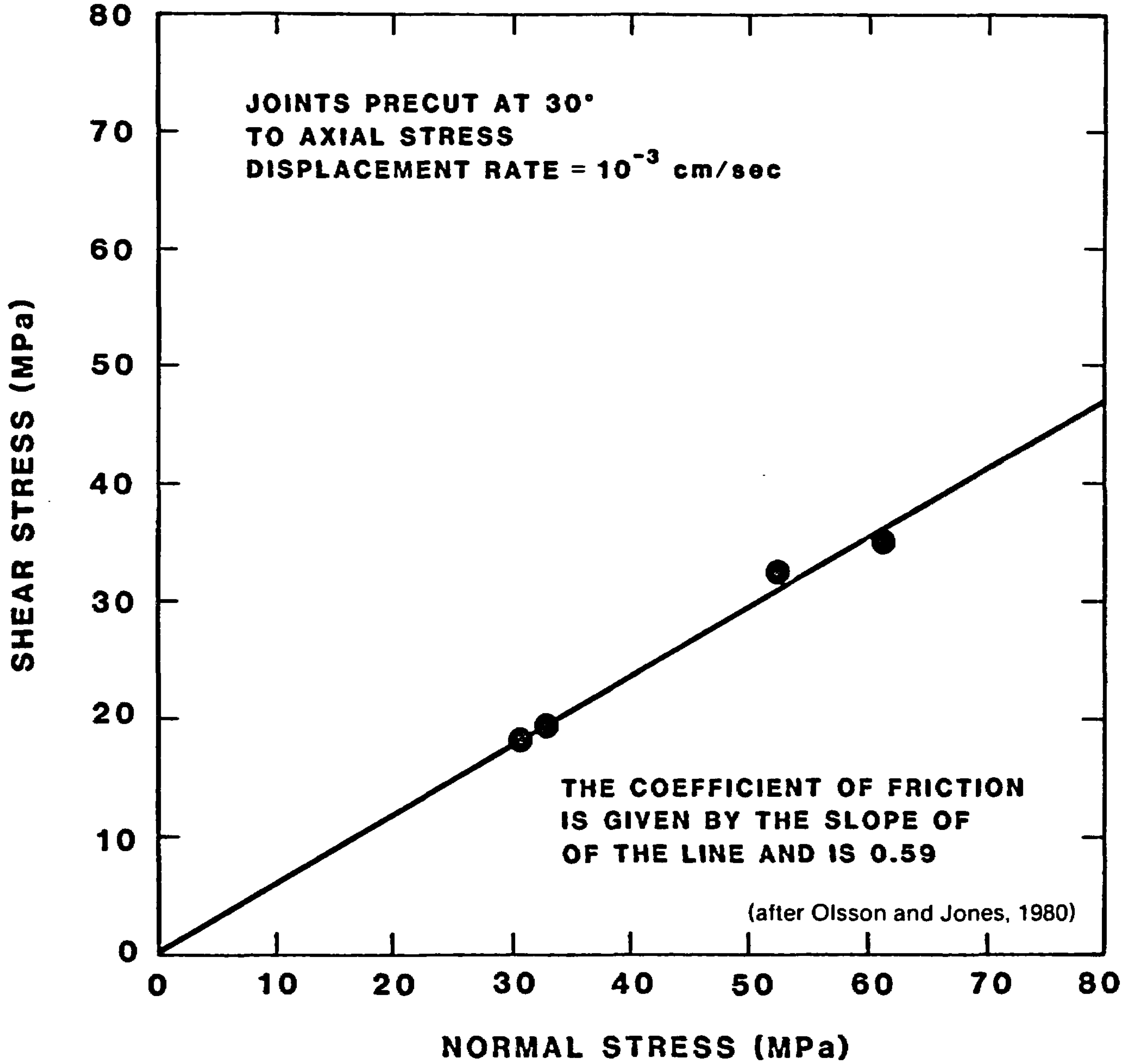


Figure 10 Shear Stress-Normal Stress Relation at Slip Initiation for Precut Joints in Prow Pass Member Partially Welded Tuff

Effects of Water Saturation. The Topopah Spring Member is above the water table, but experience at G-Tunnel suggests that very limited amounts of water may flow through some fractures. The effects of water saturation on simulated joints were investigated by Teufel (1981). The coefficient of friction of a water-saturated precut joint is independent of normal stress (and thus of moderate fluid pressures within the fracture by virtue of the effective stress principle), and the shear strength fits the linear relation described earlier. However, the coefficient of friction for the water-saturated precut is nine percent greater than for dry precuts, with a value of 0.70 (Figure 11). The behavior is attributed to a larger effective contact area along the joint resulting from increased localized failure of the matrix material when saturated, i.e., localized asperities became flatter. Although this phenomenon has been observed previously, no clear pattern of change in joint strength with saturation state is evident in tests reported on other rocks (Paterson, 1978). Based on the tuff data obtained to date and on observations made in tunnels in Rainier Mesa, it is not anticipated that variations in joint strength that result from local changes in the degree of saturation will lead to major changes in local support requirements.

Time-Dependent Behavior. Time-dependent effects on joint strength were addressed in two ways. Constant strain-rate tests provide insight into the effect of changes in sliding velocity on the sliding coefficient of friction. Hold times in these tests provide a preliminary evaluation of the increase in the static coefficient of friction of the joint as a function of time. The data were taken in an attempt to quantify the

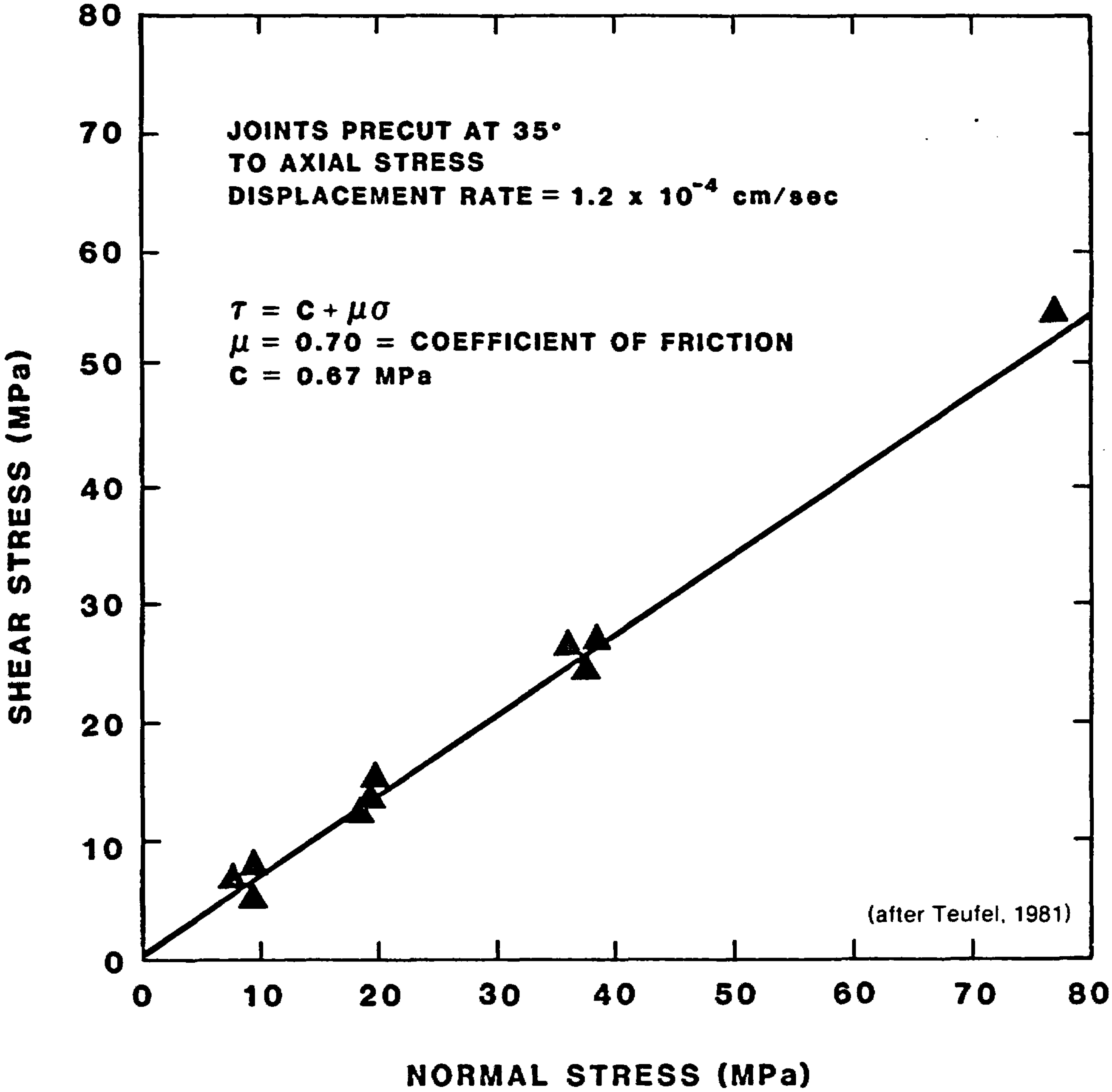


Figure 11 Shear Stress-Normal Stress Relation at Slip Initiation for Water-Saturated Precut Joints in Grouse Canyon Member Welded Tuff

amounts of joint strength increases that occur with time for use in evaluating maximum in situ joint strength.

To determine the effect of sliding velocity on the coefficient of friction of a precut joint, a series of ambient-temperature tests were conducted at 10 MPa confining pressure and axial displacement rates from $10^{-2}$ to $10^{-6}$ cm/s (Teufel, 1981). With decreasing displacement rate, the coefficient of friction for oven-dry samples increased from 0.62 at $10^{-2}$ cm/s to 0.66 at $10^{-6}$ cm/s, as shown in Figure 12. These results are consistent with the work of Dieterich (1978) and Teufel and Logan (1978) on granites and sandstones, respectively. Displacement rate effects on friction are very small -- only a six percent increase in the coefficient of friction is produced by a decrease of four orders of magnitude in the displacement rate. For water-saturated joints, the displacement rate effects are slightly greater. However, the effect is small, with only a nine percent increase in the friction coefficient produced by a decrease of four orders of magnitude in the displacement rate (Figure 12). As noted in the previous section, over the observed range of displacement rates, the coefficient of friction for water-saturated precuts is slightly greater than for dry precuts.

To evaluate time-dependent joint strength increases, the time dependence of the frictional shear strength of oven-dried and water-saturated welded tuff from the Grouse Canyon Member was investigated in triaxial compression by examining the response of 35° precuts. A confining pressure of 10 MPa was used. The test procedure was slightly different from that used in the previous quasi-static

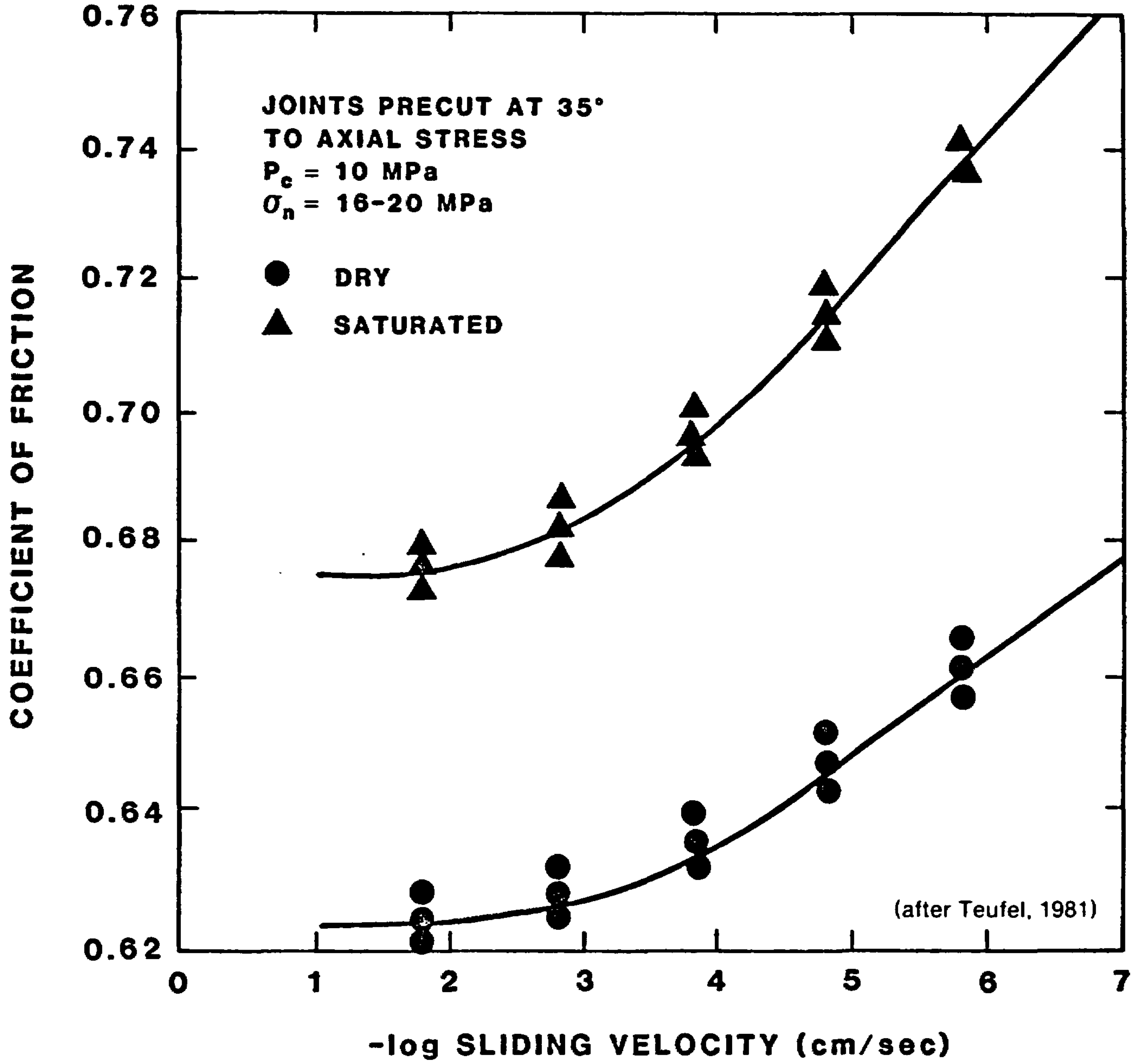


Figure 12 Coefficient of Friction as a Function of Sliding Velocity for Precut Joints in Grouse Canyon Member Welded Tuff

tests. In the tests of time-dependent behavior, axial load was increased until slip occurred along the precut at a constant sliding velocity of $1.2 \times 10^{-3}$ cm/s. The test was stopped for a given time under load and then started again at the same sliding velocity. This procedure was repeated for several different durations of contact time. A plot of the change in shear stress as a function of displacement (Figure 13) shows that, when a test was stopped for 60 seconds and then started again, there was an abrupt increase of approximately 0.4 MPa in the shear stress necessary for slip. This increase was followed by a drop back to the former stress level as slip continued at the previous sliding velocity of $1.2 \times 10^{-2}$ cm/s. With an increase in the time of stationary contact (2,400 seconds), both the stress rise required to initiate slip and the corresponding stress drop were larger. However, the stress required for stable sliding did not change significantly. A plot of the static coefficient of friction at peak stress versus the logarithm of the time of contact for oven-dried samples (Figure 14) shows that, as the time of contact increased, there was a consistent increase in the friction resisting the initiation of sliding. Also, the time-dependent increase in friction is enhanced with water saturation (Figure 12). The increased time dependence of the frictional resistance of the water-saturated tuff is attributed by Teufel (1981) to hydrolytic weakening and to time-dependent stress corrosion of asperity contacts on the sliding surface.

