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# STUDY PLAN 8.3.1.15.1.3

# Laboratory Determination of the Mechanical Properties of Intact Rock

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## ABSTRACT

Licensing of a nuclear-waste repository by the Nuclear Regulatory Commission requires, among other things, demonstration of the long-term usability of the underground portion of the repository. Such a demonstration involves analysis of the mechanical response of the rock to the presence of underground openings and heat-producing waste, which in turn requires data on the mechanical properties of the rock. This document describes (1) the rationale for obtaining mechanical-properties data on intact rock; (2) the determination of specific requirements for the data (e.g., number of samples, experiment conditions); and (3) specific experimental plans for obtaining data on each mechanical property (Young's modulus, Poisson's ratio, unconfined compressive strength, cohesion, and angle of internal friction).

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# TABLE OF CONTENTS

## CONTENTS (continued)

# LABORATORY DETERMINATION OF THE MECHANICAL PROPERTIES OF INTACT ROCK

## 1.0 Purpose and Objectives of Studies

### 1.1 Purpose

Yucca Mountain, Nevada, has been selected as a potential repository of nuclear wastes. The Yucca Mountain Site Characterization Project (YMP) of the Civilian Radioactive Waste Management Program has been assigned the task of determining the suitability of the Yucca Mountain site. Among the concerns being investigated, the characterization of the mechanical properties of the host rock has direct relevance to repository design activities, as well as to pre- and post-closure performance assessment.

The performance allocation process used in the YMP Site Characterization Plan (SCP) identified performance measures and goals. To determine whether the performance goals can be met, data must be available on various site parameters and must have associated levels of confidence. The purpose of this investigation is to provide information on the spatial distribution of several mechanical properties for intact rock as requested by design and performance issues in the SCP.

As specified in Section 8.3.1.15 of the SCP, the following mechanical properties of intact tuff are required by design and performance issues:

- Young's modulus,
- Poisson's ratio,
- unconfined compression strength, and
- parameters for the Coulomb failure criterion (cohesion and angle of internal friction).

This study plan describes the detailed testing that will be performed to obtain data on these and other important rock properties. Testing will be performed on core samples obtained from the Systematic Drilling Program (described in Study Plan 8.3.1.4.3.1.1, *Systematic Acquisition of Site-Specific Subsurface Information - Systematic Drilling Program*) and from rock samples collected in the Exploratory Studies Facility (ESF). Sufficient samples will be collected to assess the spatial and inherent variability of the properties, as well as assess the effects of several environmental factors on the properties.

The data to be collected in this study will be used as input for design and performance assessment analyses that address various regulatory requirements outlined in Section 1.3.2. In general, the analyses address questions concerning (1) repository design aspects that will contribute to the containment and isolation of radionuclides and provide flexibility to accommodate site specific conditions, (2) the development and evaluation of repository seals, (3) the option to retrieve emplaced waste during the operation of the repository, and (4) nonradiological health and safety of repository workers. The parameters listed above are a subpart of the data set needed to analyze the response of the tuff rock mass to repository construction, nuclear waste emplacement, and permanent storage. Additional information required includes the thermomechanical, thermal, geochemical, and hydrologic data for both the intact rock and the rock mass. All of these data will be used to develop constitutive relationships for deformation and failure of the rock mass and accompanying changes in the hydrologic conditions.

The potential repository horizon is within the Topopah Spring Member of the Paintbrush Tuff. This horizon is a mass of intact blocks of welded ash-flow tuff separated by approximately planar discontinuities (i.e., fractures and bedding planes). In characterizing the mechanical properties of the rock mass, the system can be considered in total (usually characterized through field, or *in situ*, experiments) or in two parts, intact rock and discontinuities, (usually characterized in a rock mechanics laboratory) with the two sets of properties combined into a rock-mass model using analytical or numerical techniques. Both approaches will be used; however, this document will focus only on the plans to study the mechanical properties of the intact rock by means of experiments in the laboratory.

## 1.2 General Petrology of the Yucca Mountain Tuffs

The tuffs at Yucca Mountain usually are described within a standard stratigraphic framework, details of which are provided in Chapter 1 of the SCP. However, most of the formal stratigraphic units contain material with mechanical properties that vary over wide ranges. Efforts have been made to categorize the tuffs into subdivisions, each having relatively uniform thermal and mechanical properties (e.g., thermal/mechanical or mineralogical/petrological) that are distinguishable from the properties of adjacent subdivisions. Samples tested for mechanical properties in the laboratory will be identified by the sample collection location (e.g., the drillhole number and depth). The sample can then be associated with any stratigraphic framework (e.g., the thermal/mechanical stratigraphy developed by Ortiz et al., 1985).

## 1.3 Rationale and Justification of Data Needs

As specified in Section 8.3.1.15 of the SCP, the mechanical properties of intact rock required by design and performance issues are Young's modulus, Poisson's ratio, unconfined compressive strength, cohesion, and angle of internal friction. The experiments outlined in this plan are intended to produce these mechanical properties data, which will be supplied to the appropriate YMP data base in order to meet the following needs:

- data from which to derive properties for the YMP Reference Information Base (RIB),
- input data for design models, such as thermomechanical models for the prediction of the stability of underground openings,
- input data for performance assessment models.

It is well known the mechanical properties of silicic rock, in general, and Yucca Mountain tuff, specifically (see Sections 3.4 and 3.5), are dependent on sample characteristics and environmental conditions. Because these conditions will be wide ranging in a repository, the experiments are also planned to provide input data for analyses of the dependence of mechanical properties on the following:

- physical properties (i.e., porosity, density, and mineralogy),
- saturation,
- pressure (pore and confining),
- temperature,
- strain rate.
- sample geometry (i.e., diameter and length-to-diameter ratio),
- sample orientation (i.e., anisotropy), and
- lithophysal content.

As a result, the laboratory mechanical data on intact rock will support many aspects of the repository license application.

### 1.3.1 Resolution of Performance and Design Issues

Performance allocation was used by the YMP to establish appropriate issue resolution strategies for performance and design issues in the YMP Issues Hierarchy. A general discussion of the performance allocation approach is provided in Section 8.1 of the SCP. This approach was then applied to each of the performance and design issues to define the site data needed to resolve each issue.

**Table 1.**
**Pre- and Post-Closure Issues, Required Parameters,**
**Thermal/Mechanical Units, and Required Confidence Level**

| Issue (SCP Section) | Parameter | Units | Confidence |
|---|---|---|---|
| 1.11 (8.3.2.2) | Young's modulus | TSw2 | High |
| 1.11 (8.3.2.2) | Young's modulus | TSw1,TSw3,CHn1 | Medium |
| 1.11 (8.3.2.2) | Young's modulus | TCw,PTn,CHn2 | Low |
| 1.11 (8.3.2.2) | Poisson's ratio | TSw2 | Medium |
| 1.11 (8.3.2.2) | Poisson's ratio | TCw,PTn,TSw1&3,CHn1&2 | Low |
| 1.11 (8.3.2.2) | Compressive Strength* | TSw1,TSw2 | High |
| 1.11 (8.3.2.2) | Unconfined Comp. Strength | TCw,PTn,TSw3,CHn1 | Low |
| 1.11 (8.3.2.2) | Cohesion | TCw,PTn,TSw3,CHn1 | Medium |
| 1.11 (8.3.2.2) | Internal Friction Angle | TCw,PTn,TSw3,CHn1 | Medium |
| 1.12 (8.3.3.2) | Unconfined Comp. Strength | TCw,TSw2,CHn1 | Medium |
| 4.4 (8.3.2.5) | Young's modulus | TSw1,TSw2 | Medium |
| 4.4 (8.3.2.5) | Poisson's ratio | TSw2 | Medium |
| 4.4 (8.3.2.5) | Poisson's ratio | TSw1 | Low |
| 4.4 (8.3.2.5) | Compressive Strength* | TCw,PTn,TSw1,TSw2 | Medium |

* The compressive strength parameter includes unconfined compressive strength, cohesion, and internal friction angle.

Performance Issue 2.4 (Waste Retrievability) and Design Issues 1.11 (Configuration of Underground Facilities - Postclosure), 4.2 (Nonradialogical Health and Safety), and 4.4 (Preclosure Design and Technical Feasibility) all have mechanical property data needs that will be met as a result of the studies defined in this plan. The data required by Performance Issue 2.4 and Design Issue 4.2 will be collected for Design Issue 4.4 and passed from Issue 4.4 to Issues 2.4 and 4.2 in order for all requirements to be met with one set of experiments (for a discussion of the issue-to-issue data flow, see SCP Section 8.3.2.1). Table 1 lists the pre- and post-closure issues that require data on the mechanical properties of intact rock, as well as the specific parameters that are required, the thermal/mechanical units for which data are needed, and the confidence with which required parameters must be known in order to resolve the appropriate issues.

### 1.3.2 Regulatory Requirements

The Issues Hierarchy has incorporated all regulatory requirements for a geologic repository. This study will provide support concerning compliance with several key regulations: 10 CFR Part 60 (Title 10, Chapter 1, Part 60), 10 CFR Part 960, and 40 CFR Part 191 of the United States Code of Federal Regulations - Energy. The following sections will briefly discuss the regulatory basis for each issue, with a reference to the appropriate SCP section for further discussion.

**Design Issue 1.11, Configuration of Underground Facilities (Postclosure), SCP Section 8.3.2.2:** Issue 1.11 identifies the parameters needed to meet the requirements defined by the post-closure design criteria. The Information Needs associated with this issue relate to site characterization, development of design concepts, and prediction of thermomechanical response of the host rock. Issue 1.11 was developed from 10 CFR Part 60, Section 60.131-133, and 10 CFR Part 960, Subpart C, Sections 4-2-3 (Rock Characteristics) and 4-2-5 (Erosion).

