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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).

The procedures used to prepare this document were done in accordance with SNL's requirements for Quality Level I.

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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 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 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 the data 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 (nonfractured) 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 rock are required by design and performance issues:

- Young's modulus,
- Poisson's ratio,
- Unconfined compressive 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 properties. Testing will be performed on core samples obtained from the systematic drilling program (SCP Section 8.3.1.4.3.1) and from core and rock samples collected in the exploratory shaft (ES) and exploratory shaft facility (ESF). Sufficient samples will be collected to assess the spatial variability of 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 1.2.2. 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 comprise a subpart of the data set needed to analyze the response of the tuff rock mass to repository construction and nuclear waste emplacement and permanent storage. Additional information required includes the thermal, thermomechanical, and hydrologic data for both the intact and rock mass. Development of the studies to obtain these data is also underway. The data will be used to develop constitutive relationships for deformation and failure of the rock mass and accompanying changes in the hydrologic conditions.

The proposed repository horizon (designated as TSw2 in the thermal/mechanical stratigraphy defined by Ortiz et al., 1985) is within the Topopah Spring Member of the Paintbrush Tuff. The TSw2 unit is a mass of intact blocks of welded ash-flow tuff separated by approximately planar fractures. The mechanical response of the tuff rock mass is being considered using two approaches: (1) large-scale, in situ experiments and (2) the combination of small-scale properties of the rock matrix and fractures into a rock mass model. This study plan pertains to the latter approach and describes only those tests being performed to establish the mechanical properties of the intact tuff. Characterization of the mechanical properties of fractures is described in Study Plan 8.3.1.15.1.4, entitled "Laboratory Determination of the Mechanical Properties of Fractures" (in preparation).

1.2 Rationale and Justification of Data Needs

SCP Section 8.3.1.15.1, entitled "Investigation: Studies To Provide the Required Information for Spatial Distribution of Thermal and Mechanical Properties," presents the overall approach for obtaining the required parameters for matrix (intact), fracture, and rock mass thermal and mechanical properties (listed in SCP Table 8.3.1.15-2). The experiments outlined in this plan are intended to produce the mechanical properties of intact tuff listed in Section 1.1 (i.e., Young's modulus, Poisson's ratio, unconfined compressive strength, cohesion, and angle of internal friction). Preliminary data are available for most of these parameters, as summarized in Sections 3.4 and 3.5; however, additional data are needed to analyze the spatial variation and, for some parameters, to obtain the required number of data. These properties will be measured directly in laboratory experiments, with the realization that, in many cases, it will be necessary to scale the results to achieve relevance to in situ conditions.

The data collected by this study will be supplied to the YMP Site and Engineering Properties Data Base (SEPDB) to meet the following needs:

- data for the Integrated Graphics Information System (IGIS) three-dimensional model,
- properties for the YMP Reference Information Base (RIB), and
- input data for specific design models for the prediction of the stability of underground openings.

In addition, it is well known that 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.

The laboratory mechanical data on intact rock will support many aspects of the repository license application, including repository design for the containment and isolation of radionuclides, the development and evaluation of repository seals, the potential retrieval of emplaced waste, and the design for the nonradiological health and safety of repository workers.

1.2.1 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 8.1.3 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.

Performance Issue 2.4 (Waste Retrievability) and Design Issues 1.11 (Configuration of Underground Facilities--Postclosure), 1.12 (Seal Characteristics), 4.2 (Nonradiological 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 8.3.1.15-1 in the SCP lists the parameters and associated issues that ultimately require data on thermal and mechanical properties. The information in Table 1 has been taken from the SCP table. 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 (see Section 2.2) for which data are needed, and the confidence with which required parameters are requested to be known by the appropriate issues.

1.2.2 Regulatory Requirements

The site characterization program follows two organizing principles. The first is the YMP Issues Hierarchy, which presents the questions the DOE feels must be resolved about the performance of the mined geologic disposal system (i.e., the waste package, the engineered repository, and the natural system at the site) to demonstrate compliance with the applicable Federal regulations. The Issues Hierarchy, therefore, is based on regulations contained in 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. The second principle is a general procedure, or "strategy," for determining how the issues are to be resolved. This general strategy was used to develop a specific strategy for the resolution of each issue (question).

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)	Angle of Internal Friction	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 angle of internal friction, as well as other failure criteria as appropriate.

One step in the application of the specific strategies results in the identification of the site information needed to support the resolution of the issues.

In general, the mechanical properties of intact tuff are necessary input for a number of design and performance analyses that address radionuclide containment and isolation, sealing, waste retrieval, and nonradiological health and safety. The five issues that require information related to the mechanical properties are briefly described in the following sections, 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: The performance allocation process for Issue 1.11 identified the parameters needed to meet the requirements defined by the post-closure design criteria in 10 CFR 60.133 and 10 CFR 960, Subpart C. The approach to resolving this issue includes the development of reference postclosure designs of the repository that are in compliance with the tentative performance goals. The design criteria for the underground facility, as expressed in 10 CFR 60.133, specify that the underground facility and the engineered barrier system be designed to (1) contribute to the containment and isolation of radionuclides; (2) incorporate sufficient flexibility to accommodate site specific conditions identified through in situ monitoring, testing, or excavation; and (3) assist the geologic setting in meeting the performance objectives.

The two design criteria that specifically address the potential for creating fractures in the rock mass and the attendant possibility of creating preferential pathways for ground-water movement and radionuclide migration to the accessible environment are presented in 10 CFR 60.133(e)(2) and (f). These criteria require that the underground openings be designed to reduce the potential for deleterious rock movement or fracturing of surrounding rock. Not meeting these requirements could impact the ability of the site to comply with the postclosure performance objectives of waste package containment, engineered barrier system release rate, and the overall system compliance with the standard for releases at the accessible environment boundary. 10 CFR Part 60.133 has an additional post-closure design criterion that the predicted thermal/thermomechanical response of the host rock will not preclude meeting the performance objectives. Satisfying the criterion requires the capability to evaluate the response of the host rock, surrounding strata, and ground-water system to the thermal and thermomechanical loads.

Design Issue 1.12, Seal Characteristics, SCP Section 8.3.3: Issue 1.12 is concerned with those activities required to develop designs and evaluate performance of seals to be placed in shafts, ramps, and drillholes associated with the development and closure of the repository. The seal system includes the seal, the seal/rock interface, and the zone of rock surrounding the seal where the hydraulic conductivity has been modified by excavation. Information from this study is needed to evaluate these areas.

Issue 1.12 is based on several sections in 10 CFR Part 60 that specifically relate to sealing, including 10 CFR 60.134, which requires seals to be designed so that following permanent closure, shafts and drillholes do not become pathways that compromise the ability of the geologic repository to meet the performance objectives for the period following permanent closure, and 10 CFR 60.112, which addresses the overall system performance for the geologic repository after permanent closure.

Performance Issue 2.4, Waste Retrievability, SCP Section 8.3.5.2: This issue addresses the ability to retrieve emplaced waste as required by 10 CFR Part 60.111(b). The repository must be designed, constructed, operated, and maintained so that all underground openings (including shafts, ramps, drifts, and emplacement drillholes) will remain usable for 84 years following emplacement of the first waste (Flores, 1986). Several of the functions for this issue are related to the mechanical behavior of the rock in reference to the need to provide access to the emplacement drillholes and waste packages and the ability to remove the waste packages from the emplacement drillholes.

Evaluation of the thermal and mechanical effects on stability of the underground openings will be an important component to the overall effort required to address this issue.

Design Issue 4.2, Nonradiological Health and Safety, SCP Section 8.3.2.4: This issue is concerned with those aspects of the underground facility design that may have an impact on the pre-closure nonradiological health and safety of repository workers. Federal regulations in 10 CFR 60.131 and 10 CFR 960.5 require that the design and development of the geologic repository operations area should not necessitate the use of engineering measures beyond the bounds of reasonably available technology for repository development and provide for worker safety.

The strategy for resolving this issue involves the examination of the evolving design to ensure that the final repository design meets the design criteria. Opening stability is an important aspect of access and drift construction, waste retrieval, and drift maintenance and must be considered as part of the activities related to resolving Issue 4.2.

Design Issue 4.4, Preclosure Design and Technical Feasibility, SCP Section 8.3.2.5: Issue 4.4 questions whether the repository can be designed, constructed, operated, and closed using reasonably available or proven technology. The strategy for resolving this issue involves development of an evolving design that meets the design criteria, expressed as performance measures and associated goals developed jointly with several design-related issues (1.11, 1.12, 2.4, 4.2, and others).

2.0 Rationale for Laboratory Studies of Intact Rock

2.1 General Rationale and Justification

The objective of the general rock mechanics program is to develop a capability to predict the response of the rock mass around a repository throughout construction, operation, and closure with sufficient accuracy to resolve the related design and performance issues. 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 low- and high-level nuclear waste. Two investigations and ten studies are planned to collect the required rock characteristics data (Figure 2-1, YMP SCP Section 8.3.1.15). The studies consist of those related to the laboratory determination of thermal and mechanical properties, the in situ experiments in the ES, and the characterization of ambient stress and thermal conditions at Yucca Mountain.

To address the information needs requested by the performance and design issues, the spatial distribution of thermal and mechanical properties must be investigated as well as the influence of sample geometry, environmental conditions, and physical rock properties on the mechanical behavior of intact rock. This study defines the experiments that are planned to investigate these effects for intact tuff in a controlled laboratory environment. At the same time that these data are being collected, the thermal properties of the tuff and the mechanical properties of the fractures will be studied. The data will eventually be combined in numerical, rock-mass models for repository analyses.