Effects of Temperature. Studies of the effects of temperature on the mechanical properties of joints and other discontinuities in tuffs have

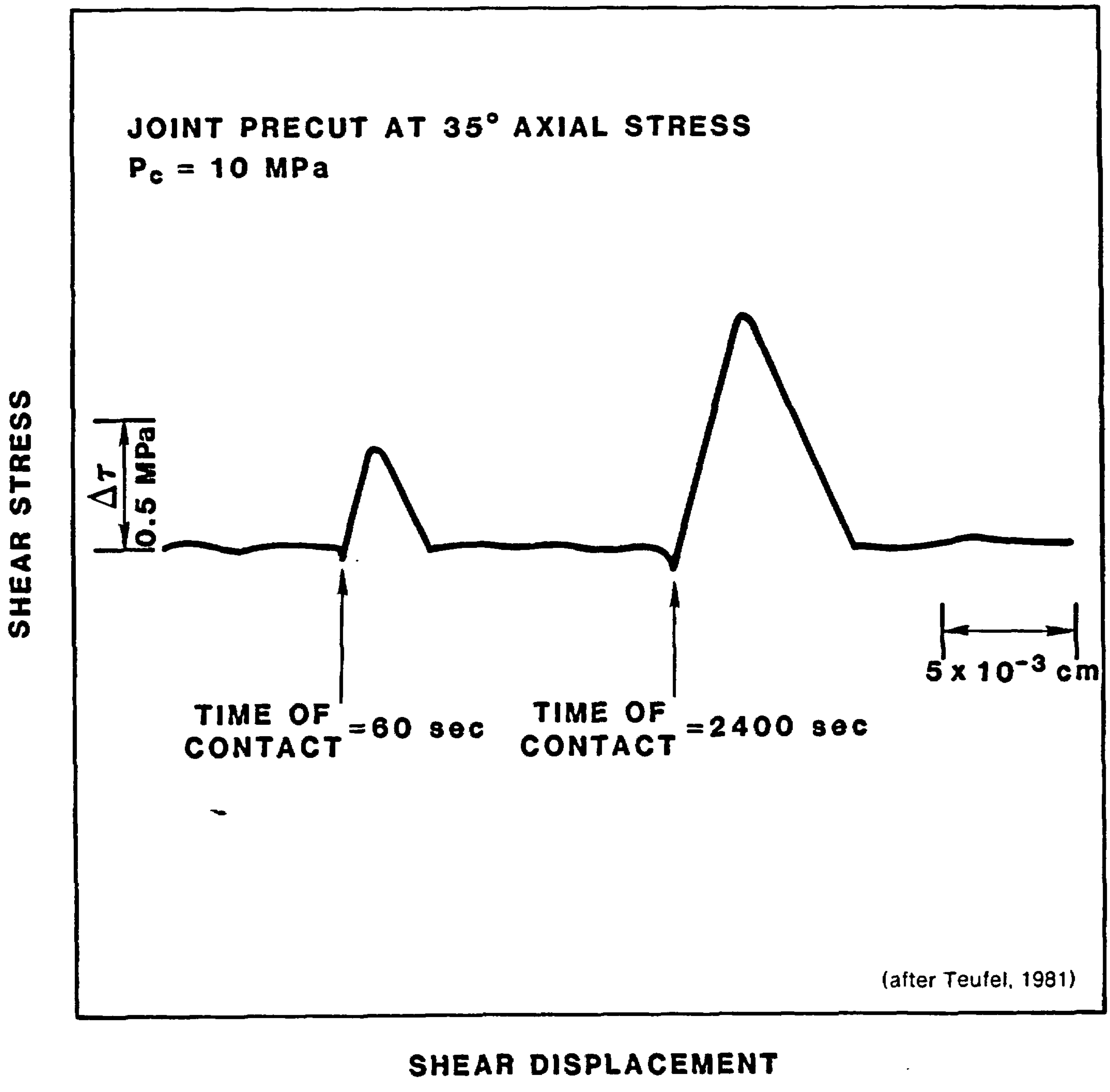


Figure 13 Shear Stress as a Function of Shear Displacement for Precut Joints in Grouse Canyon Member Welded Tuff

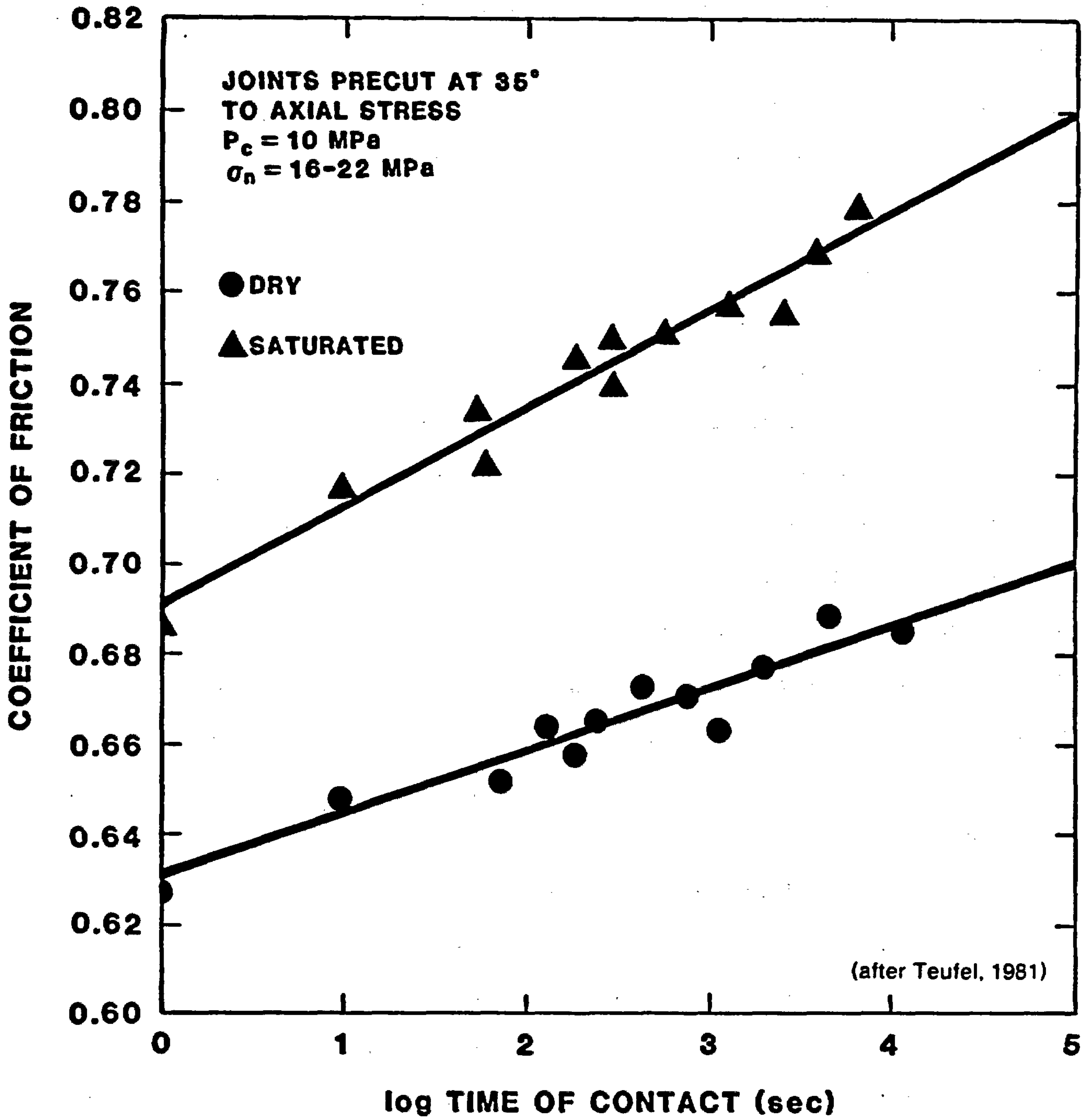


Figure 14 Static Coefficient of Friction as a Function of Time of Contact for Precut Joints in Grouse Canyon Member Welded Tuff

not yet been made. Donath, Fruth, and Olsson (1972) found that increasing the temperature from 25 to 300°C increased the coefficient of friction for sandstone only from 0.62 to 0.68. If temperature significantly affects the coefficient of friction for tuff, and if these effects prove to be potentially significant in the evaluation of the stability of waste emplacement holes or drifts, additional tests will be performed on samples with natural joints taken from the ES.

Mechanical Properties of Natural Joints

The mechanical properties of natural joints are currently being investigated. Three types of natural joints are present at Yucca Mountain: healed joints with mineralized surfaces; unhealed joints with no infilling; and unhealed joints with infilling. Preliminary results show that the healed joints approach or exceed the strength of the intact rock. Unhealed joints with no infilling have a higher coefficient of friction than simulated joints as the result of roughness effects. The coefficient of friction varies for unhealed joints with no infilling from about 0.85 to 1.0. Joints with infilling or gouge have been observed, but the quality of cores has been inadequate for representative laboratory tests. It is anticipated that joints or faults containing gouge or other infilling will have a lower coefficient of friction than clean, unfilled joints (Byerlee, 1978). Frictional behavior will depend on the composition of the gouge. The coefficient of friction for typical saturated gouges generally ranges from 0.2 to 0.6 (Morrow et al., 1982), while the coefficient of friction for dry clay gouges has a range of 0.2 to 0.5 (Shimamoto and Logan, 1981). Joint infilling materials at Yucca Mountain are expected to have coefficients of friction within the same range.

## SECTION 3. MECHANICAL PROPERTIES OF THE ROCKMASS

Rockmass mechanical properties (elasticity and strength) from in situ tests are useful in performing analyses in support of repository design. They also are used for establishing and confirming scaling techniques by which data measured in laboratory tests are extrapolated to represent the rockmass response to excavation and thermal loads.

Strength and elastic modulus measurements performed on intact unfractured rock samples in the laboratory are upper bound values for the in situ rockmass. Where joints are widely spaced in situ, field moduli and strengths may approach moduli and strengths for intact laboratory specimens. However, as the degree of jointing becomes more pervasive, as it does in welded tuffs, laboratory measurements become less representative of field values. Handbook methods for making estimates of the degraded properties in the rockmass are widely used in the mining industry. However, these methods are imprecise and have not been developed for use to evaluating the effects of thermal stress. It is therefore necessary to verify the applicability of these methods for use in repository design where the effect of thermal stresses on the rockmass must be taken into account. Because the strength and deformation characteristics of the rockmass are controlled by existing discontinuities and defects, representative estimates of or bounds on strength and moduli for the rockmass will be determined by large-scale in situ tests. These field tests will also provide an opportunity for evaluation of the validity of the coupled thermal/ mechanical models being used for thermomechanical analyses.

Rockmass properties for the NNWSI Project will be measured in field tests in G-tunnel (heated block and pressurized slot) and in in situ tests in the exploratory shaft (enhanced heated block test, plate-loading measurements, and the canister-scale heater test). Currently available data and plans for large-scale testing are summarized below.

## Definition of Terms

Definitions of mechanical properties, including elastic constants, strength parameters, and physical properties, are given in Section 1.

An important design consideration for subsurface openings is the unloading of rock as a result of stress release caused by excavation. A parameter that is useful in describing this process is the ratio of stress change to total strain change (elastic and inelastic) in repeated load-unload-load tests. This parameter is called the modulus of deformation, and is taken to be the tangent modulus. When the modulus of deformation is defined in this manner, it is a function of stress. While this modulus is based on total measured strains, the modulus of elasticity from such tests is based only on the ratio of stress to elastic strain change (see Figure 15). Both the modulus of deformation and the modulus of elasticity are used to predict how rock surrounding the opening deforms after excavation.