**Performance Issue 2.4, Waste Retrievability, SCP Section 8.3.5.2:** Rock mechanics data provide information for the performance objectives in 10 CFR 60.111(b), which addresses retrievability of waste. To satisfy this objective, the YMP position is that all underground openings (including waste emplacement holes, drifts, and access ramps from the surface) must remain stable for the operation and caretaker period of time. For emplacement drill holes (if used), there must be reasonable assurance that the walls will not deteriorate to an extent that would preclude removal of waste canisters. In addition, retrievability requirements are contained in 10 CFR 960.5-1(a)(3) and 40 CFR 191.14(f).

**Design Issue 4.2, Nonradiological Health and Safety, SCP Section 8.3.2.4:** Requirements in 10 CFR 60.131(b)(9) state that the design of the geologic repository operations area should include provisions for worker protection adequate to ensure that structures, systems, and components important to safety can perform their intended functions.

**Design Issue 4.4, Preclosure Design and Technical Feasibility, SCP Section 8.3.2.5:** Issue 4.4 identifies the site information important to characterizing the design and feasibility of the technology to be used during pre-closure (i.e., repository construction, operation, closure, and decommissioning). The data resulting from experiments defined by this study plan will serve as input to the geomechanical models that will be used in the process of designing the underground facility. This issue was developed from 10 CFR 60.131-133 and 10 CFR 960.5-2-9.

# 2.0 Overview of Laboratory Studies of Intact Rock

## 2.1 General Rationale and Justification

The objective of the general rock mechanics program is to predict the response of the rock mass around a repository throughout construction, operation, closure, and post-closure. The program is concerned with rock mechanics aspects of very-near-field (canister scale), near-field (room scale), and far-field (site scale) effects on the geologic containment and isolation of high-level nuclear waste. As part of this overall program, this plan outlines the work proposed for studying the mechanical properties of intact rock in the laboratory.

Laboratory mechanical experiments are to be performed on a variety of sample sizes under a range of saturation, pressure, temperature, and rate conditions to define the general constitutive behavior of the rock at Yucca Mountain. These sample and environmental conditions will be varied to simulate, as closely as practical, the anticipated range of repository conditions.

In parallel studies, other physical property data will be collected to support the analyses of the laboratory mechanical properties. The densities and porosities of the mechanical test samples and/or samples adjacent to these samples will be measured. Every attempt will be made to determine these properties on the actual test samples, except when the drying and saturating process would degrade the sample (e.g., zeolitic samples). In addition, the petrology, mineralogy, and dynamic mechanical properties of selected samples will be determined as a direct-support investigation under this study plan. The petrologic properties will be collected to evaluate whether correlations exist allowing extrapolation of the data. Dynamic elastic properties will be compared to the static properties from the same samples to determine the relationship between these properties. These data make it possible to use the seismic properties of the rock to estimate the variability in static properties for engineering applications.

## 2.2 General Experiment Types

To determine the constitutive behavior of the intact rock with the detail necessary to meet design and performance-assessment requirements, both compressive and tensile properties are needed. The following experiment techniques have been selected to collect these data.

For measuring the compressive mechanical properties, axisymmetric experiments (i.e., $\sigma_1 > \sigma_2 = \sigma_3$, where compressive stresses are positive) on right-circular, cylindrical samples will be run under uniaxial (or unconfined, $\sigma_2 = \sigma_3 = 0$) and triaxial (or confined, $\sigma_2 = \sigma_3 > 0$) pressure conditions. In a triaxial experiment, an initial hydrostatic stress ($\sigma_h = \sigma_1 = \sigma_2 = \sigma_3$) is applied to the sample, followed by an increase in axial stress ($\sigma_{ax} \sim \sigma_1$) while the lateral (or radial) stresses ($\sigma_{lat} \sim \sigma_2 = \sigma_3$) remain constant, producing a differential stress state. For determination of the tensile strength, laterally unconfined direct-pull or indirect tensile (or Brazilian-type) tests will be run. All of the defined tests will be performed at a constant displacement or strain rate.

## 2.3 Alternative Experiment Types

Other load paths also are used to determine the compressive mechanical properties of intact rock in the laboratory. These alternative experiment types include triaxial compression with a constant differential stress-rate, triaxial extension with a constant strain-rate or stress-rate, true triaxial, creep, relaxation, and complex load path. These test types were considered, but were not chosen as the main technique for one or more of the reasons discussed below.

A constant stress-rate, triaxial compression experiment is run essentially the same as the constant strain-rate, triaxial compression experiment. The only difference between the two being that the stress-rate experiment uses axial stress instead of axial strain as the time-based control parameter producing the increase in the axial (and therefore, the differential) stress. For rocks essentially linear-elastic up to failure, such as welded tuff at relatively low temperatures and/or high strain rates, the response of the rock is approximately the same for both methods. In general, the strain-rate loading path is more desirable because the failure path is more stable. As a sample yields in a stress-rate experiment, the loading ram begins to accelerate into the sample in an attempt to maintain the prescribed loading rate. At sample failure (and therefore loss of load-bearing capability), the ram continues to accelerate, and unless unloading is initiated immediately, the sample is completely crushed. In the strain-rate test, the ram advances at essentially a constant velocity, allowing the post-failure behavior to be observed more readily and the loading to be stopped prior to the destruction of the sample.

There are two load paths which are used in triaxial extension experiments. Both techniques begin with a predetermined hydrostatic stress state. The triaxial extension state of stress, $\sigma_1 > \sigma_2 = \sigma_3$, is produced by either (1) increasing the lateral stress $\sigma_{lat} \sim \sigma_1 = \sigma_2$, while backing the axial ram out to maintain the axial stress ($\sigma_{ax} = \sigma_3$) constant, or (2) maintaining the lateral stress constant while decreasing the axial stress by backing the axial ram away from the sample.

True triaxial (i.e., $\sigma_1 > \sigma_2 > \sigma_3$) experiments are run on cubic-shaped samples with three independent stresses applied to the faces of the cubes.

The Coulomb failure criterion assumes the intermediate principal stress ($\sigma_2$) has no effect on the brittle failure strength of rock. Investigations of the effects of changes in $\sigma_2$ on ultimate strength utilize a combination of triaxial compression experiments, triaxial extension experiments, and/or true triaxial experiments. Some of these studies (e.g., Brace, 1964) have shown that varying $\sigma_2$ has no effect on strength; however, many (e.g., Heard, 1960; Jaeger and Hoskins, 1966; Handin, Heard, and Magouirk, 1967) have shown that $\sigma_2$ does have an effect: failure strength increases as $\sigma_2$ is increased relative to $\sigma_3$. As a result, since $\sigma_2$ is at a minimum condition in triaxial compression experiments, the Coulomb failure criterion, based on triaxial compression experiments, is a lower-bound estimate of the failure strength of a rock under general pressure conditions. As a result, neither extension nor true triaxial experiments are planned by this study.

In a creep experiment, a predefined differential stress ($\Delta\sigma = \sigma_1 - \sigma_3$) is placed on a sample in a very short time interval (usually $< 100\,\text{s}$). The sample strains then are monitored while the differential stress is held constant. Similarly, relaxation experiments begin with a relatively fast application of a pre-determined quantity of axial strain. This axial strain is maintained while monitoring the decay response of the axial stress and the lateral strain.

Creep and/or relaxation experiments are normally run in conjunction with a range of constant strain-rate tests to investigate the time-dependent (rate-dependent) behavior. Preliminary creep tests on welded tuff at repository-scale differential stresses have shown these rocks to exhibit very little time-dependent deformation (Senseny and Parrish, 1981); however, some creep experiments are planned on samples of TSw2 (Section 3.6.2).

## 2.4 Rationale for Selected Number of Experiments

The number of experiments that will be necessary for site characterization in general will be different for each property considered. Statistically, a preliminary estimate of the number needed for each mechanical property could be obtained using information provided by repository design and performance assessment through the performance allocation process, if there were an adequate number of existing mechanical data. However, at the present time, there are only a limited number of mechanical property data on intact rock within the potential repository horizon (thermal/mechanical stratigraphy unit TSw2) and less on the other thermal/mechanical stratigraphic units (i.e., TCw, PTn, TSw1, TSw3, CHn1, and CHn2). As a result, making reasonable estimates of sample needs from a statistically-based argument is not possible; therefore, professional judgement has been used to determine the initial testing requirements. The numbers discussed in the following sections are preliminary estimates which will be re-evaluated as the data are collected. After data are obtained from the planned samples, the adequacy of the data for satisfying the data requirements given by the design and performance assessment issues will be examined. If the data are not adequate, the Principal Investigator (PI) will consult with the relevant design or performance assessment personnel to determine the appropriate steps to follow.

There are two major experimental investigations described within this study: (1) Baseline Studies (Section 3.6.1) and (2) Parametric Studies (Section 3.6.2). The following two subsections will discuss the sampling approach planned for the baseline studies, and the third subsection discusses the sampling scheme for the parametric studies. The number of laboratory experiments to be performed in support of an *in situ* experiment will be defined by the field test PI for each study (see list of studies in Section 2.5.8).

### 2.4.1 Sampling in New Core Holes

Previous studies on samples of intact tuff from the Yucca Mountain area (e.g., Price, 1983 and Price et al., 1987) have indicated a large variability in the mechanical properties as a function of spatial location, both horizontally within the primary area or vertically within a given thermal/mechanical unit. For complete site characterization, data from several locations are necessary in order to examine the spatial variability of mechanical properties within the primary area.

In order to coordinate with core holes planned for other YMP activities, on the order of one hundred samples from at least six of the twelve core holes suggested as the first phase of the Systematic Drilling Program (Study Plan 8.3.1.4.3.1.1, *Systematic Acquisition of Site-Specific Subsurface Information - Systematic Drilling Program*), or similar holes, will be collected for the intact rock properties study at baseline conditions. A suggested number of samples per thermal/stratigraphic unit is listed in Table 2. Data from these six holes should enable an adequate analysis of the lateral variability of the elastic and strength properties to be made, but a reevaluation of the potential need for additional data will be made following these experiments.