Laboratory mechanical experiments will be performed on a variety of sample sizes under a range of saturation, pressure, temperature, and rate conditions in order to define the general constitutive behavior of the rock at Yucca Mountain. These sample and environmental conditions will be varied in order to simulate, as closely as practical, the anticipated range of repository conditions (see Sections 2.7.2 and 2.7.3). Rock samples will be collected from locations in and around the proposed repository location to investigate the spatial variability of the rock properties.

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). These properties will be determined as part of the work defined by the Laboratory Thermal Properties Study Plan (Study Plan 8.3.1.15.1.1). In addition, the petrology, mineralogy, petrofabrics, 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 that would allow extrapolation of the data, and the dynamic elastic properties will be compared to the static properties from the same samples to determine the relationship between these properties as well as support the interpretation of seismic data collected at Yucca Mountain.

2.2 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. An effort has been made to categorize the tuffs into subdivisions, each having relatively uniform properties that are distinguishable from the properties of adjacent subdivisions. The result is a set of thermal/mechanical units;

the geometry of these divisions is discussed in Ortiz et al. (1985). This study will include testing of samples from the following units within the thermal/mechanical stratigraphy: TCw (Upper Tiva Canyon Member), PTn (Upper Paintbrush Tuff Formation), TSw1 (Upper Topopah Spring Member), TSw2 (Middle Topopah Spring Member), TSw3 (Lower Topopah Spring Member), CHn1 (Lowermost Topopah Spring and Upper Rhyolite of Calico Hills), and CHn2 (Lower Rhyolite of Calico Hills, formerly known as the tuffaceous Beds of Calico Hills). Figure 1 is a map locating the Yucca Mountain site and Figure 2 is an illustrative stratigraphic column comparing the formal geologic stratigraphy and the thermal/mechanical stratigraphy.

The tuffs being studied are all silicic deposits, but vary in degree of welding (usually directly related to porosity), vitric (glassy) content, and zeolitization. In general, TCw is welded and devitrified; PTn is nonwelded and vitric; TSw1 is welded, devitrified, and lithophysae-rich (lithophysae are gas-formed cavities); TSw2 is welded, devitrified, and lithophysae-poor; TSw3 is welded and vitric; and CHn1&2 are nonwelded and, generally, zeolitic. Because of the close proximity of Units TSw1 and TSw2 to the proposed repository, the bulk of the experiments presented in this study are from these units, and therefore, more detailed descriptions of these rock types are presented.

Microscopically, samples from unit TSw1 consist of three major components (Price et al., 1985). The components are a fine-grained matrix, lithophysal cavities, and vapor-phase-altered material. The fine-grained matrix is identifiable by its dark, generally purple or reddish-brown color. The lithophysae range in diameter from a few millimeters to several centimeters and are spherical to flattened (horizontally), usually lined with tridymite (a high-temperature polymorph of SiO_2), and always surrounded by zones of lighter-colored vapor-phase-altered material. The vapor-phase-altered material was formed by gas-alteration of