## Equipment and Procedures, Limitations, and Error Analysis

Before 1984, field measurements of the mechanical properties of tuffs were limited to measurements of modulus of deformation made in G-Tunnel using the Goodman borehole jack technique (Zimmerman and Vollendorf,

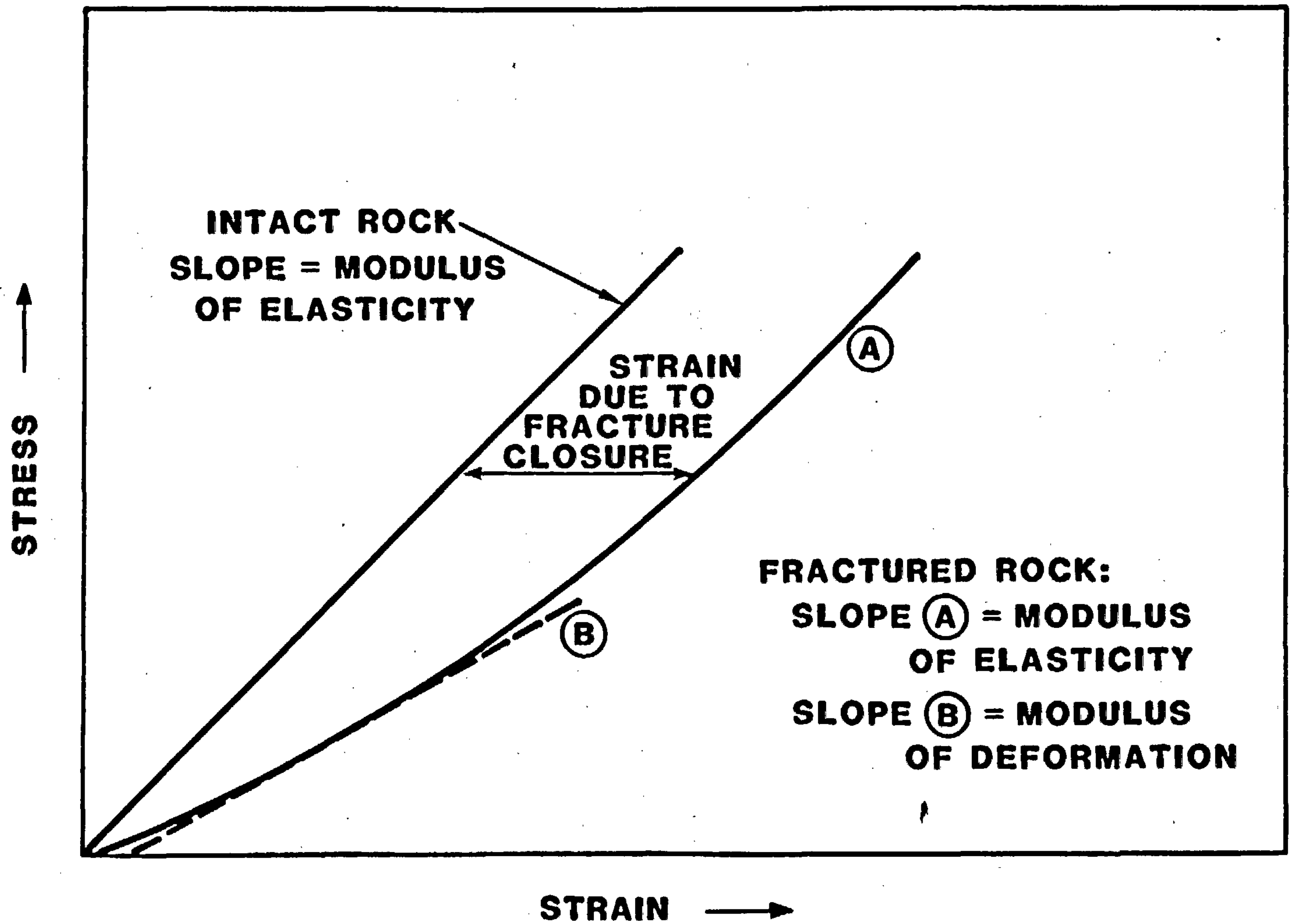


Figure 15 Comparison of Modulus of Elasticity and Modulus of Deformation

1982). The jack is a mechanical device with two diametrically opposed platens, each of which exerts radial pressure over a 90° section of a borehole wall. Displacement transducers monitor the radial displacement of the curved steel platens during loading and unloading. The ratio of changes in pressure to changes in displacement is used to compute the modulus of deformation. In general, only joints within one or two borehole diameters of the borehole wall are influenced by jacking pressures, which limits the volume of rock represented by this test. Deformation modulus values can be corrected for platen bending using the method described by Heuze and Salem (1977). Corrections for platen/borehole radius mismatch or contact angles can be made using a method described by Hustrulid (1976). These corrections were not made during the G-Tunnel testing because the changes attributable to the corrections are minor when comparing in situ moduli to laboratory values.

Large-scale studies planned or underway in G-Tunnel include heated block tests and pressurized slot experiments. Standardized test procedures do not exist for either the heated block or pressurized slot tests, so a thorough evaluation of the limitations of the instrumentation and data will be made to define in detail the procedures for testing in the ES.

## Mechanical Properties of Other Jointed Rock

Available large-scale mechanical properties data in other jointed rocks have been reviewed to allow assessment of the relative magnitude of typical in situ and laboratory-scale moduli values and to enable future comparison to tuff properties. These data are presented in Table 4.

TABLE 4

LARGE-SCALE MECHANICAL PROPERTIES OF OTHER JOINTED ROCKS

| Rock Type | Field Test Method | Average Field Modulus of Deformation (GPa) | Corresponding Laboratory Modulus of Elasticity (GPa) | Reference |
|---|---|---|---|---|
| Granite | Borehole jack | 25 | 70 | Heuze et al., 1981 |
| Basalt | Flatjack<br>Borehole jack | 40<br>20 | 87 | Lanigan, et al., 1983 |
| Quartz Diorite | Block Test (2 Meter) | 3.0 | 3.7-4.5 | Pratt et al., 1972 |
| Granodiorite | Block Test (2 Meter) | 22.8 | 37.9-57.9 | Pratt et al., 1972 |

## Mechanical Properties of Tuff - Large Scale

Measurements of modulus of deformation have been made in two NQ-size boreholes in G-Tunnel using the borehole jack. The average modulus of deformation for the twenty measurements obtained is 12.1 GPa. This value is uncorrected for the possible errors that result from the mismatch of the interfaces between the platen and the rock surface (Hustrulid, 1976; Heuze and Salem, 1977).

Ambient temperature testing of the G-Tunnel heated block has been conducted and field values for the modulus of deformation are available (Zimmerman, et al., 1984). Figure 16 shows the setup for the test. Flatjacks grouted in slots around the block are used to create uniaxial or biaxial stress fields in the block. The heaters (located outside the block) have been positioned so that relatively uniform temperatures can be obtained in the block (Blanford, 1982). Hence, independent thermal and mechanical loads can be applied to a 2-m block of jointed tuff. Ambient temperature testing is used to determine the mechanical properties, and thermal-cycle testing is used to measure an effective coefficient of thermal expansion.

A modulus of 14.2 GPa was the average value determined during the ambient temperature testing at stresses ranging from 3.1 to 10.6 MPa. The value is considered to be representative of the material under in situ stress conditions. The modulus of deformation would be expected to be lower near excavated surfaces because of joint relaxation.

A pressurized slot (modified Rocha slot) technique (Rocha, 1970) is being developed to measure the modulus of deformation and to evaluate the effect of joint proximity and orientation on the modulus. In this test

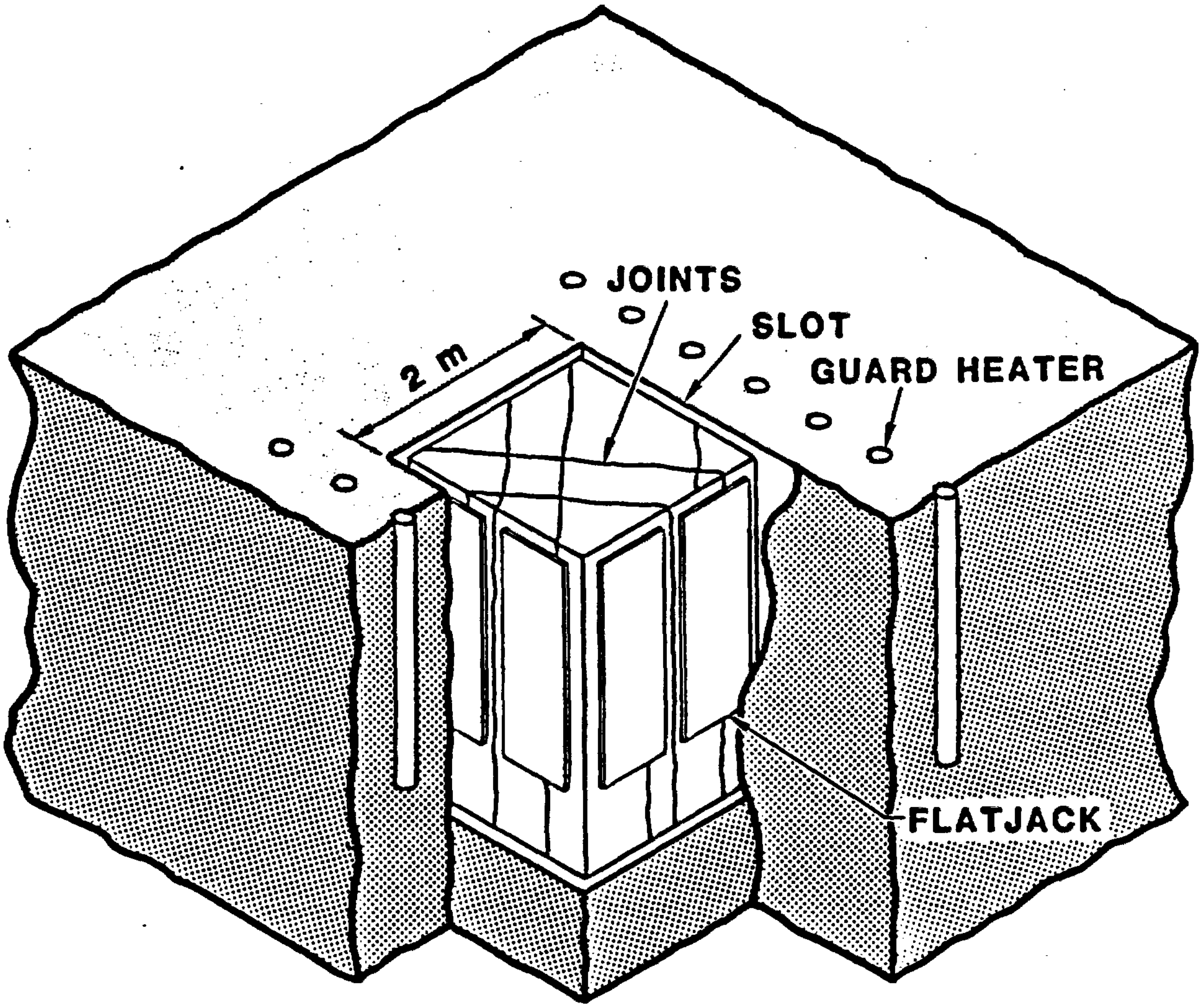


Figure 16 Heated Block Experiment in G-Tunnel Underground Facility

(Figure 17), a flatjack is inserted in a relatively narrow slot and pressurized. As in the borehole jacking test, the displacement of the flatjack is monitored during loading and unloading so that the resulting data can be used in determining the deformation modulus of the rockmass. In this test, the modulus measured is representative of a larger volume of rock than in the borehole measurements. Slot-cutting techniques being developed for these tests were evaluated in field trials in 1984, and the slot tests will be fielded in 1985.

Tests for in situ evaluation of rockmass strength are currently being evaluated with respect to geometry, loading techniques, fracture spacing, and mining requirements. To date, individual tests have not been selected.

Measurements of large-scale rockmass properties will be made in several of the tests planned in the ES. Plate-bearing tests and the enhanced block measurements will provide direct measurement of the modulus of deformation. The shaft convergence measurements, pillar-monitoring data (stress, permeability, roof bolt loads, displacements), and the motion observed in the canister-scale heater test will be used to evaluate the degree to which complicated rockmass response can be understood with the aid of available numerical analysis codes, assuming that the rockmass properties are known.

### Relationship of Laboratory Scale to Existing Field Test Results

Laboratory data include biaxial elastic modulus measurements taken on thirteen cores 14.3 cm in diameter that were strain-relieved during

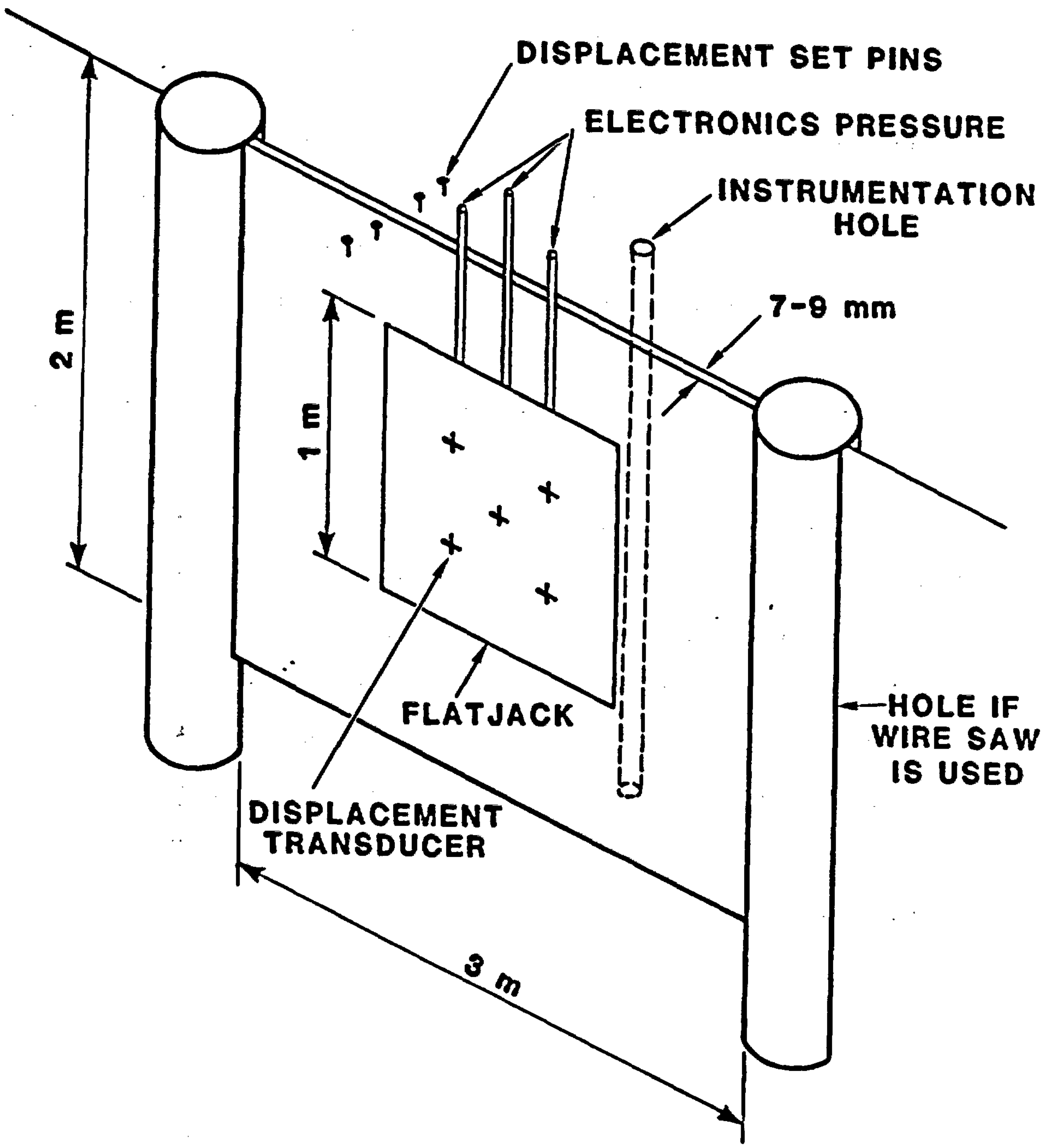


Figure 17 Pressurized Slot Test in G-Tunnel Underground Facility

overcoring (Zimmerman and Vollendorf, 1982). An average modulus of 31.3 GPa was obtained. One of the cores subjected to biaxial measurements had a fracture running nearly parallel to its axis. Measurements parallel and perpendicular to the plane of the fracture indicated that the fracture responded nonlinearly to normal pressure and appeared to close with increasing normal pressure up to 10 MPa. The modulus normal to the plane of the fracture was considerably less than the modulus parallel to the fracture.