**Table 2.**
Number of Experiments Planned for Baseline Study
Numbers are per Stratigraphic Unit for Each Drill Hole

| Unit | n |
|---|---|
| TCw | 10 |
| PTn | 10 |
| TSw1 | 25 |
| TSw2 | 30 |
| TSw3 | 5 |
| CHn1 | 10 |
| CHn2 | 5 |

### 2.4.2 Sampling in ESF

The sampling program in the ESF will consist of taking a sample at a nominal spacing of every 30 m of ramp and drift for testing under baseline conditions. Each sample should be a minimum of 100 mm on a side.

### 2.4.3 Sampling in Potential Repository Horizon

The parametric studies (Section 3.6.2) will require a large volume of material from the Topopah Spring Member tuff. This material will be extracted in the form of large blocks or large cores from the ribs (side-walls) of the drifts. The blocks for sampling will be chosen on the basis of providing a maximum number of samples (and, therefore, minimizing the number of sampled blocks). This criterion is necessary to increase the probability of interpreting the results with high confidence. In other words, the test results should mainly indicate the effects of changing experiment conditions and not changes in the gross petrology of the rock.

## 2.5 Existing Constraints

### 2.5.1 Potential Impacts from Measurement Activities

No potential impacts on the site are likely to occur as a result of this study plan other than the effects of the drilling of drillholes and the mining of the ESF.

### 2.5.2 Simulation of Repository Environmental Conditions

The ranges of saturation, confining pressure, and temperature conditions for this series of experiments (Table 3) will match or include the ranges in these parameters expected to occur around a repository in the Topopah Spring Member at Yucca Mountain. Time is one repository condition that cannot be fully simulated within the time frame of a licensing procedure. As a result, data from constant strain rate and constant stress tests will be used in a model to extrapolate to the repository time scales.

**Table 3.**

Ranges of Planned Experimental Conditions

| Parameter | Range |
|---|---|
| saturation | dry, room dry, and saturated |
| confining pressure | 0.1 to 25.0 MPa |
| pore pressure | 0.1 to 5.0 MPa |
| temperature | 22 to 250°C |
| axial strain rate | $10^{-9}$ to $10^{-3}$ $s^{-1}$ |
| creep stress | $\leq$150 MPa |
| sample diameter | 25.4 to 380 mm |
| length:diameter | 2:1 to 3:1 |

**Saturation:** Saturation will be studied at room dry and at the end-member conditions (i.e., dry and fully saturated). The repository horizon is partially saturated (reported to be 0.65±0.19

by Montazer and Wilson, 1984), but will experience drying conditions in the near-field because of the heating from the waste packages.

**Effective Pressure:** Effective confining pressure ($P_e$) was defined by Handin et al. (1963) as confining pressure ($P_c$) minus pore pressure ($P_p$). This "law" was shown, experimentally, by Handin et al. (1963) and Brace and Martin (1968) to be true when the pore fluid is chemically inert, the permeability of the sample is sufficient to insure pervasion and uniform pressure distribution, and the configuration of the pore space is such that the interstitial hydrostatic pressure is transmitted fully throughout the solid framework.

The maximum anticipated depth of the repository is approximately 400 m (Ortiz et al., 1985). When the induced thermal loads from the emplacement of waste are applied at this depth, the largest confining pressure ($\sigma_3$) around the repository will be approximately 22 MPa (Arulmoli and St. John, 1987). At the low extreme, rock next to an underground opening is effectively unconfined. The range of effective pressures to be studied is 0 to 25 MPa (confining pressures from 0.1 to 25 MPa and pore pressures from 0.1 to 5.0 MPa), which includes the repository conditions. The range of pore pressures are planned for two reasons: (1) the thermal loads around the repository may produce transient pore pressures in the near-field environment and (2) to maintain the water in a liquid state during high-temperature experiments on saturated samples.

**Temperature:** The unperturbed, *in situ* temperature of unit TSw2 rock averages about 23°C (Ehgartner, 1987). When the waste packages are emplaced, the very-near-field (~2m) will undergo heating up to temperatures in the 175°C range (Arulmoli and St. John, 1987). The effects of temperature will be investigated over the range from room temperature (~22°C) to 250°C.

**Time:** As mentioned in Section 1.3.2, all underground openings must remain stable for the operation and caretaker period of the repository. For long-term modeling of the repository (i.e., for periods on the order of the operational phase of the repository), the effect of time on mechanical properties must be known or extrapolated from known properties. To study the time-dependent behavior, experiments are being performed over a standard range of laboratory strain rates, ranging from the slowest practical rate of $10^{-9}$ $s^{-1}$ up to a high of $10^{-3}$ $s^{-1}$ (Price et al., 1992). In addition, some creep tests are planned for study of constant-stress loading.

### 2.5.3 Scale of Phenomena

The repository horizon consists of blocks of intact rock bounded by essentially planar fractures. The block size of intact rock, therefore, is limited by the spacing between fractures. Fracture spacing in the Yucca Mountain tuffs varies with thermal/mechanical unit and measurement direction; however, the average spacing in the Topopah Spring Member is approximately 0.1 m for vertical fractures and 5.0 m for horizontal fractures (Maldonado and Koether, 1983; Scott and Castellanos, 1984; Spengler, Byers, and Warner, 1981; Spengler and Chornack, 1984). As a result, a mean block volume, calculated from the average spacings, is about 0.05 $m^3$, which is very similar to the 0.047 $m^3$ volume of the largest samples of the proposed repository horizon (i.e., TSw2) to be tested (right-circular cylinders with a diameter of 0.31 m and a length-to-diameter ratio of 2:1).

Another scale consideration involves the size of inhomogeneities (e.g., lithophysae, vapor-phase-altered zones, pumice, lithic fragments, and grain size) relative to the size of the test sample. When examining intact rock properties in laboratory experiments, the suggested maximum ratio of inhomogeneity size to sample diameter is one-tenth (e.g., see Vutukuri, Lama and Saluja, 1975, p. 44). The samples tested at the baseline conditions are planned to have a diameter of 50.8 mm. For the nonwelded tuffs, this size is believed to be generally representative of the material and should yield appropriate mechanical property results for repository modeling efforts. However, to study the effects of incorporating larger inhomogeneities which occur more commonly in the welded tuffs, TSw2 samples will be tested over a wide range of diameters (i.e., 25 to 305 mm). In addition, very large samples (380 mm in diameter) of the lithophysal tuffs (TSw1) will be tested to define the effect of the lithophysal cavities and associated vapor-phase-altered zones on the mechanical properties.

### 2.5.4 Precision and Accuracy of Data

The uncertainty in each of the required measured values (e.g., stress, strain, pressure, and temperature) is a function of the precision and the accuracy of the data measured in the laboratory mechanical experiments (e.g., load, axial displacement, lateral displacement, confining pressure, pore pressure, and temperature). Accuracy is a very difficult quantity to determine in this application, because of the inherent variability in most physical properties of rock (e.g., see Nimick, Schwartz, and Price, 1991). However, the total uncertainty can be limited to the following amounts for each of the values. Uncertainty in stress will be required to be within 3% of the total range of the measurement gage, strain uncertainty will be less than 2% of the measurement gage total range, and thermocouple uncertainty will be less than 3°C. These values were chosen as reasonable limits for conventional rock mechanics equipment.

### 2.5.5 Capability and Limits of Analytical Methods

The two major areas of analysis of concern in this study are (1) statistical and (2) constitutive in nature.

Some of the statistical analyses relate to calculations of the appropriate numbers of samples that should be tested to satisfy performance and design goals, accuracies of the needed data, and for comparisons of the data from various positions within Yucca Mountain to study horizontal and vertical property variability. The method to determine the appropriate sample sizes is discussed in Section 2.4 of this study, and Section 3.9 presents a brief discussion of the statistical analyses of the data. Because no one statistical technique is being chosen to analyze the data, the only limits to these analyses are the limits of the statistical techniques in general.

The present plans for constitutive analyses include empirical and physical modeling. Empirical relationships have been developed between ultimate strength/functional porosity (functional porosity is defined as the sum of the volume fractions of pore space and montmorillonite). (Olsson and Jones, 1980; Price, 1983; and Price and Bauer, 1985), Young's modulus/functional porosity (Olsson and Jones, 1980; Price, 1983; and Price and Bauer, 1985), ultimate strength/sample size (Price, 1986), and ultimate strength/strain rate (Price, 1983; Nimick and Schwartz, 1987; and Price et al, 1992) (for a discussion of the fits, see Section 3.5). These relationships have been shown to fit the existing set of tuff data very well, and have been used as predictors for mechanical properties at the intermediate values of the independent variables. These and other functional forms will be considered when analyzing the future data. It is recognized that the modulus fit assumes linear elasticity and the strength fits assume strength isotropy. These assumptions will be examined during the collection of data for site characterization. In addition, other relationships between mechanical properties and physical or environmental properties will be developed as the need arises and the data become available.

The Coulomb criterion will be used to define the mean effect of confining pressure on ultimate strength. When a large range of confining pressures (i.e., $\geq$ 0-200 MPa) is considered, most rocks exhibit a general non-linear (broad concave downward) trend in plots of shear stress versus normal stress data. The Coulomb criterion, however, defines a linear relationship between these parameters, and over much smaller ranges of pressure this relationship has been shown to be appropriate for most rock types. The Coulomb criterion, therefore, will be used to describe the results from the tests outlined in this study because of the small range of pressures planned (i.e., 0-25 MPa). However, as noted in Section 3.5.2 of this plan, the preliminary data has indicated that the potential exists for a non-linear relationship between shear stress and normal stress. As a result, an analysis of the data collected in the future will be performed to determine whether the Coulomb criterion is appropriate, or if another criterion would be better.