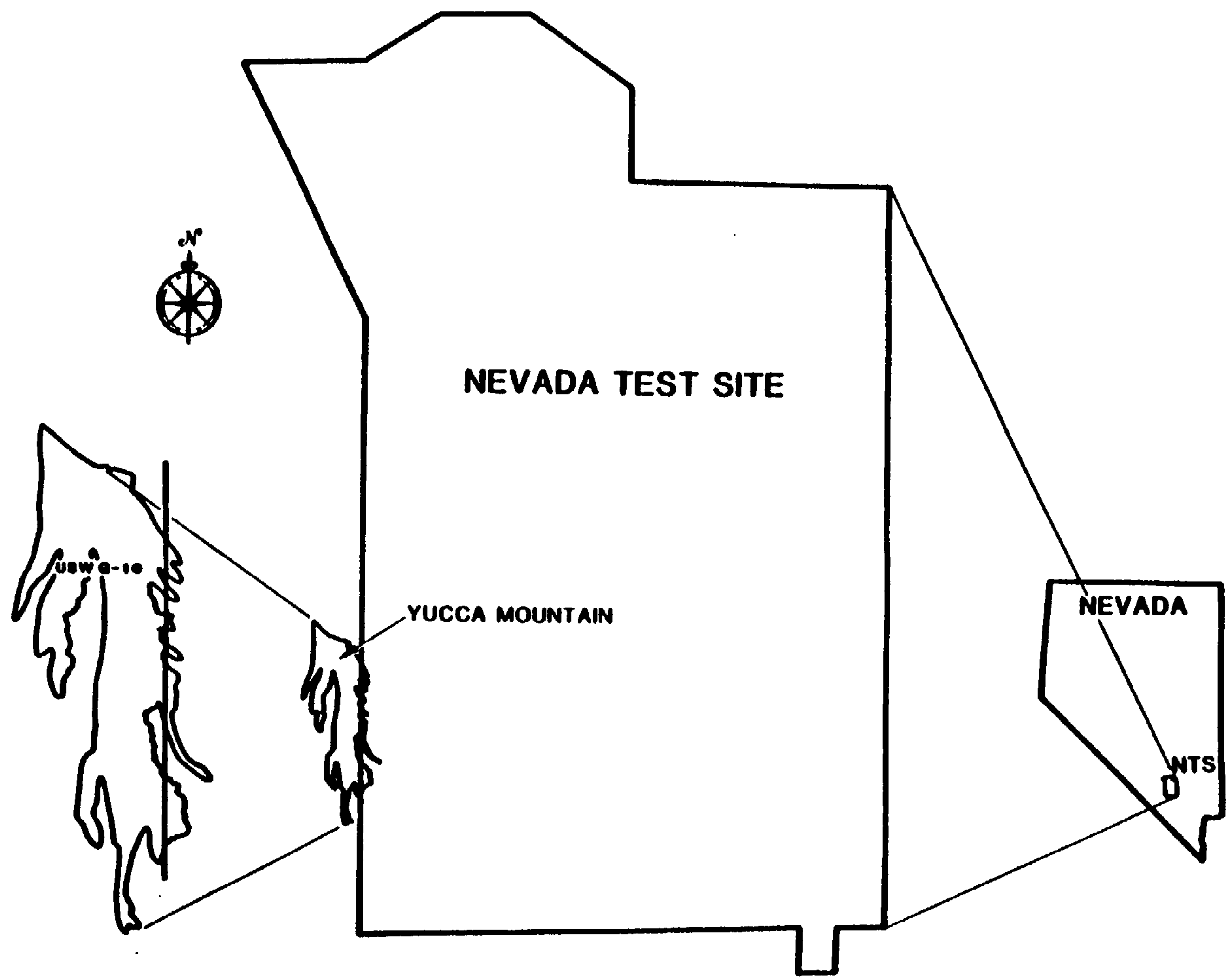

Figure 1: Location Map of Nevada Test Site and Yucca Mountain

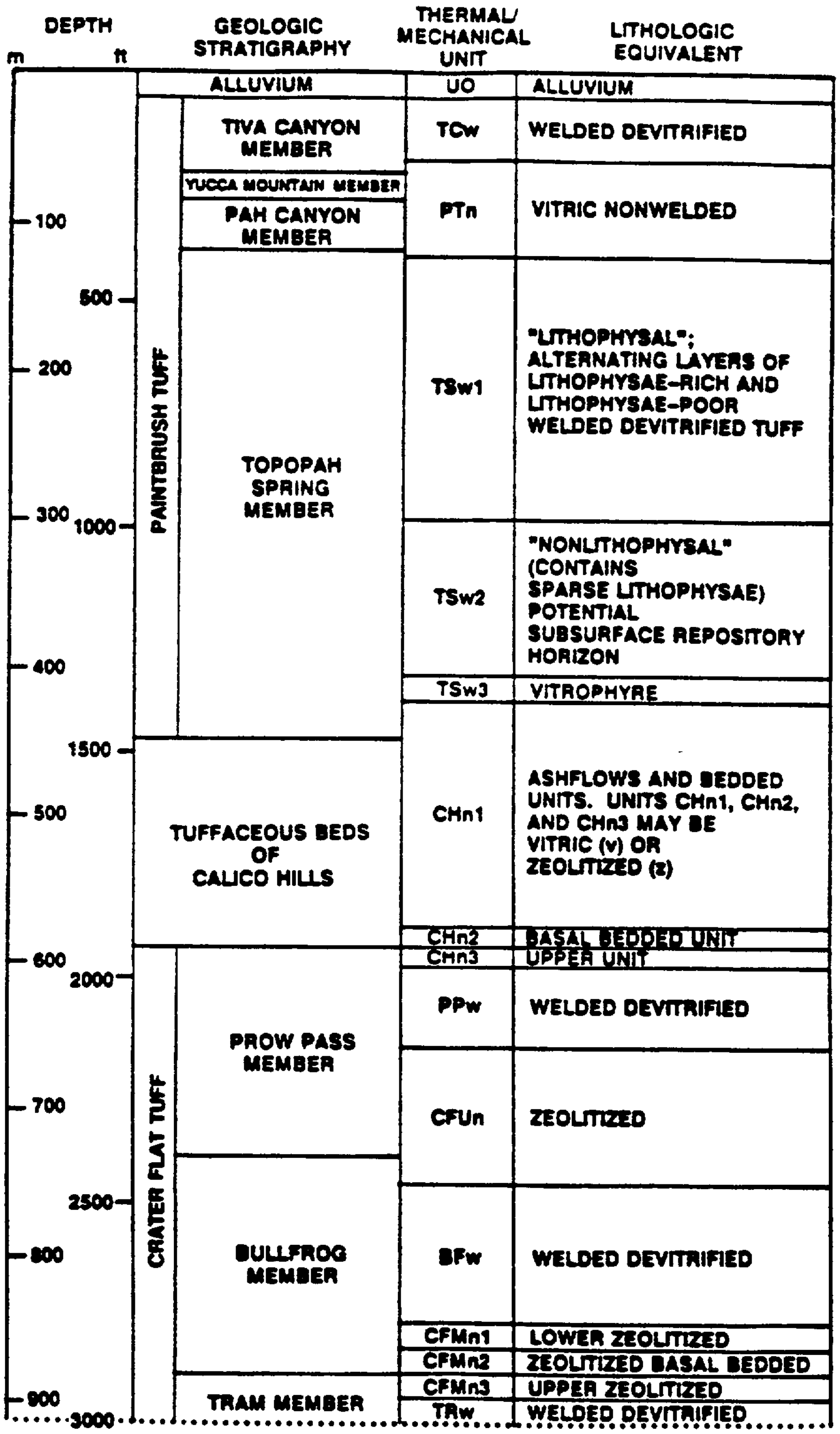

Figure 2: Comparison of Geologic and Thermal/Mechanical Stratigraphies of Yucca Mountain

the matrix. Small patches of the vapor-phase-altered material also occur in the matrix without an accompanying lithophysae.

The intact rock in the proposed host unit (TSw2) consists of two main components that are macroscopically identifiable (Price, Connolly, and Keil, 1987). The majority of the rock is a fine-grained matrix, very similar to that found in unit TSw1. Gray regions of vapor-phase-altered material vary in size and are quite common. In addition to these main components, the rock contains small (open and closed) lithophysae and "healed" (i.e., quartz- or calcite-filled) fractures. The matrix and vapor-phase-altered regions have porosity means and standard deviations of 0.08±0.01 and 0.49±0.17 (in volume fraction), respectively (Price et al., 1985; Price, Connolly, and Keil, 1987).

2.3 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, direct-pull tests will be run laterally unconfined. For both experiment types, 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.

2.4 Alternative Experiment Types

2.4.1 Compression

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, compression unloading, tri-axial extension with a constant strain-rate or stress-rate, true triaxial, torsion, creep, relaxation, and complex load path. These alternatives were all considered, but were not included 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 is 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 that behave 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 addition, the strain-rate loading path is more desirable and has been chosen for use in this study because this type of experiment is more stable, in most cases, when sample failure occurs. 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 (within a second or two), 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 destruction of the sample.

Another triaxial-compression load path is sometimes called compression unloading. A hydrostatic state of stress is placed on a sample and the differential loading (i.e., $\sigma_1 > \sigma_2 = \sigma_3$) is produced by decreasing the lateral stress while advancing the axial ram in order to maintain the axial stress constant. This type of unloading is plausible around a recently excavated underground opening; however, the largest in situ pressure at the proposed repository depth in Yucca Mountain is approximately 22 MPa (see Section 2.7.2). Very little deformation would be observed in the welded tuffs at these maximum stresses, and so this study does not include plans for this load path.

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 in order to maintain the axial stress ($\sigma_{ax} \sim \sigma_3$) 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 most commonly run following one of two techniques. The first is essentially the same as the triaxial compression experiments except that these tests are run on cubic-shaped samples with three independent stresses applied to the faces of the cubes. "Torsion of hollow or solid circular cylinders combined with axial load and fluid-confining pressure provides another method of studying failure under conditions of unequal principal stresses..." (Jaeger and Cook, 1976, p. 166).

The Coulomb failure criterion assumes that the intermediate principal stress (σ_2) has no effect on the brittle failure strength of rock. Investigations of the effects of changes in σ_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 σ_2 has no effect on strength; however, many (e.g., Heard, 1960; Murrell, 1965; Jaeger and Hoskins, 1966;

Handin, Heard, and Magouirk, 1967) have shown that σ_2 does have an effect. These studies have established that, for rocks in general, failure strength increases as σ_2 is increased relative to σ_3. As a result, since σ_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 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 relaxation experiments (in conjunction with a range of constant strain-rate tests) are normally used to investigate the time-dependent (rate-dependent) behavior of ductile materials. Preliminary creep tests on welded tuff at repository-scale differential stresses have shown that these rocks exhibit very little time-dependent deformation (Senseny and Parrish, 1981); however, some creep experiments are planned on samples of TSw2 (Section 3.6.2).

Complex load paths can follow specific changing stress or strain states that are believed to occur in a rock mass. These types of experiments are very difficult and expensive to perform, and are usually only employed in unique situations.

2.4.2 Tension

Indirect means are commonly used to obtain an approximation of tensile strength. The most prevalent of these methods is the "Brazilian" test. This experiment technique consists of diametral compression of a rock cylinder by the two platens of a compression testing machine. Although the Brazilian test will be considered as an alternative to the direct tensile test, it generally is somewhat less desirable because of the assumptions made in the calculation of tensile strength and because of the inhomogeneous stress distribution within the sample (Paterson, 1978). The direct-pull tests will be run to more completely define the failure envelope for Unit TSw2 in the tensile region of stress.

2.5 Rationale for Selected Number of Experiments

The numbers of experiments that will be necessary for site characterization in general will be different for each property considered. A preliminary estimate of the necessary number for each mechanical property can be obtained using existing mechanical data and information provided by repository design and performance assessment through the performance allocation process. In most cases, data requirements are expressed in the following form:

> How many experimental data points are needed to determine whether a proportion, γ, of the data population fall within the limits $x \pm ks$ with $(1-\alpha)$ level of confidence?

After experimental data have been obtained, they can be evaluated to determine whether the information is adequate, whether more experiments are required, or whether the parameter goals need to be adjusted. It must be noted that the data variability is expected to be primarily a function of the inherent heterogeneity of tuff, with the experimental uncertainty relatively small.

In principle, two-sided statistical tolerance limits can be used to estimate the number of samples required for laboratory mechanical properties tests (Bowker and Lieberman, 1972). In this procedure, a normal distribution for the data is assumed, with the validity of this assumption to be checked periodically during the data-gathering stage of the work. One difficulty in applying statistical tolerance limits during pre-study planning is that it requires some a priori estimates of the variability (i.e., standard deviation) of the property to be measured.

To define the number of samples, data requirements from a number of design and performance assessment issues were compiled. The results of the compilation are shown in Table 1. One of three qualitative levels of confidence has been associated with each data request--high, medium, or low. As specified in the SCP, two assumptions have been made for this study to use an assigned level of confidence to estimate a required number of samples: (1) the proportion of the population (γ) required to lie within the tolerance limits ($\pm kx$) is the same as ($1-\alpha$), where ($1-\alpha$) is the confidence level; and (2) the numerical values listed in Table 2 are associated with each qualitative confidence level.

Table 2: Values of α and γ Corresponding to Confidence Levels Defined by Issues

Specified Confidence Level	α	$\gamma = (1 - \alpha)$
High	0.05	0.95
Medium	0.10	0.90
Low	0.25	0.75

Many of the tolerance limits defined in design or performance assessment issues are expressed as a fraction of the mean value of a parameter. Bowker and Lieberman (1972) provide a table of values for a parameter k, where the tolerance limits are expressed as $x \pm ks$. Using existing data to calculate the mean value (x) and standard deviation (s) of a parameter, k can be determined by equating ks and the fraction of x required by a design or performance assessment issue. Given the values of k, α, and γ, Table 8.3 of Bowker and Lieberman (1972) can be used to obtain an estimate of the number of samples (n) necessary to provide the required statistical confidence in the parameter.

Table 3: Number of Experiments Using Normal Distribution Tolerance Limits

Unit	Number of Experiments
TCw	NA
PTn	NA
TSw1	>50
TSw2	>50
TSw3	NA
CHn1	>50
CHn2	NA

NA: The existing data are insufficient to obtain a mean and a standard deviation.

Some of the data requirements provided tighter constraints than others. Thus, the summary given in Table 3 includes sampling estimates only for the tightest constraints (i.e., the greatest number of samples). For many of the entries in this table, not enough information regarding the variability of the property is available with which to reliably estimate a preliminary number of required samples. For other entries, the calculated value of k was smaller than the smallest entry in Table 8.3 of Bowker and Lieberman (1972) (i.e., the initial estimate of the standard deviation is too high and/or the initial tolerance limit is too tight). In both cases, an alternate approach has been employed which, although arbitrary, will allow a preliminary sampling strategy to be formulated. In the alternate approach, the required number of initial test samples is estimated by determining the number of samples needed to attain a consistent but arbitrary tolerance limit (i.e., the k value). Based upon engineering judgement, a value of k equal to 2.5 was selected for determining the initial number of samples. For the three confidence levels, the corresponding numbers of samples are 3($\gamma = (1 - \alpha) = 0.75$), 11($\gamma = (1 - \alpha) = 0.90$), and 34($\gamma = (1 - \alpha) = 0.95$). These three values have been rounded to 5, 10, and 35 for the convenience of this study. These numbers of samples are consistent with previous testing experience with similar rocks and with the number of samples required for adequate estimates of the mean and standard deviation for the properties. Thus, the numbers of samples listed in Table 4 for each thermal/mechanical unit will be used in the first stage of sampling for mechanical-properties experiments at the baseline conditions (for a detailed discussion, see Section 3.6.1).