Values for the elastic moduli of the G-Tunnel welded tuff were also obtained during unconfined compressive strength tests in the laboratory. Olsson and Jones (1980) determined a value of 27.8 GPa on samples of the Grouse Canyon Member, while an average value of 26.0 GPa was obtained in more recent tests. This latter value is considered to be a more realistic value for the modulus of the intact rock than is the value obtained from biaxial testing. Comparison of the laboratory-determined modulus to the field value measured at stresses between 3.1 to 10.6 MPa suggests that a representative value for the field modulus of deformation is about 55 percent of the intact rock modulus.

## SECTION 4. THERMAL AND THERMOMECHANICAL PROPERTIES

An understanding of the temperatures and stresses that result from radiogenic heating is important in selecting the disposal horizon and establishing the underground design (drift size and spacing; emplacement hole orientation, size, and spacing; and the thermal output of the waste package) of the repository at Yucca Mountain. The thermal and thermomechanical properties that determine temperatures and thermally induced stresses in the rockmass for a given design are thermal conductivity, thermal expansion, and heat capacity (including the latent heat of vaporization).

This section contains a summary of the results obtained to date that describes the thermal conductivity, thermal expansion, and heat capacity of tuff. Descriptions of tests planned for further evaluation and field confirmation of current data are also included.

The present data base consists almost exclusively of data from laboratory measurements made on core samples. These laboratory studies were conducted for two purposes. (1) To develop a data base which defined the spatial variations in thermal properties of tuffs encountered at Yucca Mountain, and (2) To correlate the measured thermal properties with measured physical properties (such as porosity, grain density, and bulk density) in order to allow development of functional thermal conductivity and thermal expansion stratigraphies for use in heat transfer and thermomechanical stress analyses. This development relied on establishing correlations between the measured thermal properties and measured physical properties (porosity, grain density, and bulk density). These correlations allowed the extrapolation of the measured thermal properties to regions of the boreholes for which only geophysical logs and bulk properties data exist.

## Definition of Terms

### Thermal Conductivity

Thermal conductivity is a measure of the ability of a material to transmit heat. With regard to radioactive waste disposal, thermal conductivity relates to the ability of the host rock to conduct heat away from waste packages. Thermal conductivity is thus one of the critical input parameters for modeling the temperature field generated by the emplaced waste. For a given thermal loading, waste emplacement configuration, and rockmass thermal capacitance, higher thermal conductivity means more rapid heat dispersal and lower temperatures in the rock surrounding the waste package. Lower thermal conductivity results in slower heat dispersal and higher temperatures in the waste package and in the rock immediately surrounding the package.

### Thermal Expansion

Thermal expansion is a measure of the tendency of a material to undergo a volume or length change as a result of an imposed temperature change. "Thermal expansion" is used here in a broader sense than that used by most physical scientists because it is used in this report to include all phenomena that affect material volume changes, including simple expansion of constituent grains and dehydration-induced contraction or pore collapse.

A thermal expansion coefficient generally is used to describe a volume or length change due to a temperature change for a temperature range in which the volume or length change per degree change in temperature is constant. The coefficient, usually recorded as a change in linear dimension per unit original length or as a change in volume per unit original volume, per unit temperature change can be either positive or negative.

Heat generated by emplaced radioactive waste will raise the temperature of the host rock in the vicinity of the canister significantly [by as much as 200°C at the edge of the waste emplacement hole wall (Peters, 1983)]. If the host rockmass expands or contracts excessively as a result of this temperature change, then thermally induced stress fields may result in rock fracture or displacement that could affect repository performance vis-a-vis waste emplacement hole and room stability during operational and retrieval periods.

<u>Heat Capacity</u>

Heat capacity is a measure of the amount of heat energy required to raise the temperature of a substance by a fixed amount. The heat capacities of all silicate rock-forming minerals are essentially the same: on the order of 0.84 J/gm°C. The heat capacity of water is 4.18 J/gm°C, and that of air is much smaller. The effective heat capacity of the silicic tuffs in Yucca Mountain is therefore strongly dependent on both porosity and degree of saturation.

## Sample/Test Locations

Samples used in the thermal conductivity and thermal expansion laboratory studies reported herein have been taken from core extracted from three exploratory drill holes on Yucca Mountain: UE-25a#1, USW G-1, and USW G-2. The locations of these holes are shown in Figure 1. Sample numbers used herein denote depth in feet from which the sample was taken (drilling records and core log data are reported in feet).

## Thermal Conductivity

### Thermal Conductivity Data for Other Potential Repository Host Rocks

Ranges and estimated means of published values of the thermal conductivity of other rock types under study as potential disposal units are presented in Table 5. Some of the data were measured at pressures and temperatures above ambient; therefore, the upper limits of the ranges are probably slightly higher than would apply at ambient conditions. Equivalent ranges for the saturated conductivities of welded tuff and zeolitized nonwelded tuff are 1.4 to 2.5 W/m°C and 1.2 to 1.9 W/m°C, respectively.

### Laboratory Studies

Laboratory measurements on samples from different locations are used to determine the spatial variation of thermal conductivity in Yucca Mountain tuffs and to determine how much parameters such as saturation, anisotropy, and fractures affect the thermal conductivity of the tuff.

Equipment and Procedures, Limitations and Errors. Most thermal conductivity measurements reported herein, both saturated and dry, were made using the transient-line-source technique under controlled confining

TABLE 5

THERMAL CONDUCTIVITY OF OTHER POTENTIAL REPOSITORY HOST ROCKS

| Rock Type | Thermal Conductivity (W/m°C) Range | Estimated Mean | Reference |
|---|---|---|---|
| Basalt | 0.1 - 4.3 | 1.7 | Guzowski et al., 1982 |
| Salt | 1.3 - 17.7 | 5.0 | Tien et al., 1983 |
| Granite | 2.2 - 3.8 | 3.0 | This paper (literature survey) |

and fluid pressures (Lappin et al., 1982). Except at temperatures near the boiling point of water (which is variable under the experimental conditions used), these measurements of thermal conductivity appear to be precise to ±4 percent on fused silica samples (Lappin et al., 1982). Because of transient heating effects, this technique results in an apparent conductivity that is artificially high for measurements near the boiling point of water. Additionally, in reducing the data from these tests, the heat flow (outward from the center of the specimen) is assumed to be radially symmetric about the centerline of the sample. Hence, this method is applicable only to materials that are thermally isotropic and can be used only in orientations in which heat flow during testing is parallel to layering. Precision appears to be on the order of ±10 percent on actual samples of tuff (Lappin et al., 1982).

Measurements examining the possibility of thermal conductivity anisotropy in tuff and those aimed at evaluating the effects of lithophysae have been made using a thermal comparator (Moss et al., 1982). This technique is based on steady-state thermal gradients. It has the advantage of enabling measurements in anisotropic materials and in those containing irregular void spaces such as lithophysae. A disadvantage is that it is not easily amenable to the use of both confining and fluid pressures. Precision for the thermal comparator appears to be about ±5 percent (Moss et al., 1982). Comparative calibrations using fused silica indicate that, at ambient temperature, thermal conductivities measured with the thermal comparator are about eight percent lower than those measured using the transient line source (Lappin et al., 1982; Moss et al., 1982).

The methods used to obtain the physical properties (e.g., saturated bulk density, dry bulk density, and grain densities) generally are consistent with ASTM procedures and are described in Lappin et al., 1982. Porosities listed are total-calculated-void porosities. For the purpose of comparing thermal conductivity measurements of tuffs of different porosity, the results are back-calculated using geometric means formalism (Woodside and Messmer, 1961; Lappin, 1980a; Lappin et al., 1982). The thermal conductivity of tuff is sensitive to mineralogy. Variable mineralogy is reflected in grain density changes. Though variations in grain densities are not unambiguously sensitive to some variations in mineralogy (Lappin, 1980a), the use of grain density information does allow extrapolation of mineralogical results to define unit boundaries.

<u>Measured Thermal Conductivities</u>

Saturated and dehydrated thermal conductivities are variable, depending on variations in porosity and grain density (mineralogy).

Average saturated conductivities of nonzeolitized, welded, devitrified material from the Bullfrog and Tram members of the Crater Flat Tuff, and of nonlithophysal material from the Topopah Spring Member of the Paintbrush Tuff, are essentially the same within the limits of experimental error of ten percent.

The dehydrated conductivities of these same tuffs appear to differ; the Topopah Spring Member loses relatively little conductivity when dried. The matrix porosities and grain densities of the samples from the Bullfrog and Tram Members are nominally the same, while both porosity and grain density of the non-lithophysal Topopah Spring Member are significantly lower. The lower grain density in the Topopah Spring Member is caused by the presence of cristobalite.

Saturated and dehydrated conductivities, porosities, and grain densities of all nonwelded to partially welded zeolitized material examined to date appear to be consistent and independent of stratigraphic unit, depth, and hole location. The conductivities and grain densities are lower than for corresponding nonzeolitized material, while porosities are generally higher. The low grain densities of these materials reflect the presence of zeolites.

Zero-porosity or matrix conductivity is the calculated conductivity of the matrix in the absence of porosity and contained pore water. Assuming that the influence of in situ fractures on thermal conductivity can be treated in the same manner as porosity, the zero-porosity conductivity for a mineralogically homogeneous tuff layer can be used to estimate the in situ conductivity of that tuff for any given porosity, saturation, and fracture density and aperture (Lappin, 1980a; Lappin et al., 1982).

Thermal comparator measurements on welded tuff from the Grouse Canyon Member of the Belted Range Tuff were undertaken to examine the potential effects of layering anisotropy in welded tuffs (Moss et al., 1982). The results indicate that there is no statistically significant anisotropic effect of layering on matrix thermal conductivity of welded tuffs, even in the fully dehydrated state. Because welded ash flow tuffs have the strongest fabric anisotropy, it has been concluded that matrix thermal anisotropy is also negligible in nonwelded ash flows.

Lithophysae are found in varying abundance in portions of the Topopah Spring Member. Because the Topopah Spring Member in some localities contains four or more distinct flows, lithophysal distribution cannot currently be correlated reliably from hole to hole. In addition, the thermal effects of lithophysae on conductivity are difficult to measure because the void spaces, which are up to 5 cm or more in diameter, are large relative to usual laboratory specimen sizes.

Measurements of the thermal conductivity of lithophysal material have been made on two fully dehydrated samples with diameters of 10 cm which were machined from loose blocks of tuff collected from a surface outcrop of the Topopah Spring Member at Busted Butte. The conductivities were measured by means of a guarded hot-plate technique, varying both sample orientation and direction of heat flow. The measured results agree (within the limits of experimental error) with the values of dehydrated conductivity predicted by using the measured total porosities of the samples, including pores and lithophysae, and the average matrix conductivity for nonzeolitized nonlithophysal Topopah Spring Member. Based on these results, it has been concluded that measured conductivities of nonlithophysal Topopah Spring Member can be extended to lithophysal zones by considering the lithophysae simply as additional air-filled porosity. The potential reduction in thermal conductivity of dehydrated rock has been calculated as a function of lithophysal abundance (Lappin et al., 1982).

The effects of thermally induced jointing or fracture porosity on the in situ thermal conductivity of devitrified welded tuffs have been estimated based on an assumed fracture porosity of three percent (Lappin et al., 1982). This assumption ignores the possibility of the joint closure that may result from overburden pressures or from thermal expansion of the rock. It is therefore assumed that the estimate is conservative. In the case of saturated tuffs below the water table, the estimated reduction in the in situ thermal conductivity is well below 10 percent and is thus considered to be negligible.

The effect may not be insignificant in welded tuffs such as the Topopah Spring Member, which are situated above the water table. In such a setting, it may be assumed that virtually all joints are air-filled even though the matrix may be near full saturation. Under this assumption, the fully saturated ambient-temperature conductivity of nonlithophysal Topopah Spring Member may be reduced from 2.1 to 1.8 W/m°C, or by about 15 percent. A similar but smaller reduction in the conductivity of the dehydrated rockmass is also possible.

The potential effects of nontectonic fracturing on the in situ thermal conductivity of zeolitized or nonwelded tuffs appear negligible. Because these tuffs are often deposited as either ash-fall tuffs at near-ambient temperature or as marginal envelopes to ash flow sheets, such tuffs have undergone only very limited cooling in place. Thermally induced jointing should therefore be negligible. In addition, formation of zeolites alone may have greatly reduced any initial fracture porosity. Thus, it has been concluded that the saturated rockmass thermal conductivity of heavily zeolitized or nonwelded tuffs should be near to that of intact material.

In Situ Studies

In situ studies have been planned to evaluate how well the thermal conductivity data determined in the laboratory tests can represent the rockmass conductivity, particularly when the effects of thermally induced water migration are included.

Equipment and Procedures, Limitations and Error Analysis. One field test has been completed from which information on in situ thermal conductivity can be extracted. A small-scale cylindrical heater was emplaced in a hole in the Grouse Canyon Member in G-Tunnel (Johnstone, Hadley, and Waymire, 1984). By comparing the temperatures and temperature gradients predicted by thermal modeling of this test to the actual temperatures and gradients measured in situ, an assessment could be made of whether in situ thermal conductivity can be accurately predicted from laboratory values. The following specific limitations or uncertainties are inherent in such a test.

- Variable and uncontrolled degrees of saturation may have existed in the rockmass in which the heater is placed. Such variations would affect thermal conductivity, amounts of fluid released, and fluid movements during heating.
- Field instrumentation. Thermocouples in the heater emplacement hole could not be fully shielded from thermal radiation between heater and hole wall. As a result, these thermocouples registered a temperature as much as 20°C too high during the heating phase of the water migration experiment completed in G-Tunnel.
- Thermocouples in instrumentation holes, although grouted in, were placed at discrete intervals. In the test described here, the 10-cm-diameter of the heater required that the nearest instrumentation within the rockmass be effectively beyond the region of steepest thermal gradients, creating considerable uncertainty in correlating postulated very-near-field thermal conductivity changes with measured temperatures.