In addition, data obtained from work described in this study plan will support repository-scale analytical and numerical modeling efforts. As discussed in Section 2.5.3, the largest samples planned for testing are essentially equivalent in volume to the average block size in unit TSw2. No size extrapolation of intact rock properties is necessary; however, these properties are combined with the fracture properties in models for extrapolation to repository-size rock mass behavior. The primary model of the mechanical behavior of the rock mass presently being used is a compliant joint model. This model has been described by Chen (1987). The intact rock is modeled as a linear-elastic material. The Chen model can handle multiple joint sets and includes elastic-plastic joint shear behavior. (For a more detailed discussion of the repository modeling effort, see SCP Section 8.3.2.1.4.)

### 2.5.6 Time Required versus Time Available

After rock has been collected from the ESF or core, samples will be machined and the experiments will be run as efficiently as possible. The resulting data will then be integrated into project activities needing the information. The only time constraints imposed on these experiments are the license application timetable and those associated with supporting the *in situ* tests.

### 2.5.7 Statistical Relevance

Every effort is being made to insure the experiments planned in this study will provide a statistically valid data base. The number of experiments at each set of conditions should provide enough data to determine the range and reduce the uncertainty of each key parameter over a specific confidence interval. In addition, enough sample locations in the new drillholes and the ESF have been selected so the resulting data should allow for a statistically sound characterization of the lateral and vertical variability of the mechanical properties. However, following collection of these initial data, an analysis will be performed to determine whether these assumptions were valid and, if necessary, additional data should be collected.

### 2.5.8 Interrelationships of Experiments with Other Similar Activities

Some of the laboratory mechanical testing will be performed in support of the field tests planned for the ESF. These laboratory experiments will be run prior to or concurrently with the *in situ* tests planned in Study Plans 8.3.1.15.1.5 (*Excavation Investigations*), 8.3.1.15.1.6 (*In Situ Thermomechanical Properties*), 8.3.1.15.1.7 (*In Situ Mechanical Properties*), and 8.3.1.15.2.1 (*Characterization of Site Ambient Stress Conditions*). Figure 1 illustrates the flow of information to these other studies and to the resolution of specific regulatory issues.

Additional mechanical experiments on intact rock have been described in Study Plan 8.3.4.2.4.3 *Mechanical Attributes of the Waste Package Environment*). This plan is concentrating on the near-field response of the rock mass to the effects of the waste containers.

### 2.5.9 Interrelationships of Experiments with ESF Construction Activities

The only impact on the ESF construction activities are the collection of samples from the ribs of the ramps and drifts. The removal of the necessary samples should not impact ESF progress.

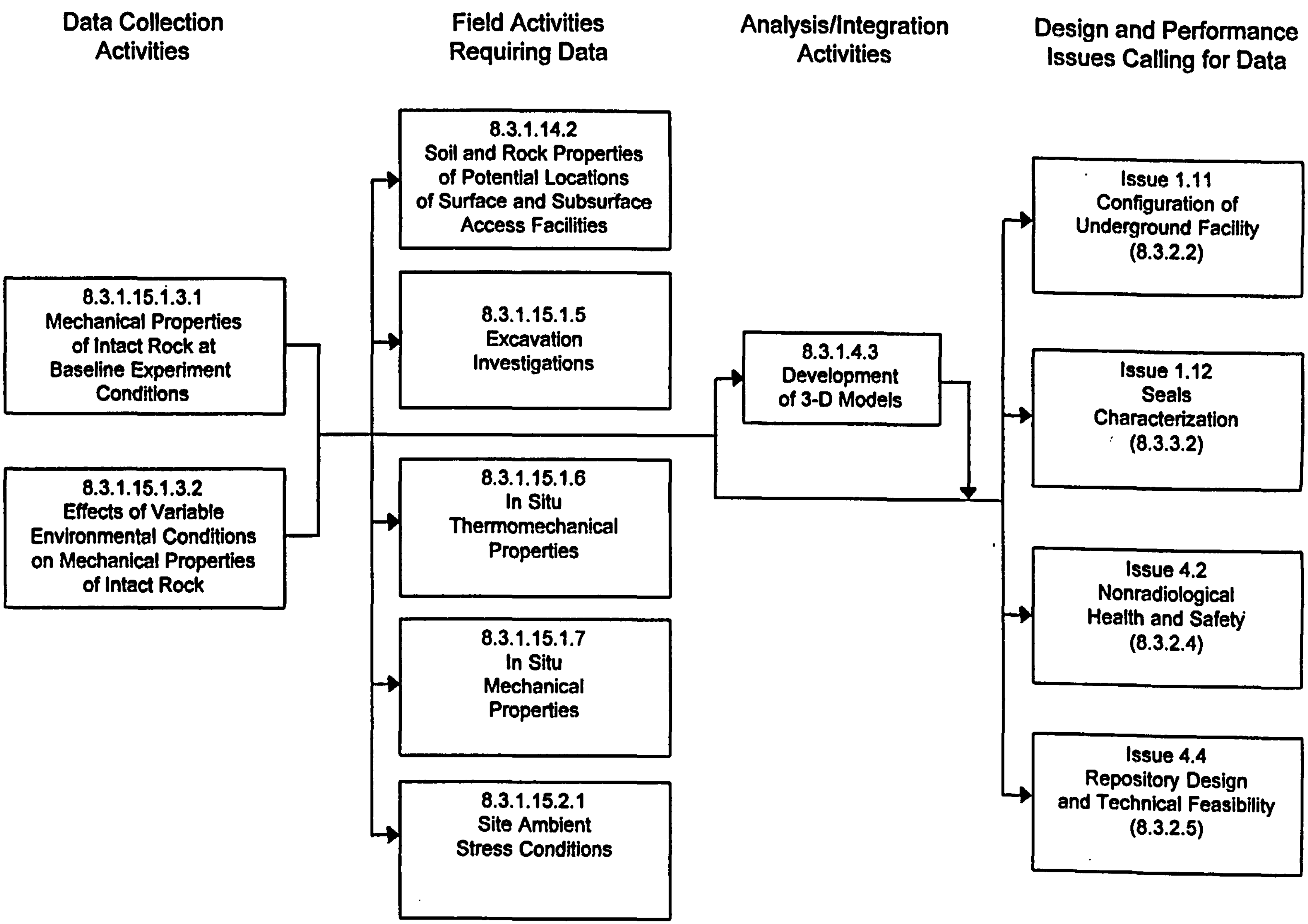


Figure 1.
Information required from Study 8.3.1.15.1.3 for other studies and issue resolution.

# 3.0 Description of Experiments, Data, and Analyses

## 3.1 General Experiment Types

The compressive mechanical properties of the tuffs will be measured in the laboratory using experiments on right-circular, cylindrical samples. These tests will be run under uniaxial (unconfined) and triaxial pressure conditions. Direct-pull or indirect (Brazilian) experiments will be performed to determine the tensile strength of the tuffs.

The differential stress will be applied, by increasing (for compression) or decreasing (for tension) the axial strain (where compressive strains are positive) at a constant rate. In the creep experiments, the differential stress will be applied at a relatively fast rate and then held constant while the strains are monitored.

## 3.2 General Experiment Procedures

Implementation of work for this study will be done using either Technical Procedures (TPs) or Scientific Notebooks. The time involved in preparation of the TPs for a given task will depend on the complexity of the task and on whether similar procedures have been written previously. When available for a specific task, nationally recognized procedures (e.g., ASTM and ISRM) will be used instead of TPs or consulted when TPs are developed.

The following pages provide an overview of the procedures for which details will be described in the appropriate documents for each series of experiments.

### 3.2.1 Sample Preparation

Following sample machining and before testing, the samples will be treated in one of two ways, depending on the defined experimental conditions.

The samples to be tested dry will be placed in an oven and slowly heated to 105°C, held at temperature for at least 120 hours, cooled in the oven, removed, and weighed. They then will be subjected to as many additional drying cycles, including heating to 105°C for 24 to 36 hours followed by cooling and weighing, as necessary to meet a constant-weight-change criterion for a dry sample.

The samples to be tested saturated will be submerged in water (to avoid any concerns over chemical impurities, either distilled or Yucca Mountain ground water will be used in these experiments) and subjected to three or more saturation cycles, each of which will include at least 18 hours under an active vacuum followed by submersion for six hours at ambient pressure. After each saturation cycle the samples will be weighed. The sequence of cycles will continue until a constant-weight-change criterion for saturated samples is met.

After these preparations, the dry samples will be kept in an air-tight container with desiccant and the saturated samples will remain submerged until they are removed for testing.

### 3.2.2 Data Acquisition

Prior to testing, the data-acquisition system will be set-up and initialized. The electronic signals from the load, displacement, pressure, and temperature measuring devices can be stored as analog or digital signals. If the data are digitally recorded, they will be taken at intervals sufficiently short to completely define the detailed nature of the differential stress/axial strain and lateral strain/axial strain curves. The complete curve description from digital data can be accomplished either by taking data at very short time intervals (<<1s) or by taking data at defined increments of some or all of the variables (i.e., time, axial load, axial displacement, lateral displacement, and pressure). The latter technique is preferable because the technique provides sufficient data to define the linear elastic portions of the curves (dense data at very short time intervals would be superfluous) and from sample yield to failure the data is taken much more rapidly to accurately define the curves.

### 3.2.3 Experiment Equipment

In performing laboratory rock mechanics experiments, there are five classes of essential components. They are as follows: (1) a load frame, (2) a load actuator, (3) environmental simulators, (4) measurement devices, and (5) a data-acquisition system. There is a wide diversity of satisfactory options for each of these machine and instrument categories. Each rock mechanics laboratory has a different combination of equipment. A few of the options are discussed below.

**Load Frame:** The load frame is designed to support the load on a sample with minimum elastic distortion. The design capacity of a frame is typically two to three times the operating (or working) load. Load frames are designed and built by highly skilled and experienced rock mechanicians for their own use, but are typically purchased from companies specializing in the manufacture of such machines.