Table 4: Number of Experiments Planned at Each Sample Location for Spatial Variability Studies at the Baseline Conditions in Compression*

Unit	n
TCw	10
PTn	10
TSw1	35
TSw2	35
TSw3	10
CHn1	10
CHn2	5

*The baseline conditions in compression are defined in Section 3.6.1.

Based upon professional judgement and existing data, the parametric studies (Section 3.6.2) will be performed by initially testing 10 samples at each set of unique experiment conditions.

It is emphasized that the numbers of experiments discussed above for the spatial variability and parametric studies are those of the initial sampling program. After data are obtained from the samples, the adequacy of the data for satisfying both the initial assumptions (e.g., normality of the statistical distribution) and the data requirements given by the design and performance assessment issues will be examined. If any assumptions are violated, the data will be reevaluated to determine whether the data requirements are satisfied without the assumptions. If not, or if data requirements are not satisfied even when the assumptions are defensible, the Principal Investigator (PI) will consult with the relevant design or performance assessment personnel to determine the appropriate steps to follow.

2.6 Rationale for Sampling Strategy

Because the units in the thermal/mechanical stratigraphy have been defined based on differences in mechanical properties, thermal properties, or both, each of the units is assumed to be independent in terms of sampling. Thus, the performance allocation process has resulted in data requirements for each pertinent thermal/mechanical unit separately. When a specific sampling location is mentioned in the following paragraphs, it is implicit that samples of each pertinent thermal/mechanical unit will be obtained at the locality unless otherwise specified. Properties within a thermal/mechanical unit are assumed to be random with respect to vertical position--an assumption that is at least partially substantiated by existing data (Nimick and Schwartz, 1987), but will be investigated further.

Figure 3 shows the location of the primary area for site characterization at Yucca Mountain. Also included on the figure are (1) the locations of existing drillholes from which samples have been obtained previously for mechanical property measurements; (2) the proposed location of the first exploratory shaft (ES-1); (3) several long lateral drifts to be excavated within unit TSw2; and (4) the location of six drillholes proposed as part of the systematic drilling program described in Section 8.3.1.4.3.1 of the SCP.

A discussion of the number of samples required for site characterization was provided in Section 2.5. The discussion did not address the possibility that one or more of the mechanical properties varies as a function of spatial location, either horizontally within the primary area or vertically within a given thermal/mechanical unit. As noted earlier in this section, the existing data seem to indicate that the properties within a thermal/mechanical unit are random with respect to vertical position. However, given the number of cases in which "NA" is the entry in Table 3 for the required number of samples, it is assumed that nothing is known about horizontal variability of

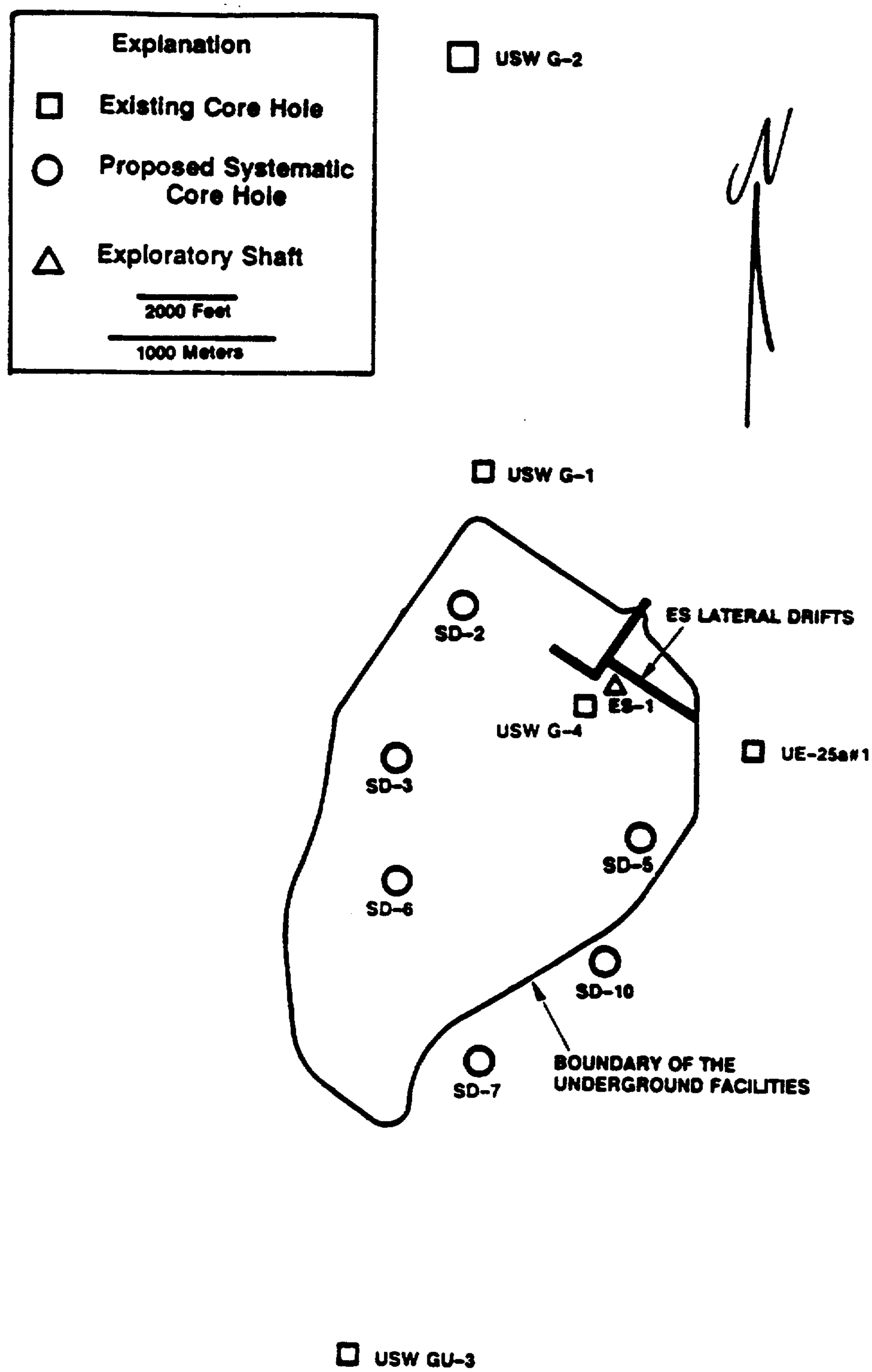

Figure 3: Map of Repository Area

mechanical properties before site characterization begins. Thus, the number of samples discussed in Section 2.5 applies for each sampling location employed in site characterization.

If large-scale (on the order of 100 to 1000 m) horizontal and relatively large-scale vertical variations in the mechanical properties of the intact rock exist, they should be detected by the planned drillhole and ES-1 testing. Medium-scale (1 to 10 m) horizontal variations will be investigated for samples of TSw2 from the long lateral drifts. Small-scale (0.1 m) variations in the mechanical properties will be studied directly and indirectly. They will be inherent in the closely spaced set of ten samples tested for each set of conditions in the parametric studies. In addition, small-scale variations in bulk properties will be studied (for a discussion, see Section 2.2.2.4.1 of Study Plan 8.3.1.15.1.1, Laboratory Thermal Properties). These bulk property data in conjunction with the known relationships between many of the intact rock properties and porosity will also provide estimates of the small-scale correlation for mechanical properties.

Not all of the relevant thermal/mechanical units will be penetrated by the subsurface excavations of ES-1 that will provide access to material for sampling. ES-1 will not be sufficiently deep to obtain samples from Units TSw3, CHn1, and CHn2. New drillholes are planned to extend to depths 61 m (200 ft) below the static water level, so that most of the thermal/mechanical units of interest should be sampled in each drillhole. The actual locations and depths of the drillholes shown in Figure 3 are contingent on completion of the YMP Surface-Based Investigations Plan. Prior to the penetration of the Calico Hills barrier below the proposed repository, an assessment of the impacts on isolation will be performed.

Additional details for each major sampling strategy are given in the following subsections.

2.6.1 Sampling in New Drillholes

Although a quantity of data on mechanical properties has already been obtained for samples from existing drillholes, examination of Figure 3 indicates that only one of the existing drillholes (USW G-4) is located within the primary area for site characterization. Thus, data from additional locations are necessary to examine the spatial variability of mechanical properties within the primary area as well as to ascertain whether the existing data are representative of the tuffs within the primary area.

To coordinate with drillholes planned for other YMP activities, six of the drillholes suggested as the first phase of a systematic drilling program (SCP Section 8.3.1.4.3.1.1) have been selected for sampling for the mechanical properties study: USW SD-3, USW SD-4, USW SD-6, USW SD-7, USW SD-10, and UE-25SD#8 (Figure 3). Data from these holes will allow a preliminary assessment of the lateral variability of mechanical properties to be made.

As stated earlier, each thermal/mechanical unit will be considered as an independent entity in terms of sampling. In each drillhole, each of the thermal/mechanical units will be divided into n sampling intervals, where n is the number of samples given in Table 4. The thickness of each sampling interval will be T/n, where T is the total thickness of the thermal/mechanical unit at the particular drillhole. Within each selected interval, an appropriate sample will be taken as close to the center of the interval as possible.