Comparison of In Situ Thermal Conductivity Data to Laboratory Data. Interpretation of the results of the one small-scale test described above indicates that in situ thermal conductivity agrees with laboratory measurements within the limitations of field instrumentation, current knowledge of in situ saturation, and the degree of sophistication in the heat transfer modeling calculations.

In situ tests completed in granite at Stripa, Sweden, indicate that fluid movement in the rockmass during heating gives rise to an effective thermal conductivity greater than that seen in laboratory measurements. The apparent magnitude of this effect appears to be minor, ranging from five to ten percent of the measured laboratory value of 3.51 W/m°C (Lundstrom and Stille, 1978). Although the matrix water content of granite is much smaller than that of tuff, the Stripa granite is sited below the water table, while the tuff heater experiment was conducted above the static water level.

Results obtained to date in tuff suggest that little additional in situ thermal conductivity testing is required in welded tuffs above the water table to determine the rockmass thermal conductivity for use in far-field or room-scale calculations. However, very-near-field temperature prediction may be strongly affected by waste package design and distribution and may require consideration of convection effects to represent vapor transport. Some thermal conductivity measurements are planned as part of the heated block test.

No additional in situ testing strictly for purposes of evaluating changes in thermal conductivity in tuffs is planned. Rather, such evaluations will be made as part of other tests conducted to evaluate thermomechanical effects in order to increase confidence in the values of thermal conductivity used in the heat transfer analyses that support repository design.

## Thermal Expansion

Data on the thermal expansion of tuff are required for determining the stresses and strains induced in the rockmass as a result of radiogenic heating of the rock by the waste. These stresses, coupled with the in situ and excavation-induced stresses, will be used to evaluate the stability of heated underground openings and waste emplacement boreholes.

### Thermal Expansion Data for Other Potential Repository Media

The expansion behavior described here for both the devitrified Topopah Spring Member and for heavily zeolitized nonwelded to partially welded tuffs, including the bulk of the Tuffaceous Beds of Calico Hills, is nonlinearly related to temperature. Most of the nonlinearity in the expansion behavior of the devitrified Topopah Spring Member occurs at temperatures above 200°C. The expansion behavior of the devitrified Tram and Bullfrog Members is approximately linear and qualitatively similar to that measured for granitic rocks of similar bulk composition but of greatly different grain size (Swan, 1978; Heard, 1980). The thermal expansion behavior of basalts is variable, with linear expansion coefficients below 200°C ranging from 4 to 7 x $10^{-6}$/°C (Guzowski et al., 1982). Little information is available for either granite or basalt, regarding trends in behavior with increasing temperature or dependence on mineralogical variability. The linear expansion coefficient of salt ranges from 36 to 55 x $10^{-6}$/°C at temperatures between 25°C and 200°C (Tien et al., 1983).

Laboratory Studies

Laboratory measurements of thermal expansion are used to determine the spatial variation of thermal expansion properties of Yucca Mountain tuff. Tests also have been designed to quantify the effects of mineralogy, bulk properties, confining pressure, and anisotropy on the expansion of tuff.

Equipment and Procedures, Limitations, and Error Analysis. Experimental equipment and analytical procedures for unconfined thermal expansion measurements have been described (Lappin, 1980b). The uncertainty in the measured expansion coefficients is considered to be $1 \times 10^{-6}$/°C for welded devitrified samples analyzed to date, the same as for the fused silica standard.

Thermal expansion of welded devitrified tuffs is independent of heating rate between 0.5 and 10°C/min, provided the sample size is small enough to allow effective thermal equilibration during heating. The major limitation in unconfined measurements on devitrified tuffs appears to be that measured expansion coefficients increase with increasing temperature more rapidly than would be predicted on the basis of mineralogy (Lappin, 1980b), possibly because of formation of microcracks during heating.

Unconfined thermal expansion measurements on zeolitized tuffs are sensitive to additional variables (Lappin, 1980b). These tuffs, like tuffs containing appreciable amounts of hydrated glass and/or expandable clays, contract when dewatered. Thus, their behavior is sensitive to the locally effective fluid pressure, which in laboratory tests is itself a function of sample size, heating rate, and permeability. Unconfined measurements on this type of tuff, which are made on samples 6 x 6 x 25 mm in size, indicate only maximum contractions at a given temperature. Even this interpretation must be based on tests run at a slow rate. Such tuffs may continue to contract slowly for time periods of greater than 24 hours when held at constant temperature. Times required to reach stable length in situ at a given temperature might be much greater if the fracture spacing is large.

Because of the concern about possible effects of both microcracking and variable fluid pressures, a method has been developed to measure thermal expansion under controlled confining and fluid pressures. At present, these tests are performed at Terra Tek, Inc., in Salt Lake City, Utah. Test procedures and calibration procedures are detailed in their Standard Laboratory Procedures TTRD-LP-3 and TTRD-CP-6 (Van Buskirk a, b, and c).

Multiple measurements on fused silica indicate that the precision and accuracy of the confined testing apparatus at a confining pressure of 10 MPa are on the order of $1.5 \times 10^{-6}/°C$.

Site-Specific Thermal Expansion Data. The results of earlier unconfined thermal expansion studies (Lappin, 1980b) and the results of more recent confined measurements are briefly summarized in the following paragraphs. The newer data are consistent with previous results and describe both the predehydration behavior of zeolitic tuffs and the effects of increased fluid pressures on the dehydration temperatures of expandable clays (neither of which can be assessed adequately in unconfined tests). Comparison of measured and calculated thermal expansion behavior for zeolitic tuffs is difficult because of a lack of data for pure phases. Data are currently being collected for pure zeolite minerals to allow calculation of the thermal expansion behavior of zeolitic tuffs.

Because of the presence of variable amounts of hydrous phases, such as clays, zeolites, glass, and opaline silica, three temperature ranges must be defined for the thermal expansion behavior of the tuffs from Yucca Mountain: pretransition, transitional, and posttransition. For the welded, devitrified Topopah Spring Member, the transitional behavior is caused by a mineralogic phase change, while mineral dehydration causes the variation in tuffs containing significant quantities of hydrous minerals. Transdehydration behavior for samples containing significant amounts of the various hydrous phases (e.g., zeolitized tuffs) is likely to vary with the amount of expansion or contraction caused by heating and the temperature range over which dewatering (dehydration) takes place.

The three paragraphs that follow summarize the currently available studies of thermal expansion behavior in silicic tuffs from Yucca Mountain to document the data used in horizon selection analyses and to provide data for evaluation of far field thermomechanical behavior. This behavior is also illustrated in Figure 18 to allow comparison of the response of the different tuffs.

The Bullfrog and Tram Members are devitrified welded tuffs, generally found below the static water level. Because of the relatively uniform mineralogy involved, expansion behavior of devitrified welded tuffs from below the static water level is quite uniform, except for effects of small amounts (generally less than five percent) of expandable clays (Bish, 1982; Waters and Carroll, 1981). Confined and unconfined results

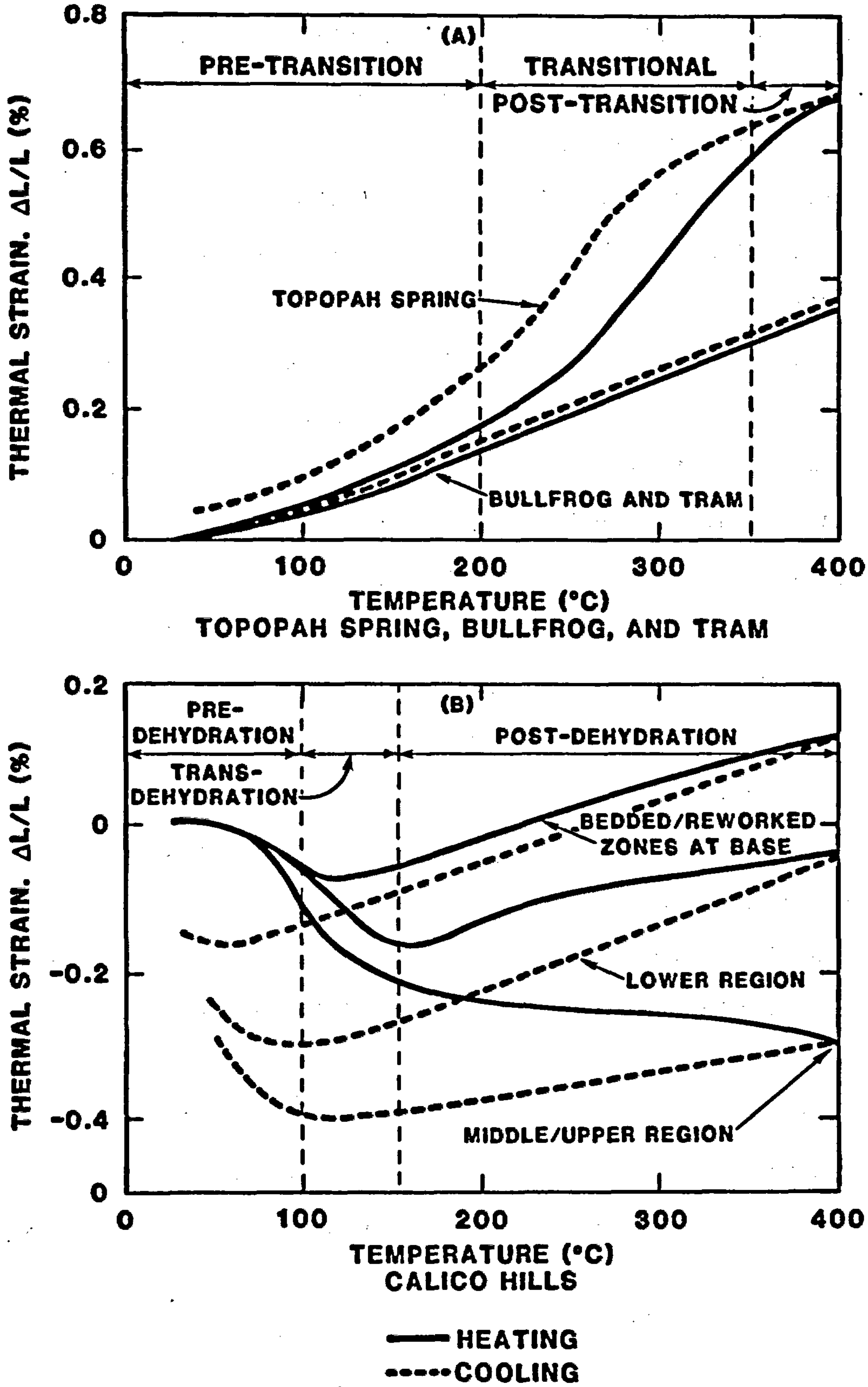


Figure 18 Schematic Representation of Unconfined Thermal Expansion of Yucca Mountain Tuffs

are consistent and agree well with calculated behavior. The only apparent effects of increasing confining and fluid pressures are to elevate the temperatures at which dehydration takes place and to make expansion at higher temperatures more linear than in unconfined tests. Thermal expansion of these tuffs appears to be independent of porosity.

The devitrified densely welded tuffs of the Topopah Spring Member are generally found above the static water level. The mineralogy of devitrified welded tuffs above the water table locally reflects past vapor-phase activity. The result has been deposition of variable amounts of secondary feldspar and cristobalite, with locally important amounts of quartz, tridymite, and, possibly, expandable clay. The thermal expansion of vapor-phase-altered tuffs changes above about 200°C because of the variable content of cristobalite and/or expandable clays. However, in unaltered or slightly altered material, or at temperatures below 200°C, this complexity can probably be ignored. Even at high waste emplacement densities, this variability would be of potential concern only in the very-near-field environment.

The expansion of welded tuffs from the Topopah Spring Member is qualitatively consistent with the calculated expansion behavior based on reported mineralogical results. On the basis of confined measurements made on lithophysal material, it appears that porosity, per se, and lithophysal porosity, in particular, have no impact on the expansion behavior of the densely welded Topopah Spring Member.

Confined thermal expansion behavior of zeolitized nonwelded to partially welded tuff layers is more complex and variable than that of devitrified tuffs. Three distinct types of behavior have been noted.

- Linear contraction upon dehydration of 0.2 to 0.3 percent to temperatures as high as 300°C, with 0.2 percent contraction generally occurring by about 150°C. This behavior is dominant in quartz- and feldspar-poor, heavily zeolitized tuffs [lower curve in Figure 18B].
- Maximum linear contraction of 0.2 percent at temperatures near 150°C (unconfined), followed by expansion to near initial length on additional heating. This type of behavior appears to be most prominent in nonwelded or partially welded zeolitized tuffs from below the static water level, which are richer in quartz and feldspar than analogous tuffs higher in the section [middle curve in Figure 18B].
- A very small amount of contraction at temperatures near dehydration, followed by expansion to greater than the initial length. This type of behavior is prominent in the few relatively thin, bedded, or reworked intervals identified in the stratigraphic section at Yucca Mountain [upper curve in Figure 18B].

In confined tests (10 MPa confining pressure, 0.1 to 1.5 MPa fluid pressure), all zeolitized tuffs expand continuously, until the onset of dehydration, at rates ranging from 2 to 13 x $10^{-6}$/°C. Detailed correlation of predehydration expansion with mineralogy is under way.

Influence of Textural Anisotropy and Jointing on Thermal Expansion. Comparison of replicate unconfined expansion runs made parallel and perpendicular to bedding in a densely welded devitrified sample (porosity = 0.15) from the Grouse Canyon Member indicates that there is no statistically significant variation in the unconfined matrix thermal expansion behavior of densely welded tuffs as a function of textural anisotropy or bedding (Lappin, 1980b). The effect of bedding orientation on confined expansion behavior has not yet been studied.

In Situ Studies

To quantify the effects of heat on the rock, in situ measurements of displacements and stresses that result from heating are planned. Evaluation of thermal expansion and mechanical properties of the rockmass will be made using both the data from these tests and the thermomechanical analyses made to interpret the test results.