**Load Actuator:** The equipment attached to the load frame that generates the applied load is the load actuator. This can be accomplished by a hydraulic cylinder, release of compressed gas, or a motor and gear set.

**Environmental Simulators:** Confining pressure is applied to the sample in a variety of ways. Test pressures are produced by solid, liquid, or gas confining mediums inside of a metal (usually steel) sleeve (called a pressure vessel) designed to contain pressures much larger in magnitude than the maximum operating pressure. Typically the sample is separated from the confining medium by a jacket. Common jacketing materials are polyolefin, neoprene, viton, lead, and thin-walled copper. Liquid (commonly silicone) systems are the most popular; however, solid and gas apparatuses are useful in many situations. Solid medium (usually salt or some other ductile material) devices are commonly used at very high confining pressures (i.e., greater than approximately 1 GPa). Gas medium (usually argon or some other inert gas) devices are often used for experiments at higher temperatures (250-500°C). When confining pressure is applied with inert gas, an internal heater can be used for the application and control of elevated temperature around a sample. In this way, the pressure vessel is not subjected to the very high, potentially destructive, temperatures.

Pore pressure is injected into a sample with water. The water accesses the sample through a small (~1 to 2 mm) hole in one or both of the sample assembly end caps, and is isolated from the confining pressure fluid by a sealed jacket around the sample, as discussed above.

There are two basic systems for creating temperature environments around a confined sample. For temperatures below 250-500° C, resistive-type heaters are usually attached to the outer surface of the pressure vessel, and the vessel, parts of the loading column, and the sample assembly are heated to the desired temperature. This technique provides a large thermal mass for temperature stability throughout the experiment. Higher temperatures can cause damage to the steel pressure vessel, so in these situations a furnace is constructed to fit around the sample and inside the vessel walls. The heat is directed toward the sample, and in this way only the sample and accompanying end pieces (usually a material with a high moduli/strength and low thermal conductivity) are heated to the extreme temperature conditions.

In an unconfined test at elevated temperature, a sample can be heated by using one of the confined systems (above) or a temperature-control chamber. This last device has no pressure capability, but is thermally insulated and able to apply precise, very stable temperatures.

**Measurement Devices:** Several important parameters are necessary for interpretation of the mechanical properties of a test sample. At a minimum, axial stress, axial strain, lateral strain, pressure, and temperature data are collected (relative to a common time base) throughout the experiment. The types of devices used for measuring these parameters are discussed in Section 3.3.1.

**Data Acquisition:** Most data acquisition is performed electronically. The data can be collected in either analog or digital format. Both strip-chart and X-Y recorders are used to collect analog data, while amplified signals from the measurement devices can be transformed in an analog-to-digital (A/D) converter and stored in a computer-based system.

### 3.2.4 Experiment Procedure

For unconfined, room-temperature experiments, the axial and transverse displacement transducers are mounted on the sample (if applicable), the sample is placed in the loading column between end caps with diameters identical to the sample, the data-aquisition program is initiated, and the experiment is begun.

Samples to be tested at elevated pressure are jacketed (see Section 3.2.3 for a discussion of jacketing material) and the jacket sealed to the end caps. The displacement gages then are mounted and/or initialized, and the sample assembly is placed in the loading column inside the pressure vessel. For the room-temperature, confined tests, the confining pressure is raised and allowed to equilibrate prior to testing. Fully saturated samples tested at elevated temperatures are initially subjected to confining and pore pressures ($P_c$ and $P_p$, respectively) high enough to ensure the water in the sample remains in a liquid state at the elevated temperature. In all cases when the samples are fully saturated, an effective confining pressure ($P_e = P_c - P_p$) of at least 0.2 MPa is maintained to preserve the integrity of the jacket so water is not allowed to invade the confining pressure system. Next, the temperature is raised slowly ($\leq 0.02°C/s$) and is allowed to equilibrate, at which time the test is begun for the effectively unconfined experiments, or the confining pressure is raised to produce the desired effective pressure level before testing.

## 3.3 Measured and Calculated Parameters

### 3.3.1 Experiment Data

Data to be determined directly from the laboratory mechanical experiments will include differential stress, axial strain, lateral strain, confining and pore pressures, and temperature. These data will be either measured directly or calculated from other measurements, but always will be obtained with the same time base.

Axial stress ($\sigma_{ax}$) is macroscopically equivalent to the greatest principal stress ($\sigma_1$) in triaxial compression experiments and the least principal stress ($\sigma_3$) in triaxial extension and tension experiments. Axial stress is calculated by dividing the axial load, measured on a standard load cell (i.e., a hollow-cylinder steel sample with strain gages wired in a full-bridge configuration), by the cross-sectional area of the rock sample. Engineering stress results from using the original cross-sectional area of the sample, while 'true' stress is obtained by using the actual area at the time the load is measured. Comparing the two techniques, if the lateral strain at failure is 0.01 (an extreme-case condition for welded tuff) the difference in stress for the two methods is about 2%. For this reason, and for ease of calculation, engineering stress is commonly used for brittle rock.

Axial strain ($\varepsilon_{ax}$) is macroscopically equivalent to the greatest principal strain ($\varepsilon_1$) in triaxial compression experiments and the least principal strain ($\varepsilon_3$) in triaxial extension and tension experiments. Axial strain can be measured directly with strain gages mounted onto either a sample or a jacket surrounding the sample. Generally, these methods are good only on low porosity, homogeneous rocks. Axial strain can also be calculated from displacement measurements and the measurement gage length. The displacements can be measured over a partial length of the sample, over the entire sample length and part of the endcaps, or along the load column remotely to the sample. The first method (i.e., measuring displacements over a partial sample length) is preferable because the latter two include deformations of other materials and of interfaces within the loading column. The relationship between the 'machine' (or non-sample) displacements and load needs to be determined prior to testing so the sample displacements can be calculated by subtracting the machine displacements from the measured displacements. In the first method, the measured displacements are divided by the gage length; in the second and third methods, the net sample displacements are divided by the entire sample length.

Strain, as with stress, can be calculated in one of two ways. Engineering strain (or elongation) is the displacement divided by the original gage or sample length, and natural (or logarithmic or true) strain is the strain accumulated by increments of displacement divided by the gage or sample length during a specific increment of deformation. For low porosity, brittle materials, the two methods are very similar (e.g., at 2% axial shortening the difference in strain calculated from the two methods is ~1%). As with stress, engineering strain is commonly used for brittle rock.

Lateral strain ($\varepsilon_{lat}$) is macroscopically equivalent to the medium and least principal strains ($\varepsilon_2 = \varepsilon_3$) in triaxial experiments. As with axial strain, lateral strain ($\varepsilon_{lat}$) can be measured directly with strain gages on the sample or jacket. Other methods of measuring lateral strain include: (1) dividing measured lateral displacements by the sample diameter, (2) dividing measured circumferential displacements by the sample circumference, or (3) measuring confining pressure fluid volume change and calculating lateral strain from the known axial and volume strains. As with axial strain, either engineering or natural strain can be calculated, but again, the difference in the two methods is very slight for brittle materials.

Electronically recorded pressure is typically measured by a standard transducer. Real-time pressure, for a visual check by the experimenter, is commonly measured on a Bourdon-tube type gage.

Temperature is usually measured at the weld-junction of a two-metal (e.g., chromel-alumel, chromel-constantan, copper-constantan) thermocouple. The thermocouple weld-junction is commonly positioned on the outside surface of the pressure vessel, in a shallow hole in the side of the vessel, at a sample/end cap interface in a small hole in the end cap, or at the surface of the sample.

### 3.3.2 Key Parameters

Differential stress, axial strain, lateral strain, and effective pressure data are used to calculate the key mechanical property parameters: Young's modulus, Poisson's ratio, unconfined compressive strength, unconfined tensile strength, cohesion, and angle of internal friction.

Young's modulus (E) and Poisson's ratio ($\nu$) will be determined from the slopes of linear regression fits to the differential stress/axial strain and lateral strain/axial strain data, respectively. In both of these cases, the fits will be obtained using only those data corresponding to stress states from 10 to 50% of the ultimate strength of the particular test sample. This range of stresses is defined to avoid low stress data which could include some minor pore collapse and/or imperfections on the interfaces within the loading column. In addition, the yield strength of tuff is typically (i.e., at all repository simulated conditions) much higher than 50% of the ultimate strength. Although in all cases, the elastic moduli will be calculated using data from this specific range of stresses, the entire stress/strain record for each experiment will be saved and available for potential future interpretations.

Unconfined compressive strength ($C_0$) and unconfined tensile strength ($T_0$) are each defined as the peak value of differential stress a sample withstands when tested at the compressive or tensile baseline experimental conditions.

The ultimate differential stress ($\Delta\sigma_u$) versus effective confining pressure ($P_e$) data are fit by linear regression and then transformed into shear stress ($\tau$)/normal stress ($\sigma_n$) space for calculation of the Coulomb failure criterion values in the same manner as described by Jaeger and Cook (1976). The Coulomb equation is as follows:

$$\tau = \tau_0 + \sigma_n(\tan\phi), \tag{1}$$

where $\tau$ is shear stress, $\tau_0$ is cohesion, $\sigma_n$ is normal stress, and $\phi$ is the angle of internal friction.

## 3.4 Range of Expected Results

Several existing laboratory studies on the mechanical properties of intact samples of the Topopah Spring Member have produced data from over 250 experiments (Blacic et al., 1982; Morrow and Byerlee, 1984; Nimick et al., 1985; Nimick, VanBuskirk, and McFarland, 1987; Olsson and Jones, 1980; Price, 1983 and 1986; Price, Nimick, and Zirzow, 1982; Price, Spence, and Jones, 1984; Price et al., 1985; Price, Connolly, and Keil, 1987; Price et al., 1991; Martin et al., 1991; Haupt et al., 1992; Martin et al., 1992; Price, Martin, and Boyd, 1993). In addition, other investigations have tested intact samples of other silicic tuff from Yucca Mountain (Blacic et al., 1982; Olsson, 1982; Olsson and Jones, 1980; Price and Jones, 1982; Price and Nimick, 1982; Price, Jones, and Nimick, 1982; Senseny and Parrish, 1981). These studies have provided a useful data base and guide for defining future studies.