An attempt will be made to avoid any bias in sampling to the extent practicable. Thus, rather than selecting the material that appears to be the best candidate for a sample, the only criterion applied will be that a sample be of sufficient size to meet any size requirements imposed by the type of experiment. If a fragment or piece of core of sufficient size is not available within any given interval, a replacement interval will be randomly selected. (The fact that a piece of core was not available in a given interval may be useful information in the analysis of spatial variability of mechanical properties data or of the material on which the data were gathered. Thus, such information will be retained for use after sampling has been completed.)

The number of samples estimated as necessary for a given property and unit may not be achievable because a thermal/mechanical unit may not be sufficiently thick in a given drill-hole for the number of sufficiently-sized samples to equal n. If necessary, adjustments will be made to the sampling program so that the random nature of the program will be maintained while still acquiring as close to n samples as possible.

2.6.2 Sampling in ES-1

The sampling program in ES-1 will be similar to that in the new drillholes; however, rather than dividing each thermal/mechanical unit into n intervals, a sampling interval will be equivalent to the thickness of material excavated by each blasting round (approximately 2.1 m or 7 ft). The number of these rounds may be relatively small, especially in the thinner units. Thus, if y is the number of rounds in a thermal/mechanical unit, and y is less than n, multiple samples will be collected from the rubble of each round within that unit. For example, if n=35 and y=7, then five samples would be taken for each round.

Material available for sampling from a blasting round will be in the form of rubble. The existing plan is for two 55-gallon drums of the rubble to be collected from each round and stored in the YMP Sample Management Facility (SMF), near Yucca Mountain. For mechanical properties testing, samples will be obtained from these drums, with two randomizations included in the process: (1) whenever possible, sampling intervals (blasting rounds) will be selected at random and (2) when a set of 55-gallon drums has been selected, the location(s) within the drum will be selected at random before opening the drums for sampling.

It is recognized that the use of the rubble material introduces additional uncertainty in the data because of possible blast effects. A limited number of samples from the ES-1 probe hole and the multi-purpose borehole (MPBH) may be tested for comparison. (Additional discussion is provided in Section 3.6.1.)

2.6.3 Sampling in DBRs and Long Lateral Drifts

The parametric studies (Section 3.6.2) will require a large volume of material from the upper and lower (or main) demonstration breakout rooms (DBRs). This material will be extracted in the form of large blocks or large cores from the ribs (sidewalls) 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.

The sampling strategy in the long lateral drifts to be excavated at the main DBR in ES-1 will be similar to that employed for the shaft itself (ES-1). Potential sampling intervals will be equated with blasting rounds, and n such rounds will be randomly selected in each drift. All three of the long drifts are anticipated to be located entirely within unit TSw2, so the sampling will enable a detailed evaluation of the lateral variability of mechanical properties within the northern part of the primary area for this unit.

As in the ES rubble, it is recognized that the use of the material from the DBRs and lateral drifts may have possible blast effects. Following excavation of the DBRs, an evaluation of the depth of damage zone in the rib (or side-wall) will be performed before a sampling approach will be developed.

2.7 Existing Constraints

2.7.1 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 drilling of drillholes and mining of ES-1 and the underground facilities.

2.7.2 Simulation of Repository Environment Conditions

The ranges of saturation, confining pressure, and temperature conditions for this series of experiments (Table 5) 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 5: Ranges of Planned Experimental Conditions

Parameter	Range
saturation	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	80 MPa
sample diameter	25.4 to 380 mm
length:diameter	2:1 to 3:1

Saturation: Saturation will be studied 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. The majority of the tests, however, will be run fully saturated (and drained), including all the compressive and tensile experiments at the baseline experimental conditions (for a definition of these conditions, see Section 3.6). This saturation condition was chosen as primary because it results in conservative strength values as a result of the hydrolytic weakening in silicate minerals (Griggs, 1967; Martin, 1972; Scholz, 1972; Swolfs, 1972; Martin and Durham, 1975).

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. 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 (σ_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 (~2 m) 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 1.2.2, all underground openings must remain usable for 84 years following emplacement of the first waste (Flores, 1986). For long-term modeling of the repository, the effect of time (for periods on the order of the operational phase of the repository) on mechanical properties must be known or extrapolated from known properties. To study the time-dependent (or rate-dependent) behavior, experiments will be 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}. In addition, experiments will be performed at elevated temperature and the lowest strain rate to simulate even lower rates, since many time-dependent deformation mechanisms are thermally accelerated. This practice of trading temperature for time is a common practice in laboratory rock mechanics (with the assumption that the mechanisms of deformation are the same under both sets of conditions). To supplement the constant strain rate tests, some creep tests are planned for study of constant-stress loading.

2.7.3 Scale of Phenomena

As mentioned earlier, 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, and lithic fragments) relative to the size of the test sample. When examining intact rock properties in laboratory experiments, one-tenth is the suggested maximum ratio of inhomogeneity size to sample diameter (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.

2.7.4 Precision and Accuracy of Data

The precision of all data to be measured in the laboratory mechanical experiments (load, axial displacement, lateral displacement, confining pressure, pore pressure, and temperature) will be required to be within 3% of the total range of the measurement gage. More specifically, load cells generally are precise to within 3%; LVDTs, other displacement gages, and pressure gages are precise to within 1%; and thermocouples are precise to within 1°C. These values were chosen as reasonable limits for conventional rock mechanics equipment.

For stress values (compressive or tensile), the experimental uncertainty (i.e., the accuracy) will be approximately 0.03 (F_{lc}/F_s), where F_{lc} is the force capacity of the load cell within the applicable testing range and F_s is the force associated with the stress of the sample. The experimental uncertainty in axial or lateral strain is approximately 0.01 (l/δ), where l is the displacement range of the transducer and δ is the measured displacement.

2.7.5 Capability and Limits of Analytical Methods

The two major areas of analysis that are 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 2.5 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. The porosity and montmorillonite values were estimated by linear interpolation of the closest known values stratigraphically above and below the mechanical property sample.) (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 and Nimick and Schwartz, 1987) (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.

Also, 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., ≥0-200 MPa) is considered, most rocks exhibit a general non-linear (broad concave downward) trend in plots of ultimate 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 confining pressures (0 to 25 MPa) planned. However, as noted in Chapter 2 of the YMP SCP and 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.

Over the planned range of several environmental conditions (i.e., saturation, pressure, and temperature), we expect the results to bound the range of in situ conditions. Considering the site characterization time constraints, however, time is one parameter that cannot be simulated in the laboratory over the appropriate range of repository conditions; consequently, extrapolation from laboratory data to repository-scale times will be required. One mechanistically-based model for brittle rock being considered as the tool for this extrapolation has been described by Costin (1983).

In addition, data obtained from work described in this study plan will support repository-scale analytical and numerical modeling efforts. As discussed in Section 2.7.3, 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.)

2.7.6 Time Required Versus Time Available

After rock has been collected from ES-1, the DBRs, 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. The major impact of this time frame is to limit the potential strain rates that can be incorporated into this plan. The slowest strain rate scheduled for this study is 10^{-9} s^{-1} (Section 2.7.2), because at least 18 months are needed to test a typical welded tuff sample at 10^{-10} s^{-1}. In addition, as mentioned in the previous section, a theoretically-based model relating strength and strain rate has been developed for brittle rocks by Costin (1983). This fracture mechanics model predicts a decrease in strength with decreasing strain rate; however, the model also predicts the strengths are constant below some specific low strain rate (Costin's model predicts the threshold rate for tuff to be in the range of about 10^{-7} to 10^{-10} s^{-1}). Consequently, the results of the planned experiments at the lowest strain rates will be interpreted in light of this model to decide what additional tests, if any, should be planned within the license application time frame.

The experiments proposed in this study plan have been defined to meet license application requirements, including the projected site characterization schedule. As with most other data needed for design, the values determined in site characterization will not necessarily be available for the early design phases (e.g., Advanced Conceptual Design). However, prior to license application, design verification will confirm that the values used in design were appropriate.

In cases of in situ test support, the laboratory data will be needed in a timely fashion to aid in the planning of these experiments and/or in the reduction and analysis of the resulting data.

2.7.7 Statistical Relevance

Every effort is being made to ensure that 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 selection locations in the new drillholes, ES-1, and underground facilities (DBRs and long lateral drifts) have been selected so that 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 will be collected. Sections 2.5 and 2.6 provide discussions of the rationale for the numbers of samples and locations of sampling. Furthermore, Section 3.9 briefly provides the plans for statistical analysis of the data to be gathered.

2.7.8 Interrelationships of Experiments with Other Similar Activities

As discussed in Section 1.1, the mechanical response of the tuff rock mass is being considered using the combination of small-scale properties of the rock matrix and fractures into a rock mass model. This study describes only those tests being performed to establish the mechanical properties of the intact tuff; plans for characterizing the mechanical properties of fractures are described in the Laboratory Determination of the Mechanical Properties of Fractures Study Plan (8.3.1.15.1.4).

Some of the laboratory mechanical testing will be performed in support of the field tests planned for ES-1 and the DBRs. The data from the laboratory experiments will aid the field investigators in the interpretation of their data and the analysts in their efforts to model the mechanical behavior observed in the field experiments. These laboratory experiments will be run prior to or concurrently with the in situ tests planned in the Excavation Investigations Study Plan (8.3.1.15.1.5), the Characterization of Site Ambient Stress Conditions Study Plan (8.3.1.15.2.1), the In Situ Thermomechanical Properties Study Plan (8.3.1.15.1.6), and the In Situ Mechanical Properties Study Plan (8.3.1.15.1.7).