Equipment and Procedures, Limitations, and Error Analysis. Measurements of in situ rockmass thermal expansion have been accomplished by means of standard extensometers (wire and/or rod) (Lappin et al., 1981). Techniques such as laser strain interferometry have been attempted (Johnstone, Hadley and Waymire, 1984). In the case of rod extensometers, especially in vertical orientation, convection of air within the extensometer tube can affect results by changing the temperature distribution in the rod. The test design includes features that should mitigate correction effects. Likewise, care must be taken to ensure that rods (even Invar rods) are properly heat treated to have as reproducible an expansion coefficient as possible and are calibrated carefully over the temperature range of interest. Wire extensometers have not been proven to be stable for the lengths of time required for meaningful in situ testing. In the case of the laser interferometer, the lack of a suitably stable platform from which to make the measurement made data difficult to interpret (Johnstone, Hadley and Waymire, 1984).

Comparison of In Situ Thermal Expansion Data to Laboratory Data. The attempt to measure thermal expansion of welded tuff in situ using laser interferometry, described by Johnstone, Hadley, and Waymire (1984), were essentially unsuccessful. However, measurement of thermally induced stresses was at least partially successful. Measured stress changes were approximately forty percent of the changes calculated by using laboratory-derived expansion values. In field tests, measured stresses and displacements that are smaller than those predicted using laboratory-measured thermal conductivity, expansion, and elastic moduli are more likely attributable to differences between the rockmass deformation modulus and the matrix elastic modulus than to thermal expansion differences.

Similar results have been obtained in the in situ testing in granite (Witherspoon et al., 1980). Initial results indicated displacements and stresses about forty percent of expected values. Later, more detailed laboratory work on the temperature dependence of thermal expansion, thermal conductivity, Young's modulus and Poisson's ratio improved agreement between measured and calculated results but did not remove all of the ambiguity.

## Heat Capacity

### Heat Capacity Data for Other Potential Repository Media

Available data indicate that heat capacities of both basalt and granite are near 0.84 J/gm°C (Guzowski et al., 1982; Pratt et al., 1977). Measured heat capacity of granite from Stripa, Sweden (three measurements) ranges only from 0.82 to 0.84 J/gm°C (Pratt et al., 1977). Heat capacities for Hanford Reservation basalt range from 0.71 to 1.17 J/gm°C (Guzowski et al., 1982). The heat capacity of salt ranges from 0.79 to 0.96 J/gm°C (Tien et al., 1983). Calculated heat capacities for the Topopah Spring tuff range from 0.84 to 1.30 J/gm°C, depending on porosity and saturation and assuming a constant value of 0.84 J/gm°C for the silicate mineral assemblage.

### Laboratory Studies

No measurements of specific heat or heat capacity have yet been made on tuffs as part of this project. Instead, it is felt that these variables can be calculated with acceptable accuracy (approximately ±20 percent) under most conditions, assuming a constant heat capacity for the silicate mineral assemblage of 0.84 J/gm°C, water heat capacity of 4.18 J/gm°C, and air heat capacity of zero. Calculated values of the heat capacity/density product (Table 6) indicate a broad range that depends strongly on both porosity and degree of saturation. The high water content of tuffs from Yucca Mountain gives rise to a large endothermic reaction associated with volatilization of contained pore fluids at temperatures near the in situ boiling point of water. Uncertainty in the in situ temperatures and pressures expected near a repository lead to an

TABLE 6

CALCULATED THERMAL CAPACITANCE AS
A FUNCTION OF POROSITY AND SATURATION

| | $(\rho C_p)_{bulk}$*(J/cm$^3$•C) | | | |
|---|---|---|---|---|
| | $\rho_g$ = 2.65 gm/cm$^3$ | | $\rho_g$ = 2.38 gm/cm$^3$ | |
| Porosity | Saturated | Dry | Saturated | Dry |
| 0.0 | 2.22 | 2.22 | 2.01 | 2.01 |
| 0.1 | 2.43 | 2.01 | 2.22 | 1.80 |
| 0.2 | 2.59 | 1.76 | 2.43 | 1.59 |
| 0.3 | 2.80 | 1.55 | 2.64 | 1.38 |

*$(\rho C_p)_{bulk} = \rho_g(1-\phi)C_p(\text{silicates}) + \rho_{H_2O}S\phi C_p(\text{water})$

$C_p$ = heat capacity (J/gm°C) = 0.84 for silicates, 4.18 for water, and 0.0 for air.

$\rho_g$ = grain density (gm/cm$^3$)

$\rho_{H_2O}$ = density of water = 1 gm/cm$^3$

S = saturation

$\phi$ = porosity

uncertainty in the importance of this volatilization to heat transfer calculations. This uncertainty in the calculations is felt to be greater than any uncertainty that results from inaccuracies in calculated heat capacities.

## SECTION 5. EXCAVATION CHARACTERISTICS OF THE ROCKMASS

Excavation characteristics in tuff with respect to the dimensions of mined openings, support requirements for these openings, excavation methods, damage to the rock that results from excavation, and water inflow are reviewed in this Section. The data for this evaluation come from observations and measurements made on cores from each of the horizons considered for waste emplacement in Yucca Mountain coupled with data from the mined openings in G-Tunnel. Additional evaluations will be made in the ES in both the initial breakout room and in the planned drift-and-pillar monitoring.

### Excavation Characteristics for Other Rockmasses

Excavation characteristics of other rockmasses are considered explicitly in the extensive data base used to develop and evaluate both of the rockmass classification techniques discussed in the following paragraphs. Therefore, no explicit list of the characteristics of other formations is provided.

### Site-Specific Data on Excavation Characteristics

#### G-Tunnel Experience

For definition of the mining methods to be used in the repository, the most applicable data come from experience gained in the development of an adit (normally referred to as G-Tunnel) on the NTS. G-tunnel experience and planned excavations in Yucca Mountain are similar in many ways.

- Depths (425 m), opening dimensions (span of up to 5 m) and excavation methods will be similar.

- Degrees of saturation are similar (0.8 to 0.95).
- Thermal, mechanical, and bulk properties of the tuffs are similar (see Table 7).
- Fracture characteristics (spacing at 1 m or less in welded tuff) are similar.

Because of these similarities, the data obtained from tests and observations in G-Tunnel substantially increase confidence in the design and analysis of a repository in the Topopah Spring Member.

In 1961, the development of G-Tunnel was started, and about 3,500 m of drift have been excavated into the Tunnel Beds (informal units of nonwelded to moderately welded tuffs in Rainier Mesa). These beds are similar to the Tuffaceous Beds of Calico Hills in Yucca Mountain and are substantially weaker than the welded Topopah Spring Member. Currently, a mechanical mining machine (Alpine miner) is used to excavate the Tunnel Bed tuff. No formal investigations have been performed to quantify the damage to the rock produced by this mining technique, but an examination of the ribs and roof reveals very little visible damage. In the initial few hundred meters of excavation, steel sets and lagging were used. Since then, roof bolts and wire mesh have been used successfully to stabilize the openings.

As part of the NNWSI Project, about 130 m of drift have been excavated in the welded tuff of the Grouse Canyon Member (which is similar to the nonlithophysal portion of the Topopah Spring Member at Yucca Mountain). The welded tuff in G-Tunnel was, in general, excavated using controlled drill-and-blast techniques. An examination of the ribs and roof showed more damage to the finished rock surfaces in the welded tuff than occurred in the Tunnel Beds. However, because the Grouse Canyon Member is more highly

## TABLE 7

## COMPARISON OF PROPERTIES OF TUFF FROM YUCCA MOUNTAIN AND RAINIER MESA

| Property | G-Tunnel Grouse Canyon | Yucca Mountain Topopah Spring* | G-Tunnel Tunnel Bed 5 | Yucca Mountain Calico Hills |
|---|---|---|---|---|
| Matrix Porosity | 0.16 ± 0.05 | 0.17 ± 0.09 | 0.40 | 0.32 ± 0.02 |
| Grain Density ($gm/cm^3$) | 2.60 ± 0.02 | 2.55 ± 0.03 | 2.33 | 2.40 ± 0.02 |
| Saturation | 0.6-0.9 | 0.8 | 0.9 | 0.90 |
| Saturated Thermal Conductivity (W/m°C) | 1.82 ± 0.06 | 1.8 ± 0.4 | 1.3 | 1.33 ± 0.10 |
| Dry Thermal Conductivity (W/m°C) | 1.44 ± 0.09 | 1.6 ± 0.4 | 0.4-0.6 | 1.0 ± 0.05 |
| Coefficient of Linear Thermal Expansion ($10^{-6}$/°C) | 8.5 ± 0.05 | 10.7 ± 1.7 | Not Available | 6.7 ± 3.7 |
| Young's Modulus (GPa) | 32.1 ± 10 | 26.7 ± 7.7 | 5.7 ± 1.6 | 8.1 ± 2.3 |
| Poisson's Ratio | 0.13 ± 0.04 | 0.14 ± 0.05 | 0.18 ± 0.07 | 0.16 ± 0.06 |
| Unconfined Compressive Strength (MPa) | 136 ± 49 | 95.9 ± 35 | 21.9 ± 8.0 | 30.6 ± 11.1 |

*Topopah Spring data are for material assumed to have 5% lithophysal porosity in addition to normal matrix porosity.

jointed than the nonwelded material, it is more difficult to assess whether damage to finished rock surfaces is the result of the mining technique. The mechanical miner was successfully used to cut the welded tuff and level the floors. Relatively rapid wear of the picks attached to the rotating drum was noted.

Spans of G-Tunnel openings in the welded material range from 3.4 to 5 m. The cross section of the experiment drift identified is 5 m wide by 5 m high, approximately the dimensions being considered for the drifts in the repository. During the excavation of the extensometer drift, miners were unavailable for one to two months after seven blasting rounds had been shot, which left an unsupported roof along 14 m of drift. During this time, no deterioration of roof material was evident. Following this hiatus, roof bolts and wire mesh were successfully installed in the roof.

Rockmass Classification of Yucca Mountain Tuffs

Rockmass classification systems have been applied in an assessment of excavation characteristics and support requirements for mined openings in Yucca Mountain (Johnstone, Peters, and Gnirk, 1984). These classification systems use rock strength data, rock quality designations as determined from core observations, joint characteristics (spacing and condition), and groundwater conditions. Two rockmass classification systems were used: the NGI (Norwegian Geotechnical Institute) Classification System proposed by Barton et al. (1974a) and the CSIR (South African Council for Scientific and Industrial Research Geomechanics) Classification System proposed by Bieniawski (1976). Each system emphasizes joint characterization. Barton's system also considers a stress factor. These calculation systems are used mainly for single tunnels but have been applied to multiple underground openings that have pillar dimensions on the order of 15 m with extraction ratios of 25 to 50 percent. A summary of evaluations to date is presented below.

Before final selection of the disposal horizon, several Yucca Mountain stratigraphic units were classified using the systems described above. These units included the nonlithophysal Topopah Spring Member, the upper ashflow of the Tuffaceous Beds of the Calico Hills, and the welded devitrified portions of the Bullfrog and Tram Members. The Tunnel Beds and the welded portion of the Grouse Canyon Member in G-Tunnel were also rated for comparison. The units from Yucca Mountain must be rated on the basis of vertical information only, because no horizontal cores are available.

Comparative ratings for each unit are presented graphically in Figure 19.* The scales for the two classification systems have been correlated according to Bieniawski (1976). It should be emphasized that Bieniawski's system does not include a stress reduction factor. Therefore, the classification value for the two deepest units, the Bullfrog and Tram Members, is significantly lower in Barton's system than in Bieniawski's system. Tunnel Bed 5 also has a significantly lower rating in Barton's system. Although the drifts in the Tunnel Beds are shallow (420 m), the strengths of the units are low.

*Values for parameters have been chosen to span expected characteristics. Calculated ratings should not be interpreted to imply that there are areas of faulted or strongly jointed rock.

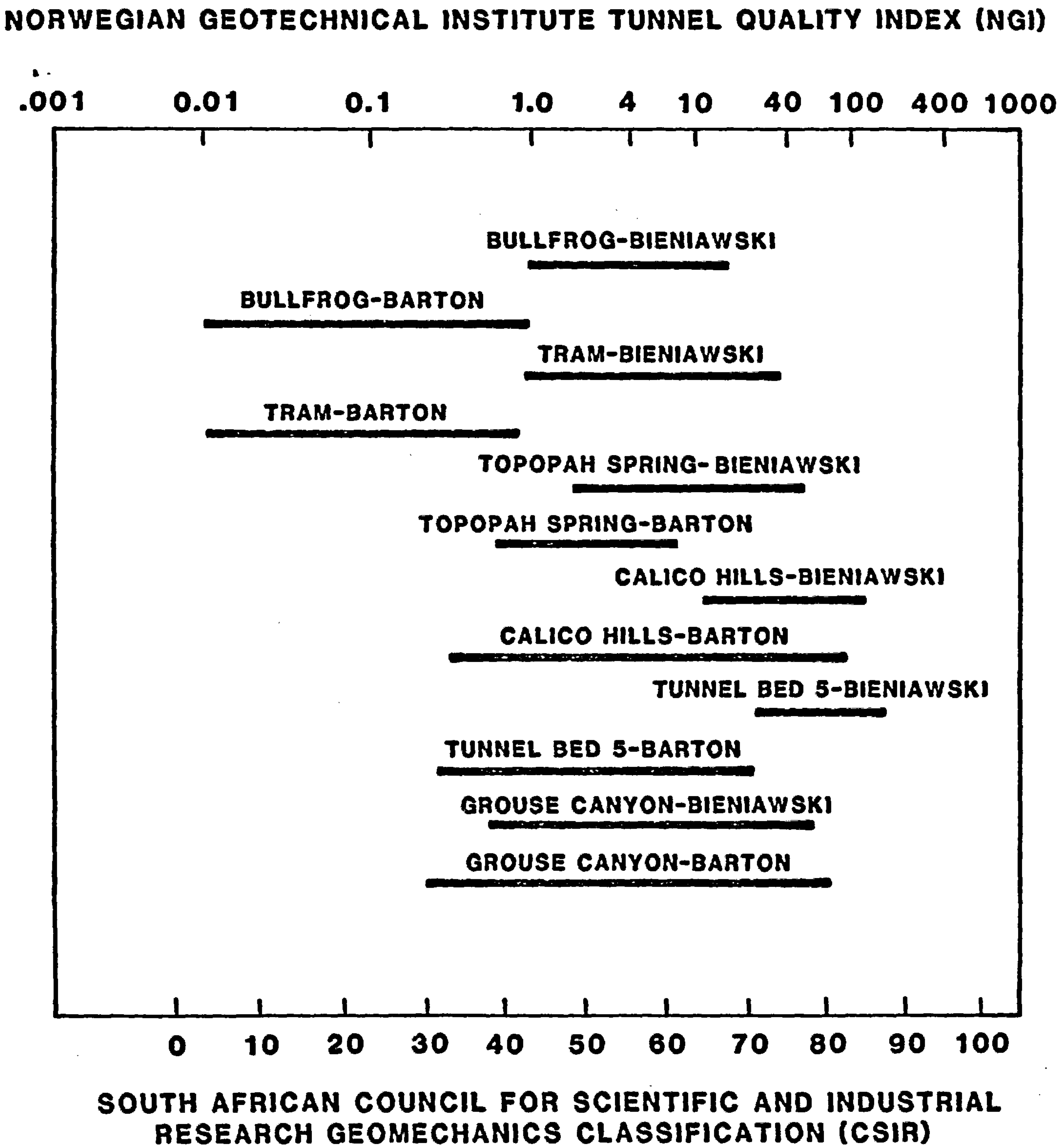


**Figure 19.** Rockmass Classification Values for Various Tuff Units. Bieniawski Entries Are for the CSIR Classification System. Barton Entries Are for the NGI Classification System.