The Young's modulus ($E$), Poisson's ratio ($\nu$), unconfined compressive strength ($C_0$), unconfined tensile strength ($T_0$), cohesion, and angle of internal friction data from the above-mentioned studies have shown wide ranges of results in these parameters. To illustrate this point, the mean, standard deviation, and number of experiments for each of these parameters resulting from testing of small (25.4 mm diameter), TSw2 samples at the baseline conditions are presented in Table 4.

**Table 4.**

Statistical Summary of TSw2 Mechanical Property Data

| Parameter | Units | Number of Tests | Mean | Standard Dev. |
|---|---|---|---|---|
| $E$ | GPa | 53 | 30.4 | 6.3 |
| $\nu$ | - | 28 | 0.24 | 0.06 |
| $C_0$ | MPa | 53 | 162.8 | 65.2 |
| $T_0$ | MPa | 15 | 15.2 | NA |

NA: Not Available

The Yucca Mountain samples used in the previous studies were from five drillholes (UE-25a#1, USW G-1, USW G-2, USW GU-3, and USW G-4) and an outcrop on the southeast flank of Busted Butte (just to the southeast of the southern end of Yucca Mountain). Also, the samples were taken from a variety of depths within each drillhole and from two stratigraphic horizons in the outcrop. As a result, the ranges, means, and standard deviations resulting from these studies are interpreted to be generally representative for the sample size and test conditions used, and will probably not change significantly as a result of the additional experiments planned by this study. What may change as a result of the plans described here are the magnitudes of the confidence intervals, which are expected to decrease when the much larger data sets planned by this study are available at each set of conditions.

## 3.5 Previous Analyses

As mentioned above in Section 3.4, many studies have already been completed on silicic tuffs from Yucca Mountain. The results from these investigations will be used as supportive data to the characterization data to be collected from the experiments proposed by this study. In addition, these results have served as a guide to the appropriate experiment techniques, expected range of results, and the general relationships between the mechanical properties and the independent parameters (i.e., experimental conditions and physical features).

### 3.5.1 Variability of Results: Physical Sample Differences

**Lateral and Vertical Variability:** Tuffaceous rocks are, in general, heterogenous in their mineralogy, texture, and porosity. The tuffs of Yucca Mountain vary widely in degree of welding (usually directly related to porosity), vitric (glassy) content, and zeolitization. Variability in these physical characteristics can produce large variations in the mechanical properties obtained from samples of these rock types (e.g., see Price et al., 1992; Price, Martin, and Boyd, 1993). The large standard deviations in the values of the key parameters for samples of the Topopah Spring Member (Table 4) result from variable physical characteristics. However, some key empirical relationships between these physical characteristics and the mechanical properties have been developed. In addition, the heterogeneity of the tuff (and the resulting scatter in the mechanical property data) has prompted the planning of a greater number of experiments (see Section 2.4) than had previously been run at each set of conditions (which was typically 2, 3, or 4 experiments). The expanded number of experiments will increase confidence in the results by decreasing uncertainty in the general representativeness of the measured values.

Empirical relationships of Young's modulus versus functional porosity and ultimate strength versus functional porosity for samples of Yucca Mountain silicic tuffs have been developed from existing data (including data from all seven units to be tested under this study plan). The detailed discussion of the development of these relationships can be found in Price and Bauer (1985) and is summarized in the following paragraphs.

Price and Bauer (1985) analyzed the results from more than 100 experiments on 25.4 mm diameter, saturated samples deformed in compression at atmospheric pressure, room temperature, and a constant axial strain rate of $10^{-5}\,s^{-1}$. As a result, the Young's modulus/functional porosity data were best fit by a simple exponential expression and the ultimate strength/functional porosity data were best fit by a power-law model. These tuffaceous test specimens ranged in porosity from 0.09 to 0.39 and in functional porosity from 0.10 to 0.41, with one additional Yucca Mountain tuff sample having a porosity and functional porosity of 0.54 and 0.64, respectively.

The exponential relationship found by Price and Bauer (1985) to best fit the Young's modulus/functional porosity data (for the experiments discussed above) is as follows:

$$E = 86.\, e^{-7.0n}, \tag{2}$$

where E is Young's modulus (GPa) and n is functional porosity (volume fraction). The correlation coefficient (R) is 0.93 for the linear fit in (ln E) versus n space, which resulted in the above model.

Price and Bauer (1985) also determined the relationship best describing the trend of the unconfined compressive strength versus functional porosity data (for the experimental conditions described above) is a power-law. The general expression is the same as Dunn et al. (1973) found for sandstone and similar to the equation Kowalski (1966) fit to his limestone data. Other studies, however, have developed somewhat different expressions for a range of rock types (for a complete review of studies involving the relationship between strength and porosity see Friedman, 1976). Price and Bauer's fit to the large data set is as follows:

$$\sigma_u = 4.0\,n^{-1.9}, \tag{3}$$

where $\sigma_u$ is ultimate stress (MPa) and n is functional porosity (volume fraction). The curve is an excellent fit to the data trend (the correlation coefficient, R, is 0.93 for the linear fit in [$\ln \sigma_u$] versus [$\ln n$] space); however, because the model predicts infinite strength at zero porosity, it must be considered invalid at some functional porosity value less than 0.10 (the minimum value for any of the samples modeled).

General, but less distinct, inverse relationships have also been observed for unconfined tensile strength, cohesion, and angle of internal friction versus porosity or functional porosity (e.g., Price, 1983). The Poisson's ratio data collected to date, however, have been widely scattered and apparently independent of functional porosity (Price, 1983).

**Sample Size:** To investigate the influence of sample size on elastic moduli and strength, Price (1986) ran 34 unconfined compression experiments on intact samples of the Topopah Spring Member (TSw2) from an outcrop on Busted Butte. The samples ranged in diameter from 25.4 to 228.6 mm, and all had a length-to-diameter ratio of 2:1. The experiments were performed on water-saturated samples at room temperature and a nominal strain rate of $10^{-5}$ $s^{-1}$.

Data on Young's modulus and Poisson's ratio as a function of sample diameter do not reveal a distinct trend in elastic properties with changing sample size (Price, 1986). In general, the Young's modulus and Poisson's ratio data appear to be independent of sample size. This same result also has been observed for other rock types (e.g., Lama and Vutukuri, 1978, p. 62).

Experimental investigations on rocks deformed in compression have produced a range of strength/sample size relationships (for general reviews see Vutukuri, Lama, and Saluja, 1975, p.38, or Paterson, 1978, p.33). These various behaviors are the result of many factors, including rock type (i.e., porosity, grain size, inhomogeneity size, isotropy, etc.), range of sample sizes tested, sample shape, sample length-to-width ratio, and test conditions. A majority of the previous experimental studies, however, have indicated an inverse strength/size relationship, and this trend was found to be true in Price's investigation. Specifically, in many of the cases where strength and sample size were inversely related, the data were fit well with a simple power-law. Price found:

$$\sigma_u = 5.6\, D^{-0.85} + 70., \tag{4}$$

where $\sigma_u$ is ultimate strength (MPa) and D is sample diameter (m).

### 3.5.2 Variability of Results: Differences in Environmental Conditions

Although the occurrence of inhomogeneities (e.g., small healed fractures, open and closed lithophysae, and small pumice and lithic fragments) and the volume of functional porosity in the test sample are the primary factors in determining the scatter and trend, respectively, of mechanical properties of the intact tuff, changes in saturation, confining and pore pressure, temperature, and deformation rate have also been shown to produce characteristic variations in the properties. Many of these preliminary results summarized below are inconclusive, but should be better understood with the results from the much larger data sets planned by this study.

**Saturation Effects:** One study (Haupt et al., 1992) showed a slight difference in elastic properties with different saturation conditions. However, no distinct trends have been observed in the Young's modulus and Poisson's ratio data relative to extreme saturation changes from dry to saturated (and drained).

The strength/saturation results have been neither consistent nor conclusive. In general, the saturated samples tested were weaker than the dry samples, with observed strength decreases ranging from 15 to 30% effect (Price and Jones, 1982; Price, Connolly, and Keil, 1987). This water-weakening effect is what has been found in most mechanical property studies on silicic rocks (e.g., Griggs, 1967) and previously noted for another Nevada tuff (Olsson and Jones, 1980).

**Pressure Effects:** The small number of data at confining pressures up to 20 MPa seem to indicate Young's modulus and Poisson's ratio are independent of changes in pressure.

The ultimate strength/effective confining pressure results obtained to date are inconclusive because of small data sets, data scatter, and the low correlation coefficients obtained in the $\Delta\sigma_u/P_e$ fits. In general, however, the parameters are directly related for the following Yucca Mountain units: TCw (Olsson and Jones, 1980), TSw2 (Nimick et al., 1985; Nimick, VanBuskirk, and McFarland, 1987; Olsson and Jones, 1980; Price, Nimick, and Zirzow, 1982), CHnl (Price and Jones, 1982), and BFw (Bullfrog Member of the Crater Flat Tuff) (Olsson, 1982).

**Temperature Effects:** Young's modulus decreases with increasing temperature. Over the range of temperatures from 22 to 150°C, an average decrease of 5 to 15% in Young's modulus is observed for samples of TSw2.

In general, the mean ultimate strength of TSw2 samples decreases approximately 15% resulting from increasing the temperature from 22 to 150°C. This result has been observed at both 0 and 5 MPa effective confining pressures (Price, Connolly, and Keil, 1987).

**Strain Rate Effects:** In the studies of Yucca Mountain tuffs, Young's modulus and Poisson's ratio have been shown, in general, to be independent of rate over the range from $10^{-7}$ to $10^{-3}$ $s^{-1}$.