The Shaft Convergence experiments in the Excavation Investigations Study Plan and the techniques described in the Characterization of the Site Ambient Stress Conditions Study Plan will determine the in situ stress in several locations. The stress data will help to delineate local variations in the stress state within the Topopah Spring Member. The stability of the underground openings is contingent on the response of the rock mass to the in situ stress state plus the induced thermal and mechanical stresses. Data from the In Situ Thermomechanical Properties Study Plan experiments will be used to validate the thermal and thermal-stress models. The In Situ Mechanical Properties Study Plan will provide deformation moduli and evaluate empirical strength and design criteria.

2.7.9 Interrelationships of Experiments with ES-1 Construction Activities

Five series of experiments will be coordinated with ES-1 construction activities. The samples for these tests will be extracted from ES-1, the DBRs, and the long lateral drifts.

Shaft Phase Testing: The vertical variability of laboratory mechanical properties will be investigated by testing samples from many levels along the entire length of ES-1. These experiments are scheduled to begin three months after mining of ES-1 is initiated.

Lithophysal Testing: The effects of lithophysal cavities on the laboratory mechanical properties will be studied on samples taken from the upper DBR in unit TSw1. This activity is planned to start twenty-three (23) months after the beginning of ES-1 mining.

Parameter Effects Testing: A laboratory test series is planned to study the effects of changes in sample size, saturation, pressure, temperature, and strain rate on samples of the repository horizon (TSw2). These samples will be collected from the main test level (the lower DBR) approximately twenty-three (23) months after the beginning of ES-1 mining.

Lateral Drift Testing: The lateral variability of the mechanical properties of intact rock will be studied on samples taken from lateral drifts mined from the lower DBR. These experiments are planned to begin about twenty-seven (27) months after the ES-1 mining is begun.

In Situ Test Support: Approximately ten (10) months after the beginning of ES-1 mining there will be a need for mechanical properties to aid in the interpretation of the in situ test data. This activity will continue for about a year and a half.

3.0 Description of Experiments, Data, and Analyses

3.1 General Experiment Types

As discussed in Section 2.3, both compressive and tensile properties will be collected. The following experiment techniques have been selected to collect these data.

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

For both experiment types (compression and tension), the differential stress will be applied, in a majority of cases, 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 Experiment Procedures (EPs). These documents will outline the work, as well as the appropriate technical and quality assurance (QA) requirements. One or more EPs will be written and approved before initiation of each of the tasks outlined in Section 3.6 of this study plan. The listing of the step-by-step procedures to be followed for all aspects of sample preparation, calibration, and the experiment will be written as Technical Procedures (TPs). The time involved in preparation of the EP(s), and associated TPs, for a given task will depend on the complexity of the task and whether similar procedures have been written previously.

When available for a specific task, nationally recognized procedures (e.g., ASTM and ISRM) will be consulted when TPs are developed.

The following pages provide an overview of the procedures for which details will be described in the EPs and TPs 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 criterion for a dry sample. (For greater detail on this procedure, refer to TP-65, entitled "Procedure for Drying Geologic Core Samples to Constant Weight.")

The samples to be tested saturated will be submerged in water (to avoid any concerns over chemical impurities, either distilled water 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 criterion for saturated samples is met. (For greater detail on this procedure, refer to TP-64, entitled "Procedure for Vacuum Saturation of Geologic Core Samples.")

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 that are 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 (<<1 s) or by taking data at defined increments of all the variables (i.e., time, axial load, axial displacement, lateral displacement, and pressure). The latter technique is preferable because very few points are necessary to define the linear elastic portions of the curves (and dense data at very short time intervals would be superfluous), but from sample yield to failure the data must be 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: A load frame is an apparatus designed for applying a load (usually a one-dimensional load) to a sample. The design capacity of a frame is typically two to three times the operating (or working) load. Load frames can be 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 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) that is 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 silicon) 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); however, questions have been raised about uneven pressure distribution on the sample with this technique. Gas medium (usually argon or some other inert gas) devices are often used for experiments at temperatures higher than about 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 normally is applied to 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 approximately 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 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 A/D (analog-to-digital) 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 that of the sample, the data-acquisition 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 that 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 that water is not allowed to invade the confining pressure system. Next, the temperature is raised slowly (≤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 (σ_{ax}) is macroscopically equivalent to the greatest principal stress (σ_1) in triaxial compression experiments and the least principal stress (σ_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.

Similarly to axial stress, axial strain (ε_{ax}) is macroscopically equivalent to the greatest principal strain (ε_1) in triaxial compression experiments and the least principal strain (ε_3) in triaxial extension and tension experiments. Axial strain can be measured directly with strain gages mounted either onto a sample or on a jacket surrounding the sample. These methods are good only on very low porosity (~1%), 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 another portion of the load column away from the sample. The first method (i.e., measuring displacements over a partial sample length) is preferable because the latter two methods include deformations of other materials and of interfaces within the loading column. For methods that include such deformations, the relationship between the "machine" (or non-sample) displacements and load needs to be determined before testing so that 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 that 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%). Again, as with stress, engineering strain is commonly used for brittle rock.

As with axial strain, lateral strain (ϵ_{lat}) can be measured directly with strain gages on the sample or jacket. Methods of indirectly measuring lateral strain include: (1) dividing measured lateral displacement by the sample diameter, (2) dividing measured circumferential displacement 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 small for brittle materials.

Electronically recorded pressure is typically measured by a standard pressure gage that uses a small load cell with a known cross-sectional area. 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, or at a sample/end cap interface in a small hole in the end cap.

3.3.2 Key Parameters

Differential stress, axial strain, lateral strain, and effective pressure data will be 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 (ν) 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 early 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) 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 defined as the peak value of differential stress a sample withstands when tested by uniaxial compressive or tensile loads, respectively.

The ultimate differential stress ($\Delta\sigma_u$) versus effective confining pressure (P_e) data will be fit by linear regression and then transformed into shear stress (τ)/normal stress (σ_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:

$$\tau = \tau_o + \sigma_n(\tan\phi) \quad , \qquad (1)$$

where τ_o is cohesion and ϕ 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; P. Senseny, personal communication). These data are summarized in a report by Nimick and Schwartz (1987). 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, Poisson's ratio, unconfined compressive strength, unconfined tensile strength, cohesion, and angle of internal friction data from the above-mentioned studies have shown that there are wide ranges of results in these parameters. To illustrate this point, the mean, standard deviation, and number of experiments for some of these parameters resulting from testing of TSw2 samples at the baseline conditions are presented in Table 6.

Table 6: Statistical Summary of TSw2 Mechanical Property Data (from Nimick and Schwartz, 1987)

Parameter	Units	Number of Tests	Mean	Standard Deviation
E	GPa	53	30.4	6.3
ν	-	28	0.24	0.06
C_o	MPa	53	162.8	65.2
T_o	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) (Figure 1). 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 presented here 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. As mentioned in Section 2.2, 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. The large standard deviations in the values of the key parameters for samples of the Topopah Spring Member (Table 6) 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 2.5) than had previously been run at each set of conditions (which was typically 2, 3, or 4 experiments). The expanded number of experiments should 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 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 simple 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 to best fit the Young's modulus/functional porosity data (for the experiments discussed above) is as follows:

$$E = 86.e^{-7.0n} \quad , \qquad (2)$$

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 also determined that 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:

$$\sigma_u = 4.0n^{-1.9} \quad , \qquad (3)$$

where σ_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 distinctive, inverse relationships have also been observed for unconfined tensile strength, cohesion, and angle of internal friction versus porosity or functional porosity (Price, 1983; Nimick and Schwartz, 1987). The Poisson's ratio data collected to date have been widely scattered and apparently independent of functional porosity (Price, 1983).

Sample Size: To investigate the influence of sample volume, 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}.

Plots of Young's modulus versus sample diameter and Poisson's ratio versus sample diameter for the data from Price's experiments do not reveal a distinct trend in elastic properties with changing sample size. In general, the Young's modulus and Poisson's ratio data appear to be independent of sample size. As discussed by Lama and Vutukuri (1978, p. 62), this same result also has been observed for other rock types.

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. More specifically, in many of the cases where strength and sample size were inversely related, the strength decreases were fit well with a simple power-law model. Price found this to be appropriate for his data, and the resulting fit is as follows:

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

where σ_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, 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: 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% (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; Martin, 1972; Scholz, 1972; Swolfs, 1972; Martin and Durham, 1975) and previously noted for another Nevada tuff (Olsson and Jones, 1980).

Pressure Effects: Very little, if any, effect of pressure on Young's modulus or Poisson's ratio has been observed.

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), CHn1 (Price and Jones, 1982), and BFw (Bullfrog Member of the Crater Flat Tuff) (Olsson, 1982).

Temperature Effects: Young's modulus decreases with increasing temperature for the temperature range from 22 to 150°C. Over this range of temperatures, 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% with a change in 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, with the strength/rate data, the trends 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), have shown a direct relationship between ultimate strength and strain rate (i.e., when rate increases, strength increases). A few sets of data, however, have shown the reverse effect (Price, Connolly, and Keil, 1987).

Anisotropy: The assumption of isotropy has been tested in two experimental studies; however, the results have been ambiguous. One study showed a distinct anisotropy (Olsson and Jones, 1980) and the second no anisotropy (Price, Spence, and Jones, 1984) in the elastic properties of welded tuff. In both of these studies, conclusions about anisotropy are preliminary because determination of anisotropy was not a primary goal of either study.