## Estimated Support Requirements Based on Rockmass Classification

Based on Barton's NGI Classification System and his study of approximately 200 case histories of tunnels (Barton et al., 1974b), preliminary estimates of support requirements were made (Table 8). Despite the variation in rockmass classification for the various units, the support estimates indicate that either untensioned grouted rock bolts

TABLE 8

ESTIMATED SUPPORT REQUIREMENTS BASED ON BARTON'S NGI ROCK CLASSIFICATION SYSTEM

| Unit | Classification Value (Q) | Suggested Support Requirements |
|---|---|---|
| Welded Devitrified Bullfrog Member | 0.99 to 0.01 | b – d |
| Welded Devitrified Tram Member | 1.05 to 0.01 | b – d |
| Nonlithophysal Topopah Spring Member | 8.33 to 0.75 | a – c |
| Tuffaceous Beds of Calico Hills | 96 to 0.44 | a – c |
| Tunnel Bed No. 5 | 29.2 to 0.44 | a – c |
| Welded Grouse Canyon Member | 60 to 0.36 | a – c |

a = None.

b = Untensioned grouted rockbolts with unreinforced shotcrete.

c = Tensioned grouted rockbolts with wire mesh-reinforced shotcrete.

d = Cast concrete arches for swelling and squeezing ground.

with shotcrete or tensioned grouted rock bolts with shotcrete should suffice in most cases. These estimates are based on an assumed span width of 5 m. It is further assumed that the drifts need permanent support similar to that required for underground power stations, major road and railway tunnels, and civil defense chambers (somewhat in excess of the support required for a permanent mine opening). The actual support requirements for the Tunnel Beds and the Grouse Canyon Member approximate estimated support requirements. Actual support for these members consists of patterned rock bolts (grouted) and wire mesh.

More detailed studies and evaluations of requirements for permanent support systems will be made in the ES.

<u>Estimates of Groundwater Inflow and Dewatering Requirements</u>

As expected above the water table, there is no uniform flow of water through any of the drifts in G-Tunnel except that quantity removed by the ventilation system. Observed water flow is limited to downward flow in locally saturated faults or fractured zones oriented more or less vertically. Quantities of water are estimated to be less than 0.0009 L/s (20 gal/day) and would be removed by routine pumping of a small sump area.

It is anticipated that similar behavior will be observed in the Topopah Spring Member in Yucca Mountain and that dewatering requirements will be minimal.

<u>Excavation Methods</u>

The following conclusions have been drawn from the observations made in G-Tunnel as related to repository design in the Topopah Spring Member.

- Controlled drill-and-blast mining techniques can be successfully used for excavating welded tuff.

- Because the welded tuff was successfully cut (during floor leveling) with a mechanical mining machine, tunnel-boring machines and advanced mechanical miners could possibly be used.

SUMMARY

The development of the data base of geoengineering properties required for use in technical decisions related to the repository at Yucca Mountain is well under way. At present, the data base consists primarily of the results of laboratory tests on core samples, but it is enhanced by initial results from field observations and tests being made in G-tunnel at Rainier Mesa. The selection of the Topopah Spring Member as the target horizon for the repository was based in part on the average thermal and mechanical properties defined (for each of the four horizons considered) from approximately 75 thermal conductivity tests, 95 thermal expansion tests, 35 mineralogical/petrological analyses, 60 mechanical tests on jointed rock samples, and 120 unconfined and 50 pressure-dependent mechanical properties tests. Definition of the properties to be expected in the candidate disposal horizons relied upon combining the measured thermal and mechanical properties data with the corresponding bulk properties (porosity and grain density) to produce functional thermal and mechanical properties units. The units are consistent among the exploration holes drilled to date, although individual layers vary in thickness and, in places, do not coincide with identified lithologic tuff units. The geoengineering properties (collectively summarized in Table 9) are provided both to document the data that was input to the horizon selection decision and to identify the Topopah Spring Member data being used in initial design trade-off analyses that are reported in Jackson (1984).

TABLE 9

RECOMMENDED THERMOMECHANICAL PROPERTIES OF THE TOPOPAH SPRING MEMBER, TUFFACEOUS BEDS OF CALICO HILLS, AND TRAM AND BULLFROG MEMBERS

| Variable | Topopah Spring* | Tuffaceous Beds | Bullfrog | Tram |
|---|---|---|---|---|
| Porosity | 0. 17±0.09 | 0.32±0.02 | 0.23±0.03 | 0.19±0.03 |
| Grain Density ($gm/cm^3$) | 2.55±.003 | 2.40±0.02 | 2.59±0.02 | 2.64±0.04 |
| Saturation | 0.8 | 1.0 | 1.0 | 1.0 |
| Saturated Bulk Density ($gm/cm^3$) | 2.29 | 1.95 | 2.22 | 2.33 |
| Dry Bulk Density ($gm/cm^3$) | 2.12 | 1.63 | 1.99 | 2.14 |
| Saturated Thermal Conductivity ($W/m^oC$) | 1.8±0.4 | 1.4 | 2.0±0.1 | 2.2±0.1 |
| Dry Thermal Conductivity (W/m°C) | 1.6±0.4 | 1.0±0.05 | 1.4±0.2 | 1.6±0.2 |
| Thermal Capacitance ($J/cm^3 {}^\circ C$) | 2.18 | 2.72 | 2.64 | 2.59 |
| Pretransition Linear Expansion Coefficient ($10^{-6} {}^oC^{-1}$) | 10.7±1.7 | 6.7±3.7 | 8.3±1.4 | 8.3±1.4 |
| Transitional Linear Expansion Coefficient ($10^{-6} {}^oC^{-1}$) | 31.8 (to 300°C) | -56.0 (to 150°C) | -12.0 (to 125°C) | -12.0 (to 125°C) |
| Posttransition Linear Expansion Coeficient ($10^{-6} {}^oC^{-1}$) | 15.5±3.8 (to 400°C) | -4.5±4.0 (to 300°C) | 10.9±0.8 (T>125°C) | 10.9±0.8 (T>125°C) |
| Young's Modulus (GPa) | 26.7±7.7 | 8.1±2.3 | 15.5±4.5 | 21.8±6.3 |
| Poisson's Ratio | 0.14±0.05 | 0.16±0.06 | 0.19±0.08 | 0.19±0.07 |
| Unconfined Compressive Strength (MPa) | 95.9±35.0 | 30.6±11.1 | 56.9±20.8 | 79.2±28.9 |
| Matrix Cohesion (MPa) | 28.5 | 10.9 | 18.1 | 24.0 |

TABLE 9 (Continued)

RECOMMENDED THERMOMECHANICAL PROPERTIES OF THE TOPOPAH SPRING MEMBER, TUFFACEOUS BEDS OF CALICO HILLS, AND TRAM AND BULLFROG MEMBERS

| Variable | Topopah Spring* | Tuffaceous Beds | Bullfrog | Tram |
|---|---|---|---|---|
| Angle of Internal Friction (degrees) | 26.0 | 15.6 | 22.1 | 24.7 |
| Tensile Strength of Matrix (MPa) | 12.8±3.5 | 0.1±3.5 | 7.7±3.5 | 11.1±3.5 |
| Joint Cohesion (MPa) | 1 | 1 | 1 | 1 |
| Coefficient of Friction for Initiation of Sliding of Joints | 0.8 | 0.8 | 0.8 | 0.8 |

*Topopah Spring data are for material assumed to contain 5 percent lithophysal porosity in addition to normal matrix porosity.

Studies of the mechanical properties of intact samples from Yucca Mountain indicate that observed variations between the four horizons studied are primarily a function of porosity. Preliminary assessments of the effects of water, temperature, confining and fluid pressure, loading time, lithophysae, and anisotropy have been performed in order to enable estimates of the degree of conservatism in values of properties used in modeling calculations. Additional testing is being focused almost entirely on the Topopah Spring Member. Large-scale laboratory tests (sample diameters up to 30 cm) are being initiated to evaluate the effects of lithophysae and of sample size on mechanical properties.

Studies of the mechanical properties of discontinuities (joints, bedding planes, and faults) have focused on the mechanical properties of simulated joints precut in samples of tuffs from the Grouse Canyon and Prow Pass

Members. These results are included in this report because of the physical and mechanical similarities of these units to the Topopah Spring Member. Variations in the mechanical properties of simulated joints that result from changes of displacement rate, water saturation, and time-dependent behavior have been quantified for use in predicting rockmass mechanical response. Characterization of the type, spacing, and orientation of discontinua at the repository level will be done in the ES.

To date, there has been no large-scale testing of the tuffs from Yucca Mountain and only one limited field study on the mechanical behavior of the Grouse Canyon Member welded tuff in G-Tunnel. Both the heated block and pressurized slot tests to be fielded in G-Tunnel will provide data with which to calculate the rockmass modulus. These data can be used with the laboratory results for the Grouse Canyon Member to determine how much the intact sample Young's modulus needs to be reduced to describe the rockmass. Currently, it is estimated that the in situ modulus of deformation will be on the order of one-half of the Young's modulus values obtained in the laboratory.

Once access to the disposal horizon is available, large-scale in situ tests will be performed to directly measure rockmass mechanical properties and to evaluate whether complicated rockmass response can be predicted using available numerical analysis codes if the rockmass properties are known. These tests will be designed and positioned to be representative of the rockmass, including discontinuities. Plate-bearing tests, borehole-jacking tests, and the enhanced block measurement will emphasize properties evaluations. Shaft and drift monitoring, along with the canister-scale heater test, will assist in the design approach by permitting evaluation of the effects of construction and waste emplacement on a larger scale than in the properties tests.

Saturated and dehydrated thermal conductivities show dependence on variations in porosity and grain density (mineralogy). Studies indicate that the effects of layering (fabric anisotropy) on the thermal conductivity of welded and nonwelded tuffs are negligible. It appears that the effects on conductivity of air-filled lithophysae that occur within the Topopah Spring Member can be modeled as additional air-filled porosity. The presence of fractures is expected to have a negligible effect on in situ, ambient-temperature rockmass conductivity below the static water level. Within the target horizon and at other locations above the static water level, fractures may decrease thermal conductivity by as much as 15 percent.

Laboratory measurements of the thermal expansion of samples from Yucca Mountain indicate that because of the presence of variable amounts of hydrous phases and cristobalite, three temperature ranges must be defined for the thermal-expansion behavior of Yucca Mountain tuffs. At low temperatures (pretransition), expansion is approximately linear. During the transitional interval (characterized by dehydration or by a phase change), either expansion or contraction may occur, depending on the rock type, and behavior is nonlinear. At higher temperatures (posttransition), linear behavior again is characteristic, and may be either expansion or contraction. Studies indicate that the effects of bedding and textural anisotropy on matrix thermal expansion behavior of densely welded tuffs are negligible. The presence of thermally induced or pre-existing fractures is expected to reduce thermally induced rockmass stresses to below those predicted using thermal and mechanical properties measured in the laboratory, primarily because lower elastic moduli are measured in the field.

The estimated heat capacity of the silicate minerals in tuff is 0.84 J/gm°C. Calculated values for the tuff are strongly dependent on porosity and degree of saturation and somewhat dependent on mineralogy (grain density). However, it is felt that the accuracy with which the heat capacity can be calculated (±20 percent) is acceptable under most conditions because uncertainty in the temperature range over which pore fluids will be volatilized in situ is greater than uncertainties in the calculated heat capacities.

Experience gained in G-Tunnel and the similarity of tuffs at Yucca Mountain and Rainier Mesa indicate that controlled blasting techniques can be used to excavate the welded tuff. In addition, it should be possible to stabilize openings using only roof bolts and wire mesh. Control of water flow should not be a significant factor in the design of a repository in the Topopah Spring Member. Evaluation of the excavation characteristics of tuffs from Yucca Mountain has been completed using several empirical approaches with information obtained from boreholes and core samples. These empirical correlations suggest that no unusual support systems will be required to construct the ES or openings in the disposal area in the Topopah Spring Member. Confidence in the predictions by empirical methods was gained by applying them to Tunnel Bed 5 (nonwelded) and Grouse Canyon Member (welded) tuffs of Rainier Mesa, where there is substantial experience with excavations.

## CONCLUSIONS

The following conclusions can be drawn from the detailed discussions and data presented.

- The development of the data base of geoengineering information is well under way, and average thermal and mechanical properties (and their anticipated variations) in the tuffs from Yucca Mountain have been defined.
- Field measurements that are appropriate to quantify thermal and mechanical properties of the rockmass and to calibrate thermal and structural analysis techniques are being made in G-tunnel and will be made in the ES.
- It is anticipated that existing mining technology can be used to develop stable underground openings in a repository in the Topopah Spring Member, and that repository operations can be carried out safely from the beginning of construction through repository closure. This statement is based on over twenty years of excavation experience in tuff, the rock properties determined in laboratory measurements, and stress analyses that include the effects of heating of the rockmass by the waste.

# REFERENCES


AMERICAN SOCIETY OF TESTING AND MATERIALS (ASTM) STANDARD TEST PROCEDURES:

Bulk Properties

- ASTM C97-47 (reapproved 1977) - Absorption and Bulk Specific Gravity of Natural Building Stone.
- ASTM C135-66 - True Specific Gravity of Refractory Materials by Water Immersion.
- ASTM C604-79 - True Specific Gravity of Refractory Materials by Gas-Comparison Pycnometer.
- ASTM C118-71 - Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens.