Again, the trends in the strength/rate data have been inconsistent. Most published results on rock, including most of the data from Yucca Mountain tuffs (Olsson and Jones, 1980; Price and Jones, 1982; Price and Nimick, 1982; Price, Nimick, and Zirzow, 1982; Nimick et al., 1985; Nimick, VanBuskirk, and McFarland, 1987; Price et al., 1992), have shown a direct relationship between ultimate strength and strain rate (i.e., when rate increases, strength increases). A few sets of data have shown the reverse effect (Price, Connolly, and Keil, 1987); however, this result is undoubtedly due to sample variability instead of an actual behavioral response.

**Anisotropy:** The assumption of isotropy has been tested in several experimental studies; however, the results have been ambiguous. The data from some studies have shown distinct anisotropy (Olsson and Jones, 1980; Price et al., 1991; Martin et al., 1992), but one study concluded no anisotropy (Price, Spence, and Jones, 1984) in the elastic properties of welded tuff. As a result, conclusions about anisotropy are preliminary.

## 3.6 Planned Range of Experimental Conditions

The investigation of the laboratory mechanical properties of intact rock will be divided into two main activities: (1) experiments at a set of baseline conditions and (2) experiments at a variety of sample sizes and environmental conditions. These general work areas will be described, followed by discussions of more specific investigations planned.

### 3.6.1 Compression Experiments: Baseline Conditions

The baseline conditions have been defined in Section 8.3.1.15.1 of the SCP for the Yucca Mountain site. For each experiment at baseline conditions, a saturated, right-circular cylinder with a diameter of 50.8 mm and a length-to-diameter ratio of 2:1 will be deformed in compression at atmospheric confining and pore pressure, room temperature, and a constant axial strain rate of $10^{-5}$ $s^{-1}$. All baseline experiments will be run drained (i.e., the pore fluids allowed to vent through a hole in at least one of the end caps). The pore pressure in these experiments is assumed to be the same as atmospheric pressure (or about 0.1 MPa).

Samples from various horizontal and vertical sections of the Yucca Mountain tuffs around the proposed repository will be statistically analyzed for the variability of the mechanical properties with location. These variations are the result of naturally occurring mineralogic, texture, and porosity changes throughout the tuff units. The sampling strategy for these experiments is discussed in Section 2.4.

### 3.6.2 Parametric Studies Experiments

Other experimental series will investigate the effects of changes in the test conditions from baseline. With the exception of the sample size and lithophysal studies, these experiments will be performed on right-circular cylinder samples with nominal diameters of 50.8 mm. A set of 10 samples will be tested at each unique set of experiment conditions (i.e., saturation, confining pressure, pore pressure, temperature, axial strain rate or creep stress, sample size, sample orientation, sample geometry, and tension). All of the major test series will be discussed in the following paragraphs. Each section is headed by a bold-faced, short title and the names of the thermal/mechanical unit(s) from which the test samples will be taken.

**Parameter Effects (TSw2):** A large number of samples will be taken from rock extracted from the potential repository horizon (TSw2) for a major series of experiments designed to investigate the effects of changes in saturation, pressure, temperature, strain rate, sample geometry, and anisotropy (the conditions to be investigated are listed in Table 5) on the elastic and strength properties. The parameter effects study will be accomplished by deviating only one condition at a time from the baseline set of conditions (discussed in the previous section). This strategy is based on the assumption that the parameter effects are independent of each other. If the failure mechanisms do not change, the assumption of independence is probably valid. There are, however, some planned exceptions to this philosophy; furthermore, the validity of the basic assumption will be continuously questioned as data is collected and analyzed.

**Table 5.**
Parameter Effects (TSw2)

| Parameter | Experimental Condition(s) |
|---|---|
| Saturation: | Dry, Water Saturated |
| Confining Pressure: | 0.1, 5, 10, 15, 25 MPa |
| Pore Pressure: | 0.1, 5 MPa |
| Temperature: | 22 to 250°C |
| Strain Rate: | $10^{-9}$, $10^{-7}$, $10^{-5}$, $10^{-3}s^{-1}$ |
| Diameter: | 25, 50, 85, 130, 205, 305 mm |
| Length-to-Diameter Ratio: | 2:1, 2.5:1, 3:1 |
| Anisotropy: | 0, 45, 90°* |

*: Orientation relative to normal to fabric (vertical, if fabric not apparent).

Saturation effects will be studied at room dry conditions and at the two extreme conditions of dry and saturated. A large series of experiments at specific intermediate saturation conditions other than room dry are not planned, because a uniform intermediate state of saturation is very difficult to achieve and maintain within a sample. Furthermore, it is even more difficult to reproduce the same state in additional samples for statistical studies.

Effective confining pressures will range from 0 to 25 MPa, confining pressures from 0.1 to 25 MPa, and pore pressures from 0.1 to 5.0 MPa. Investigations over the ranges of temperature from room temperature (~22°C) to 250°C and strain rate from $10^{-9}$ to $10^{-3}$ $s^{-1}$ will also be included.

To study the effects of sample size, the sample diameters will be varied from 25 to 305 mm. The results will be compared to the earlier study (Price, 1986) on TSw2 samples from an outcrop on the southeast flank of Busted Butte. Since Price's data (1986) showed the strength decrease with increasing sample size leveling off at the largest sample diameter (230 mm) for which data were obtained, it is assumed that testing of samples up to more than 30% larger should be adequate to assess the validity of the apparent asymptotic trend. In addition, because of the inherent block sizes of the rock *in situ* (Section 2.5.3), obtaining larger size samples would be very difficult.

Most of the near- and far-field modeling is being performed under the assumption tuffs are mechanically isotropic. However, if the tuff is elastically anisotropic, then the *in situ* stresses calculated using an isotropic model could be significantly distorted. As discussed earlier, the assumption of isotropy has been tested in two experimental studies, with ambiguous results. Therefore, a set of experiments has been planned to answer this specific question in samples of the repository unit. In addition to static mechanical experiments, wave velocity measurements will aid in the evaluation of elastic properties anisotropy.

All experiments to date have been and all experiments planned by this study (excluding the test series described in this paragraph) will be run on samples with a nominal length-to-diameter (L:D) ratio of 2:1. Lama and Vutukuri (1978) conclude from several studies by other investigators that the elastic moduli of rock are not significantly affected by changes in L:D ratios between 1:1 and 3:1. Many studies, however, have shown distinct effects in ultimate strength over the same range of L:D ratios; however, most of the effect occurs on L:D ratios less than 2:1. (For a discussion, see Vutukuri, Lama, and Saluja, 1975, p.33.) In reviewing several studies, Paterson (1978) points out these results are better understood in the light of theoretical studies demonstrating the important role end effects can play. As a result of some concerns with using samples with an L:D ratio of 2:1, this study will include testing of samples ranging between 2:1 and 3:1. These experiments will be run as early in the testing sequence as possible to determine whether or not the assumptions leading to the decision to use 2:1 samples were valid. The conclusions drawn from this study will be considered along with the impact on cost and other project studies if the L:D ratio was increased (and, therefore, the sample volume needs were increased).

**Creep (TSw2):** Creep (constant stress) experiments will be run on samples of TSw2 at temperatures up to 250°C (Table 6). The duration of these tests will be approximately 2 months. These experiments will be run in conjunction with experiments at the lowest practical laboratory strain rates ($10^{-9}$ $s^{-1}$) to study the time-dependent (or rate-dependent) deformation of intact samples of the TSw2 unit. If the results from this study indicate time-dependent deformation may be significant under repository-type conditions, then additional testing will be planned to investigate the behavior in more detail.

**Table 6.**
Creep (TSw2)

| Parameter | Experimental Condition |
|---|---|
| Saturation: | Water Saturated |
| Confining Pressure: | 5 MPa |
| Pore Pressure: | 4.5 MPa |
| Temperature: | 22 to 250°C |
| Creep Stress: | ≤150 MPa |
| Diameter: | 50 mm |
| Length-to-Diameter Ratio: | 2:1 |
| Anisotropy: | 0°* |

*: Orientation relative to normal to fabric (vertical, if fabric not apparent).

**Table 7.**
Lithophysae (TSw1)

| Parameter | Experimental Condition |
|---|---|
| Saturation: | Water Saturated |
| Confining Pressure: | 0.1 MPa |
| Pore Pressure: | 0.1 MPa |
| Temperature: | 22°C |
| Strain Rate: | $10^{-5}s^{-1}$ |
| Diameter: | 380 mm |
| Length-to-Diameter Ratio: | 2:1 |
| Anisotropy: | 0°* |

*: Orientation relative to normal to fabric (vertical, if fabric not apparent).

**Lithophysae (TSw1):** Several large samples (~380 mm in diameter) will be collected from the lithophysal-rich zone of the Topopah Spring Member (TSw1). These will be used to investigate the effects of the large (sometimes larger than 50 mm in length) lithophysal cavities on the mechanical properties of the welded TSw1 tuff; the planned experiment conditions are listed in Table 7. The results will be compared to an earlier study on TSw1 samples (Price et al., 1985).

**Pressure (TCw, PTn, TSw1):** To study pressure effects on sample failure, a series of experiments will be performed at confining pressures up to 25 MPa (Table 8) for each of three thermal/mechanical units above the repository horizon. The results from these experiments will be used to calculate Coulomb failure criterion parameters for these units.

**Table 8.**

Pressure (TCw, PTn, TSw1)

| Parameter | Experimental Condition(s) |
|---|---|
| Saturation: | Water Saturated |
| Confining Pressure: | 0.1, 5, 10, 15, 25 MPa |
| Pore Pressure: | 0.1 MPa |
| Temperature: | 22°C |
| Strain Rate: | $10^{-5}s^{-1}$ |
| Diameter: | 50 mm |
| Length-to-Diameter Ratio: | 2:1 |
| Anisotropy: | 0°* |

*: Orientation relative to normal to fabric (vertical, if fabric not apparent).