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 that have been planned. Table 7 presents an approximation of the total number of experiments in the initial characterization of intact mechanical properties of the tuffs around the proposed repository horizon.

Table 7: Approximate Number of Experiments for Each Planned Experimental Series

Series	Total Experiments
Baseline Conditions:	900
Parameter Effects (TSw2):	350
Creep (TSw2):	10
Lithophysae (TSw1):	10
Pressure (TCw, PTn, TSw1):	120
Tension (TSw2):	10
In Situ Experiment Support:	120

3.6.1 Experiments at the 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 2.6.

New Drillholes: For each of the six new holes to be sampled, a series of 115 experiments is planned on samples from the following units within the thermal/mechanical stratigraphy: TCw, PTn, TSw1, TSw2, TSw3, CHn1, and CHn2. From the performance allocation process, primary concern for mechanical properties will be on units TSw1 and TSw2, while TCw, PTn, TSw3, and CHn1 will be of secondary interest (SCP Section 8.3.1). The mechanical properties of unit CHn2 are needed for far-field modeling.

Exploratory Shaft (ES-1) and Long Lateral Drifts: The same type testing sequence as described for the new drillholes has been defined for rock obtained from the ES-1 and the lateral drifts mining activities.

There is one potential problem inherent in the testing series that will use samples from the ESF. The samples will be taken from blocks of rock resulting from the drill, blast, and muck operations. This material may be damaged as a result of the mining process. If the damage is extensive, then the results from laboratory mechanical tests on samples of this material will be altered. The elastic and strength properties could be altered and/or more scattered than those from core material, even if the in situ mineralogy and petrofabric of the materials are essentially the same and the experimental conditions are identical. A statistical comparison between the two data sets will be performed to determine whether the two data sets are, in fact, significantly different. If the results from the mined samples are found to be statistically different in Young's modulus and/or strength, then additional testing on samples from sidewall core, rib core, or core from drillholes adjacent to the ES will be performed to determine whether the difference is due to the mining process or is just a local, inherent rock characteristic.

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. As discussed in Section 2.5.2, 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 name 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 lower DBR within the 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 anistropy (the conditions to be investigated are listed in Table 8) on the elastic and strength properties. The parameter effects study will be accomplished with the philosophical approach of 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 examined as data are collected and analyzed.

Table 8: Outline of Planned Experimental Series Parametric Studies: Parameter Effects (TSw2)

Parameter	Experimental Condition(s)
Saturation:	Dry, Water Saturated
Confining Pressure:	0.1, 5, 15, 25 MPa
Pore Pressure:	0.1, 5 MPa
Temperature:	22, 250°C
Strain Rate:	10^{-9}, 10^{-8}, 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 bedding (vertical, if bedding not apparent).

Saturation effects will be studied at the two extreme conditions of dry and saturated. Experiments at specific intermediate saturation conditions 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 that same state in additional samples for statistical studies. However, some samples with undetermined saturation states (i.e., intermediate) may be tested to ensure that results are bounded by the experiments on samples with extreme saturation conditions.

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 2.7.3), obtaining larger size samples would be difficult.

Most of the near- and far-field modeling is being performed under the assumption that the tuffs are mechanically isotropic. If this assumption is incorrect, and the tuff is elastically anisotropic, then for example 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 concern in samples of the repository unit. In addition to static mechanical experiments, sonic velocity measurements are being considered to 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 that these results are better understood in the light of theoretical studies demonstrating the important role that 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 outcrop samples of TSw2 for approximately 2 months at 250°C (Table 9). These experiments will be run in conjunction with experiments at the lowest practical laboratory strain rates (10^{-9} and 10^{-8} 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 that time-dependent deformation may be significant under repository-type conditions, then additional testing will be planned to investigate the behavior in more detail.

Table 9: Outline of Planned Experimental Series Parametric Studies: Creep (TSw2)

Parameter	Experimental Condition
Saturation:	Water Saturated
Confining Pressure:	5 MPa
Pore Pressure:	4.5 MPa
Temperature:	250°C
Creep Stress:	80 MPa
Diameter:	50 mm
Length-to-Diameter Ratio:	2:1
Anisotropy:	0°*

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

Lithophysae (TSw1): Several large samples (~380 mm in diameter) will be collected from the upper DBR in the lithophysal zone of the Topopah Spring Member (lower part of TSw1). These will be used to investigate the effects of the large (up to 50 mm in length) lithophysal cavities on the mechanical properties of the welded TSw1 tuff; the planned experiment conditions are listed in Table 10. The results will be compared with an earlier study on outcrop samples from the same horizon (Price et al., 1985).

Table 10: Outline of Planned Experimental Series Parametric Studies: 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 bedding (vertical, if bedding not apparent).

Table 11: Outline of Planned Experimental Series Parametric Studies: Pressure (TCw, PTn, TSw1)

Parameter	Experimental Condition
Saturation:	Water Saturated
Confining Pressure:	0.1, 5, 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 bedding (vertical, if bedding not apparent).

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 11) 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.

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 12).

Table 12: Outline of Planned Experimental Series Parametric Studies: 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 bedding (vertical, if bedding not apparent).

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 ES-1 and in the two DBRs (see SCP Section 8.3.1.15.1). To aid in the interpretation of the results from these in situ experiments, some laboratory mechanical experiments in compression and tension will be run on samples of rock adjacent to each experiment. Descriptions of the specific laboratory experiments that will be required will be presented in the study plans associated with the specific in situ experiments (see Section 2.7.8).

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 in order to determine their petrology, mineralogy, and petrography. These data will be collected primarily to address four 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 determine whether or not samples from the ES-1 muck, the DBRs, and drillholes have conspicuous differences in their petrofabric which could have resulted from the method of sampling (i.e., blasting and coring).

4. To examine some post-test samples for identification of potential deformation-induced mechanisms (e.g., micro-fracturing and grain boundary sliding) and for determination whether 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 two questions.

1. To determine the dynamic elastic properties of the rock.

2. To determine if there is a significant relationship between the dynamic and static elastic properties.

3.7 Locations of Testing Laboratories

Only two locations have been determined where experiments on samples of intact TSw2 will be run. The two laboratories presently involved are (1) the Geomechanics Division, Sandia National Laboratories (SNL), Albuquerque, NM and (2) New England Research, Inc., Olcott Commerce Park, Wilder, VT. At a minimum, the Geomechanics Division will be performing the anisotropy studies and New England Research (NER) will be testing the samples of TSw2 at low strain rate and creep conditions.

These or other laboratories also may be used when other series of experiments are specifically defined. When considering what laboratory should run experiments in these series, many factors will be taken into consideration, including cost, available equipment, personnel, and ability to meet the necessary Quality Assurance requirements.

3.8 QA Requirements

The Quality Assurance (QA) requirements that apply to this study are shown in Appendix A.

The laboratory mechanical data collected from experiments on intact samples of tuff planned by this study will be used in the license application. Table 13 presents a list of the existing and planned SNL YMP Technical Procedures (TPs) relevant to this study. Additional TPs will be written as the progress of this laboratory study develops. Each TP, however, will be available a minimum of 45 days before use in data-gathering activities. Technical procedures for this work will be standard procedures and will incorporate relevant portions of nationally recognized procedures.

3.9 Statistical Analysis of Data

As discussed in Section 2.7.5 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 analysis that are planned 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 ES-1), horizontal (drillhole to drillhole), intra-unit, and inter-unit variability.

3. When appropriate, perform correlation analysis of properties with each other (e.g., ultimate strength and functional porosity).

Table 13: The Planned and Existing Experiment and Technical Procedures Relevant to Study 8.3.1.15.1.3

Number	Title	Date
EP-TBD	TBD	TBD
TP-51	Preparing Cylindrical Samples Including Inspection of Dimensional and Shape Tolerances	10/22/87
TP-53	Procedure for Determination of Compressive Mechanical Properties	TBD
TP-54	Procedure for Determination of Tensile Mechanical Properties	TBD
TP-59	Procedure for Laboratory Sample Petrology Determination	11/16/87
TP-60	Procedures for Preparation of Polished Thin Sections	10/29/87
TP-62	Laboratory Procedures for Mineralogic Analysis by X-Ray Powder Diffraction, Part 1: Data Gathering	9/17/87
TP-64	Procedure for Vacuum Saturation of Geologic Core Samples	3/31/87
TP-65	Procedure for Drying Geologic Core Samples to Constant Weight	5/24/88

4.0 Application of Results

Section 8.1.3 of the SCP and Section 1.2 of this study plan discuss 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.

4.1 Resolution of Performance and Design Issues

The primary objective of this study is to provide mechanical properties of intact tuff to aid in the development of near- and far-field thermomechanical repository models to meet the issue needs as discussed in Section 1.2.2. More specifically, the mechanical properties are necessary input for a number of design and performance analyses that address radionuclide containment and isolation, sealing, waste retrieval, and nonradiological health and safety.

Following collection of a set of mechanical property data in the laboratory, all technical data and associated planning, implementing, and reporting documents are initially placed in a branch of the SNL NNWSI Project Local Record Center (LRC), titled the Data Records Management System (DRMS). The DRMS organizes the technical data and supporting documentation into "data sets" which are given unique identifiers. When a data set is completed, a data report is written which contains data reduced to a usable form. Following review of a data report, the data in the report are released for entry into the YMP Technical Data Base (TDB). The TDB is made up of two parts: (1) the Site and Engineering Properties Data Base (SEPDB) which contains the reduced numerical data, and (2) the Interactive Graphics Information System (IGIS) which is used for manipulation and presentation of SEPDB data that are particularly useful in graphical form. The TDB is used to create products that make the data available for support of other YMP technical activities. In response to the technical needs of the project, some of the data from the SEPDB is distilled into products that are included in the Reference Information Base (RIB). The RIB was established to maintain and control the flow of interpreted technical reference information for use by design and performance assessment activities and to provide a technical basis for an eventual repository license application. Processing of SEPDB data for inclusion in the RIB involves a thorough review by the YMP technical staff and approval for baselining by the appropriate change-control authority.