Thermal And Thermomechanical Properties

- ASTM C202-71 (reapproved 1977) - Thermal Conductivity of Refractory Brick.
- ASTM C351-61 (reapproved 1973) - Mean Specific Heat of Thermal Insulation.
- ASTM E228-71 (reapproved 1979) - Linear Thermal Expansion of Rigid Solids With a Vitreous Silica Dilatometer.

Mechanical Properties

- ASTM D2664-80 - Triaxial Compressive Strength of Undrained Rock Core Specimens Without Pore Pressure Measurements.
- ASTM D2938-79 - Unconfined Compressive Strength of Intact Rock Core Specimens.
- ASTM D2845-69 (reapproved 1976) - Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock.
- ASTM D3148-80 - Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression.
- ASTM D3967-81 - Splitting Tensile Strength of Intact Rock Core Specimens.

Barton, N, 1973, "Review of New Shear Strength Criterion for Rock Joints," Eng. Geol., V. 7, pp. 287-332.

Barton, N., R. Lien, and J. Lunde, 1974a. "Engineering Classification of Rockmasses for Design of Tunnel Support," Rock Mechanics, V. 6, No. 4, pp. 189-236.

Barton, N., R. Lien, and J. Lunde, 1974b. "Analysis of Rockmass Quality and Support Practice in Tunneling and a Guide for Estimating Support Requirements," Internal Report, Norges Geotekniske Institute.

Bieniawski, Z.T., 1976, "Rockmass Classification in Rock Engineering," Proceedings of the Symposium on Exploration for Rock Engineering (November, Johannesburg, South Africa).

Bieniawski, Z.T., and W. L. Van Heerden, 1975, "The Significance of In Situ Tests on Large Rock Specimens," Inter. Jour. Rock Mech. Min. Sci., V. 12, pp 101-113.

Bish, D.L., 1982, "Detailed Mineralogical Characterization of the Bullfrog and Tram Members in USW-G1, With Emphasis on Clay Mineralogy," LA-9021-MS, Los Alamos National Laboratory, Los Alamos, New Mexico.

Blacic, J., J. Carter, P. Halleck, P. Johnson, T. Shankland, R. Anderson, K. Spicochi, and A. Heller, 1982, "Effects of Long-Term Exposure of Tuffs to High-Level Nuclear Waste-Repository Conditions," LA-9174-PR, Los Alamos National Laboratory, Los Alamos, New Mexico.

Blanford, M. L., 1982, "Heated Block Test Conceptual Design Calculations," SAND81-1841, Sandia National Laboratories, Albuquerque, New Mexico.

Byerlee, J.D., 1978, "Friction of Rocks," Pageoph, V. 14, pp. 615-627.

Carlsson, H., 1978, "A Pilot Heater Test in the Stripa Granite," LBL-7086 (SAC-067), Lawrence Berkeley Laboratory, Berkeley, California.

Carmichael, R.S., 1982, ed. Handbook of Physical Properties of Rocks, Volume II, CRC Press, Inc., Boca Raton, Florida.

Costin, L.S., 1983, "A Microcrack Model for the Deformation and Failure of Brittle Rock," J. Geophys. Res., v. 88, no. B11, pp. 9485-9492.

Dieterich, J.H., 1978, "Time-Dependent Friction and the Mechanics of Stick-Slip," Pageoph, V. 116, pp. 790-807.

Donath, F. A., L. S. Fruth, Jr., and W. A. Olsson, 1972, "Experimental Study of Frictional Properties of Faults," Proceedings of the 14th Symposium on Rock Mechanics, Pennsylvania State University, pp. 189-222.

Eaton, R.R., D.E. Larson , and C. M. Korbin, 1981, "Sensitivity of Calculated Pore Fluid Pressure to Repository Fracture Geometry," in Scientific Basis for Nuclear Waste Managment, V. 3, J. G. Moore, ed., pp 591-598.

Griggs, D.T., 1939, "Creep of Rocks," Jour. Geol. V. 47, pp. 225-251.

Guzowski, R.V., F.B. Nimick, and A.B. Muller, 1982, "Repository Site Definition in Basalt, Pasco Basin, Washington," NUREG/CR-2352 (also SAND 81-2088).

Handin, J.W., and Carter, N.L., 1981, "Rheology of Rocks at High Temperatures," Proc. 4th Int. Cong. on Rock Mechanics, Montreaux, Switzerland, pp. 97-106.

Handin, J.W., R. Hager, M. Friedman, and J. Feather, 1963, "Experimental Deformation of Sedimentary Rocks under Confining Pressure: Pore Pressure Tests," A.A.P.G. Bull., 47, pp. 717-755.

Heard, H.C., 1980, "Thermal Expansion and Inferred Permeability of Climax Quartz Monzonite to 300°C and 27.6 MPa," Int. Jour. Rock Mech. Sci. and Geomech. Abstr., V. 17, pp. 289-296.

Heuze, F.E., V.C. Patrick, R.V. De La Cruz, and C.F. Cross, 1981, "In Situ Geomechanics, Climax Granite, Nevada Test Site", UCRL-53076, Lawrence Livermore Laboratory, Livermore, California.

Heuze, R.R., and A. Salem, 1977, "Rock Deformability Measured In Situ, Problems and Solutions," International Symposium of Field Measurements in Rock Mechanics, Zurich, Switzerland, V. 1, pp. 375-387.

Hustrulid, W.A., 1976, "An Analysis of the Goodman Jack," 17th U.S. Symposium on Rock Mechanics, paper 4B10, Snowbird, Utah.

Jackson, J.L. (ed.), 1984, "Nevada Nuclear Waste Storage Investigations Preliminary Repository Concepts Report," SAND83-1877, Sandia National Laboratories, Albuquerque, NM.

Johnstone, J.K., G.R. Hadley, and D.R. Waymire, in preparation, "In Situ Tuff Water Migration/Heater Experiment: Final Report," SAND 81-1918, Sandia National Laboratories, Albuquerque, New Mexico.

Johnstone, J.K., R.R. Peters, and P. Gnirk, 1984, "Unit Evaluation at Yucca Mountain, Nevada Test Site: Summary Report and Recommendation," SAND 83-0372, Sandia National Laboratories, Albuquerque, NM.

Lanigan, D.C., M.L. Cramer, and K. Kim, 1983, "Determination of Rockmass Deformation Modulus in Closely Jointed Columbia River Basalt," EOS, Trans. Amer. Geophys Union, v. 64, no. 9, p 87.

Lappin, A.R., 1980a. "Thermal Conductivity of Silicic Tuffs: Predictive Formalism and Comparison With Preliminary Experimental Results," SAND 80-0769, Sandia National Laboratories, Albuquerque, New Mexico.

Lappin, A.R., 1980b. "Preliminary Thermal Expansion Screening Data for Tuffs," SAND 78-1147, Sandia National Laboratories, Albuquerque, New Mexico.

Lappin, A.R., R.K. Thomas, and D.F. McVey, 1981, "Eleana Near-Surface Heater Experiment Final Report," SAND 80-2137, Sandia National Laboratories, Albuquerque, New Mexico.

Lappin, A.R., R.G. Van Buskirk, D.O. Enniss, S.W. Butters, F.M. Prater, C.B. Muller, and J.L. Bergosh, 1982, "Thermal Conductivity, Bulk Properties, and Thermal Stratigraphy of Silicic Tuffs from the Upper Portion of Hole USW-G1, Yucca Mountain, Nye County, Nevada," SAND 81-1873, Sandia National Laboratories, Albuquerque, New Mexico.

Lundstrom, L. and H. Stille, 1978, "Large-Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test," LBL-7052 (SAC-02), Lawrence Berkeley Laboratory, Berkeley, California.

Mellor, M. and I. Hawkes, 1971, "Measurement of Tensile Strength by Diametral Compression of Discs and Annuli", Eng. Geol., V. 5, pp. 173-225.

Morgan, M.T. and G.A. West, 1980, "Thermal Conductivity of Rocks in the Bureau of Mines Standard Rock Suite," ONRL/TM-7052, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Morrow, C.A., L.Q. Shi, and J.D. Byerlee, 1982, "Strain Hardening and Strength of Clay-Rich Fault Gauges," Journ. Geophys Res., V. 87, No. B8, pp 6771-6780.

Moss, M., J.A. Koski, G.M. Haseman, and T.V. Tormey, 1982, "Thermal Conductivity of Welded Tuff: The Effects of Composition, Porosity, Bedding Plane Orientation, Water Content, and a Joint," SAND 82-1164, Sandia National Laboratories, Albuquerque, New Mexico.

Olsson, W.A., 1982, "Effects of Elevated Temperature and Pore Pressure on the Mechanical Behavior of Bullfrog Tuff," SAND 81-1664, Sandia National Laboratories, Albuquerque, New Mexico, February 1982.

Olsson, W.A. and A.K. Jones, 1980, "Rock Mechanics Properties of Volcanic Tuffs from the Nevada Test Site," SAND 80-1453, Sandia National Laboratories, Albuquerque, New Mexico, November 1980.

Paterson, M.S., 1978, Experimental Rock Deformation - The Brittle Field, Springer-Verlag, p. 92.

Peters, R.R., 1983, "Thermal Response to Emplacement of Nuclear Waste in Long, Horizontal Boreholes," SAND82-2497, Sandia National Laboratories, Albuquerque, New Mexico.

Peters, R.R., E.A. Klavetter, I.J. Hall, S.C. Blair, P.R. Heller, and G.W. Gee, 1984, "Fracture and Matrix Hydrologic Characteristics of Tuffaceous Materials from Yucca Mountain, Nye County, Nevada," SAND84-1471, Sandia National Laboratories, Albuquerque, New Mexico.

Pratt, H.R., A.D. Black, W.S. Brown, and W.F. Brace, 1972, "The Effect of Specimen Size on the Mechanical Properties of Unjointed Diorite," Int. J. Rock Mech. & Mineral Science. V. 9, pp. 513-529.

Pratt, H.R., T.W. Schrauf, L.A. Bills, and W.A. Hustrulid, 1977, "Thermal and Mechanical Properties of Granite: Stripa, Sweden, Terra Tek Summary Report," TR-77-92, Salt Lake City, Utah.

Price, R.H, 1983, "Analysis of Rock Mechanics Properties of Volcanic Tuff Units from Yucca Mountain, Nevada Test Site," SAND 82-1315, Sandia National Laboratories, Albuquerque, New Mexico.

Price, R.H., W.R. Wawersik, D.W. Hannum, and J.A. Zirzow, 1981, "Quasi-static Rock Mechanics Data for Rocksalt from Three Strategic Petroleum Reserve Domes," SAND 81-2521, Sandia National Laboratories, Albuquerque, New Mexico.

Price, R.H. and A.K. Jones, 1982, "Uniaxial and Triaxial Compression Test Series on Calico Hills Tuff," SAND 82-1314, Sandia National Laboratories, Albuquerque, New Mexico.

Price, R.H., A.K. Jones, and K.G. Nimick, 1982, "Uniaxial Compression Test Series on Bullfrog Tuff," SAND 82-0481, Sandia National Laboratories, Albuquerque, New Mexico.

Price, R.H. and K.G. Nimick, 1982, "Uniaxial Compression Test Series on Tram Tuff," SAND 82-1055, Sandia National Laboratories, Albuquerque, New Mexico.

Price, R.H., K.G. Nimick, and J.A. Zirzow, 1982, "Uniaxial and Triaxial Compression Test Series on Topopah Spring Tuff," SAND 82-1723, Sandia National Laboratories, Albuquerque, New Mexico.

Rocha, M., 1970, "New Techniques in Deformability Testing of In Situ Rock Masses, ASTM-STP-477, American Society of Testing and Materials, Philadelphia, PA, pp. 39-57.

Sinnock, S., and J. A. Fernandez, 1982, "Summary and Conclusions of the NNWSI Area-To-Location Screening Activity", NVO-247 (DE82022540), Department of Energy, Las Vegas, Nevada.

Shimamoto, T., and J.M. Logan, 1981, "Effects of Simulated Clay Gouges on the Sliding Behavior of Tennessee Sandstone," Tectonophysics, v. 75, pp. 243-255.

Swan, G., 1978, "The Mechanical Properties of Stripa Granite," LBL-7074, Lawrence Berkeley Laboratory, Berkeley, California.

Teufel, L.W., 1981, "Frictional Properties of Jointed Welded Tuff," SAND 81-0212, Sandia National Laboratories, Albuquerque, New Mexico.

Teufel, L.W., and J.M Logan, 1978, "Effect of Displacement Rate on the Real Area of Contact and Temperatures Generated During Frictional Sliding of Tennessee Sandstone," Pageoph, V. 116, pp. 840-865.

Tien, P.-L., F.B. Nimick, A.B. Muller, P.A. Davis, R.V. Guzowski, L.E. Duda, and R.L. Hunter, 1983, "Repository Site Data and Information in Bedded Salt: Palo Duro Basin, Texas", NUREG/CR-3129 (also SAND82-2223).

Van Buskirk, R.G., (a), "Measurement of Thermal Expansion in Geologic Materials Under Simulated In Situ stress, Temperature, and Pure Fluid Pressure," Terra Tek Procedure PR8265, in preparation, Salt Lake City, Utah.

Van Buskirk, R.G., (b), "Standard Laboratory Procedures, Calibration of Thermal Expansion System Using A Known Sample," Terra Tek Procedure TTRD-CP-6, Salt Lake City, Utah.

Van Buskirk, R.G., (c), "Standard Laboratory Procedures, Thermal Expansion Tests, Terra Tek Procedure TTRD-LP-3," Salt Lake City, Utah.

Waters, A.C. and P.R. Carroll, 1981, "Preliminary Stratigraphic and Petrologic Characterization of Core Samples from USW-G1, Yucca Mountain, Nevada," LA-8840-MS, Los Alamos National Laboratory, Los Alamos, New Mexico.

Witherspoon, P.A., N.G.W. Cook, and J.E. Gale, 1980, "Progress with Field Investigations at Stripa," LBL-10559 (SAC-27), Lawrence Berkeley Laboratory, Berkeley, California.

Woodside, W., and J.H. Messmer, 1961, "Thermal Conductivity of Porous Media, I, Unconsolidated Sands," Journ. Appl. Phys., V. 32, pp. 1688-1698.

Zimmerman, R.M., M.P. Board, E.L. Hardin, and M.D. Voegele, 1984, "Ambient Temperature Testing of the G-Tunnel Heated Block", Proc. 25th Symp. on Rock Mechanics, p. 281-295.

Zimmerman, R.M. and W.C. Vollendorf, 1982, "Geotechnical Field Measurements, G-Tunnel, Nevada Test Site," SAND 81-1971, Sandia National Laboratories, Albuquerque, New Mexico.

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