**Table 9.**

Tension (TSw2)

| Parameter | Experimental Condition |
|---|---|
| Saturation: | Water Saturated |
| Confining Pressure: | 0.1 MPa |
| Pore Pressure: | 0.1 MPa |
| Temperature: | 22°C |
| Strain Rate: | $10^{-5}s^{-1}$ |
| Diameter: | 50 mm |
| Length-to-Diameter Ratio: | 2:1 |
| Anisotropy: | 0°* |

*: Orientation relative to normal to fabric (vertical, if fabric not apparent).

**Tension (TSw2):** For each of 10 experiments a saturated sample with a diameter of 50.8 mm will be deformed in tension at atmospheric confining pressure, room temperature, and a constant axial strain rate of ($10^{-5}$ $s^{-1}$) (Table 9).

**Radiation (TSw2):** Intact rock samples will be irradiated and tested under a separate study (Study Plan 8.3.4.2.4.3, entitled "Mechanical Attributes of the Waste Package Environment").

**Support of *In Situ* Experiments:** Several *in situ* mechanical experiments will be performed in the ESF. To aid in the interpretation of the results from these *in situ* experiments, some laboratory mechanical experiments will be run in compression and tension on samples of rock adjacent to each *in situ* experiment. Descriptions of the required laboratory experiments will be presented in the study plans associated with the specific *in situ* experiments (see Section 2.5.8).

### 3.6.3 Rock Property Support Studies

Selected samples of the tuffs will be analyzed by standard x-ray diffraction, electron microprobe, and microscopy techniques to determine their petrology, mineralogy, and petrography. These data will be collected primarily to address three questions.

1. To measure the volume fraction of montmorillonite in a sample, for inclusion with the pore volume fraction in calculating the functional porosity of the rock.

2. To determine if a significant mineralogic or textural variation exists either vertically or laterally in a particular thermal/mechanical stratigraphic unit.

3. To examine some post-test samples for identification of potential deformation-induced mechanisms (e.g., microfracturing and grain boundary sliding) and for indications that the transformations of $SiO_2$ polymorphs have been significant at the lower-rate, higher-temperature experimental conditions.

The normal and shear ultrasonic wave velocities on other selected tuff samples will be measured by standard techniques. These data will be collected to address the following three questions:

1. to determine the dynamic elastic properties of the rock,

2. to determine if a significant relationship exists between dynamic and static elastic properties, and

3. to estimate the anisotropy of the rock.

## 3.7 Locations of Testing Laboratories

All investigations described in this plan are the responsibility of SNL, Albuquerque, NM. When laboratories are chosen to run experiments in this study, many factors which will allow the investigators to best address the technical aspects of the work will be taken into consideration (e.g., technical abilities, cost, available equipment, personnel, and ability to meet the necessary QA requirements).

## 3.8 Quality Assurance Requirements

All of the existing laboratory rock mechanics studies mentioned in Section 3.3 either had an assigned QA level of III or no QA level.

Certain experiments designed for technique and procedure development will be conducted with less QA constraints than the activities involving the collection of data for licensing purposes. All work will be performed in accordance with the SNL Quality Assurance Program Plan and associated documents. Details of the QA plan will be included in a grading package at a future date.

## 3.9 Statistical Analysis of Data

As discussed in Section 2.5.5 of this study, no specific statistical technique has been chosen to analyze the data. The results from experiments performed for this study will be analyzed using whatever statistical techniques are deemed appropriate (e.g., those used by Nimick and Schwartz, 1987; Price, 1983 and 1986; and Price and Bauer, 1985). Some of the general methods of planned analysis are as follows:

1. Examine the nature of the statistical distribution of data resulting from samples gathered from a specific location and tested under an identical set of conditions.
2. Examine the spatial correlation of the data. This will be done to investigate vertical (along the drillholes and the ESF ramps and drifts), horizontal (drillhole to drillhole and the ESF ramps and drifts), intra-unit, and inter-unit variability.
3. When appropriate, perform correlation analysis of properties with each other (e.g., ultimate strength and functional porosity).

# 4.0 Applications of Results

Section 1.3 of this study plan discusses the manner in which the data from this study will be used to address or resolve a number of the regulatory requirements and project issues. The issue numbers are listed in Table 1. The characterization of the mechanical properties of the host rock will provide data with direct relevance to repository design activities, as well as to pre- and post-closure performance assessment.

## 4.1 Resolution of Performance and Design Issues

The primary objective of this study is to provide mechanical properties to aid in the development of near- and far-field thermomechanical repository models to meet the issue needs as stated in Section 1.3. The specific rationale for each data-need is provided in the appropriate section of the SCP. The results from the experiments defined in this plan will help to ensure an adequate design for a stable underground facility.

## 4.2 Resolution of Characterization Issues

The results from these studies will provide useful data relating to a number of other site investigations. Laboratory experiments on intact rock will be performed in conjunction with fracture properties studies in order to support thermomechanical rock-mass modeling. The results from these models will be compared to the data from *in situ* experiments in order to further our understanding of the scale effects on the geomechanical properties of the rock mass.

## 4.3 Support of Field Experiment Activities

As mentioned in Section 2.5.8, mechanical properties obtained in the laboratory will be provided to support the interpretation of data collected during *in situ* experiments.

# 5.0 Schedule and Milestones

## 5.1 Scheduling Relative to Construction and Other Studies

Most of the work under this study will be performed on a schedule that is contingent on the schedule for drillhole operations and the construction schedule for the ESF. Since all the laboratory experiments on intact rock will be performed at locations other than the Nevada Test Site, this study is dependent on the drillholes and the ESF only for obtaining samples of rock, from which the finished test specimens will be machined. This study is independent of other studies, except that some laboratory testing will be run in support of certain *in situ* experiments.

## 5.2 Milestones

There are several major milestones planned to report the progress of the work described in this study. These milestones are all planned as SAND Reports and are listed in Table 10.

**Table 10.**
Milestones

| Number | Description |
|---|---|
| M058 | Intact Mechanical Properties (ESF Samples) Data Report |
| M059 | Intact Mechanical Properties (ESF Samples) Analysis Report |
| M065 | Intact Mechanical Properties (TSw1 Samples) Data Report |
| M067 | Intact Mechanical Properties (Parametric Studies) Data Report |
| M068 | Intact Mechanical Properties (Parametric Studies) Analysis Report |
| M069 | Intact Mechanical Properties (TSw1 Samples) Analysis Report |
| T330 | Intact Mechanical Properties (Drillhole Samples) Analysis Report |
| T331 | Final Analysis Report of all Mechanical Properties Data |

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SNL-SP-8.3.1.15.1.3, R1

The following is for the Office of Civilian Radioactive Waste Management Records Management purposes only and should not be used when ordering this document:

Assession number: MOL:19950502.0003

**Enclosure 2 List of Technical Procedures**

| | |
|---|---|
| TP-51 | Preparing Cylindrical Samples, including Inspection of Dimensional and Shape Tolerances |
| TP-64 | Procedure for Vacuum Saturation of Geological Core Samples |
| TP-65 | Drying Geologic Samples to Constant Weight |
| TP-90 | Confined Compression Experiments at 250$^0$C and a Strain Rate of $10^{-8}5^{-1}$ |
| TP-91 | Unconfined Compression Experiments at 22$^0$C and a Strain Rate of $10^{-9}5^{-1}$ |
| TP-92 | Constant Stress (CREEP) Experiments at 250$^0$C |
| TP-93 | Load Cell Calibration at New England Research, Inc. |
| TP-94 | LVDT Calibration at New England Research, Inc. |
| TP-95 | Furnace and Thermocouple Calibration at New England Research, Inc. |
| TP-96 | Pressure Transducer Calibration at New England Research, Inc. |

ENCLOSURE 2

## Enclosure 3 SCA Open Item Analysis

### SCA Comment #55

The discussion and/or use of statistics in this chapter is not clear. A statistical approach has been suggested to determine numbers of tests required to determine various rock properties, but the approach suggested is confusing and apparently overlooks several considerations that should be factored into such an approach. Also, needed confidences of "low," "medium," or "high" have been assigned without explaining the basis for such assignments.

### General Statement on Comment and Response Applicability

SCA Comment #55 refers to a section in the SCP that applies to a series of four Study Plans (numbers 8.3.1.15.1.1, 8.3.1.15.1.2, 8.3.1.15.1.3 and 8.3.1.15.1.4). The following text addresses the specific response for Study Plan 8.3.1.15.1.3; however, this reply can be used as the basis for a general response for all four studies.

### Response to SCA Comment #55 - Study Plan 8.3.1.15.1.3

The original statistical approach presented is a standard method to determine the number of tests that are necessary based on knowing something about the characteristics of the data and the level of confidence needed in the results for the given application.

When this study plan was originally drafted, only a limited set of data on the mechanical properties of intact rock from Yucca Mountain existed. Furthermore, the existing data had not been collected under a fully-qualified QA Program. In addition, the needed confidences ("low" etc.) were defined in SCP Table 8.3.2.15-1 by investigators involved with the activities that called for mechanical properties. The numerical values attached to the qualitative confidences (e.g., "low" equals 75% confidence level) were specified by the same individuals. As a result, the statistical approach was adopted to meet the data needs in a defensible manner. A reasonable number of samples to be initially tested at each set of conditions was determined with the explicit understanding that the situation would be reevaluated when more data had been collected and the repository modeling concepts and efforts had been more fully developed.

However, as a result of the confusion expressed in this comment, the discussion of this statistical approach has been deleted and a more pragmatic approach has been taken. The study plan now offers a suggested number of samples per drillhole based on Project experience; however, these numbers are varied depending on the quality of the samples collected in a certain cored section of rock and on the number of these samples that are available for lab mechanical properties testing. Please see Section 2.4 for the present content.