4.2 Resolution of Characterization Programs

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 a study of discrete fractures (Laboratory Determination of the Mechanical Properties of Fractures Study Plan 8.3.1.15.1.4) to support thermomechanical rock-mass modeling. The results from this modeling will be compared to data from in situ experiments (i.e., the experiments described in the Excavation Investigations Study Plan 8.3.1.15.1.5, the Characterization of Site Ambient Stress Conditions Study Plan 8.3.1.15.2.1, the In Situ Thermo-mechanical Properties Study Plan 8.3.1.15.1.6, and the In Situ Mechanical Properties Study Plan 8.3.1.15.1.7) to further our understanding of the scale effects on the geomechanical properties of the rock mass.

5.0 Schedule and Milestones

5.1 Scheduling Relative to Construction and Other Studies

All of the work under this study will be performed on a schedule that is contingent on the construction schedule for the ES-1 Facility (see Section 2.7.9) or the drillhole schedule within the YMP Surface-Based Investigations Plan.

Because all the laboratory experiments on intact rock will be performed at locations other than the Nevada Test Site, this study will impact the ES-1 schedule only for obtaining large blocks of rock in the DBRs. The finished test specimens will be machined from these blocks. This study is independent of other studies within the ES Facility, except that some laboratory testing will be run in support of certain in situ experiments. The approximate schedule for the work under this study that will use material from ES-1, relative to the ES-1 mining activities, is shown in Figure 4. (Note: The "Final Report Due" date also reflects the date of data submission to the YMP Site and Engineering Properties Data Base, or SEPDB.) Details of the schedule may change with changes in the timing of ES-1 construction and testing activities.

Obtaining the drillhole samples will be dependent on the drilling schedule (contained in the Surface-Based Investigations Plan), core handling procedures (e.g., logging, waxing, boxing, and shipping), and the process of integrating sample requests. The YMP Sample Overview Committee (SOC) has the responsibility to distribute the available rock samples to best meet the needs of the project. The Surface-Based Investigations Plan is presently being developed and the sample handling and distributing procedures are being written. As a result, an absolute schedule for mechanical experiments cannot be presently adopted. The mechanical experiments on drillhole samples (from each specific drillhole) are planned to be completed within approximately six (6) months of the time samples are received.

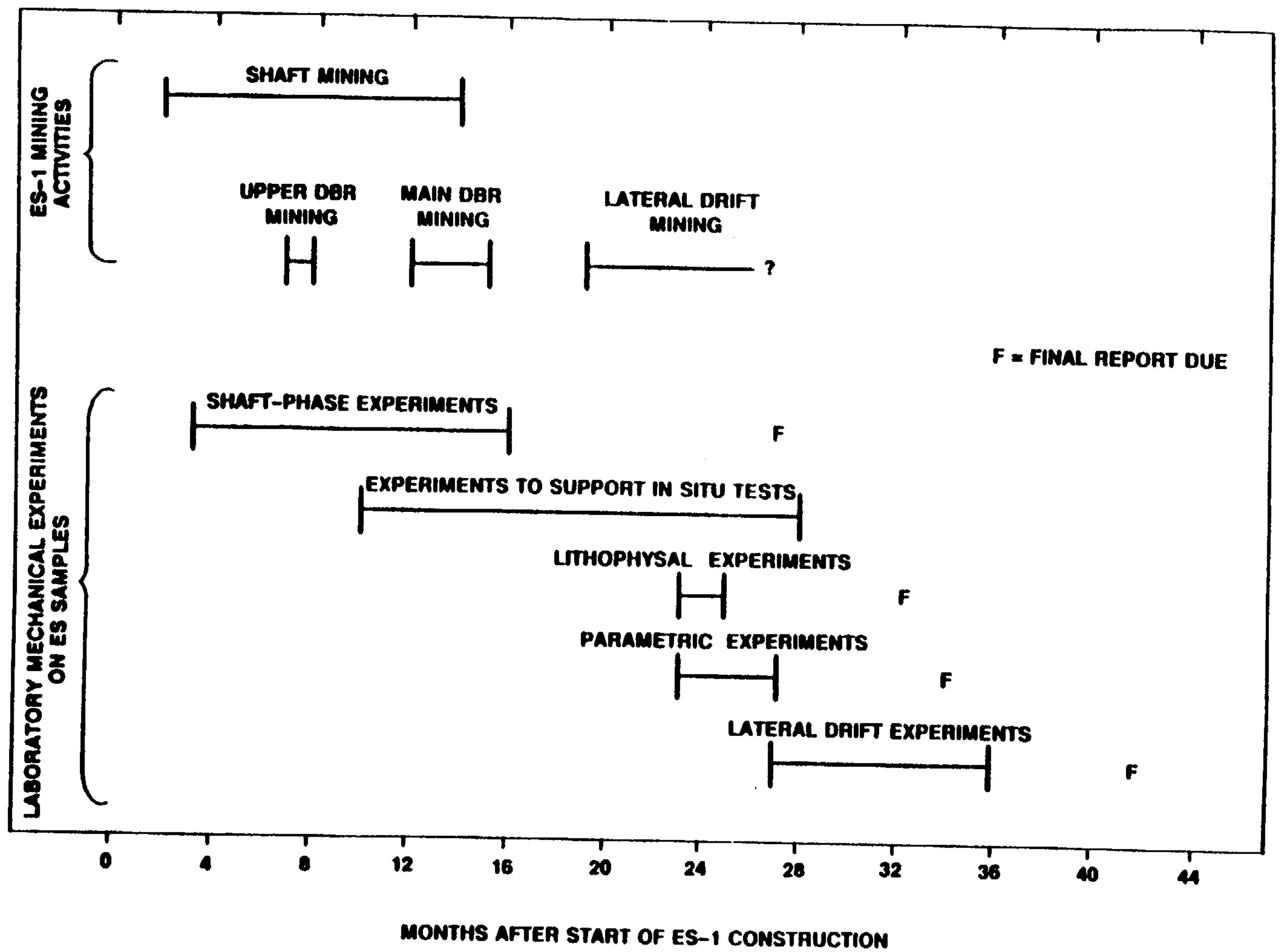

Figure 4: Schedule of Testing Relative to ES-1 Mining Activities

In addition to the experiments on material from ES-1, measurements also will be made on material from any new drillholes that may be initiated as part of the Site Characterization activities. The schedule for testing of samples from these holes will depend on the timing of the holes relative to the testing of ES-1 samples. As a result, a precise schedule for testing of drillhole samples cannot be defined at this time.

5.2 Milestones

There are several milestones that are planned to report the progress of the work described in this study. These are listed in Table 14.

Table 14: Milestones

Number	Description	Deliverable	Date Due*
M058	Data Report on Laboratory Properties for Shaft Construction Phase	SAND Report	27*
M065	Data Report - Mechanical Properties of Lithophysal Tuff	SAND Report	32*
M067	Data Report - Parametric Sensitivity of Laboratory Mechanical Properties	SAND Report	34*
M069	Data Report - Laboratory Properties from Lateral Drifts	SAND Report	42*
Z803	Data Report on Mechanical Properties of Samples from New Core Holes	SAND Report	26+

*The "dates" here refer to number of months following initiation of ES-1 mining.
+The "dates" here refer to number of months following initiation of the Systematic Drilling Program.

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APPENDIX A

QUALITY ASSURANCE REQUIREMENTS

Determination of the quality status for the activities of this study will be made separately, according to AP-6.17Q, "Determination of the Importance of Items and Activities," which implements NUREG-1318, "Technical Position on Items and Activities in the High-Level Waste Geologic Repository Program Subject to Quality Assurance Requirements." The results of that determination will be contained in the Q-List, Quality Activities List and Non-Selection Record, which will be controlled documents.

QA grading packages for the activities of this study plan will be prepared separately, according to AP-5.28Q, "Quality Assurance Grading." The resultant Quality Assurance Grading Report will be be issued as a controlled document.

TABLE A-1

NQA-1 CRITERIA FOR STUDY 8.3.1.15.1.3
AND IMPLEMENTING DOCUMENTS AND PROCEDURES

NQA-1 Criteria #	Documents Addressing These Requirements
1. "Organization	The organization of the OCRWM program is described in the Mission Plan (DOE/RW-005, June 1985) and further described in section 8.6 of the Site Characterization Plan (SCP) (DOE, 1988).
2. "QA Program"	The Quality Assurance Programs for the OCRWM are described in NNWSI/88-9, and OCR/B3, for the Project Office and Headquarters, respectively. The SNL QA Program is outlined in the Sandia National Laboratories (SNL) Nuclear Waste Repository Technology (NWRT) Department Quality Assurance Program Plan (QAPP) and includes a program description addressing each of the NQA-1 criteria. Each of these QA programs contains Quality Assurance Procedures (QAPs) and Department Operating Procedures (DOPs) that further define the program requirements. An overall description of the QA Program for site characterization activities is found in section 8.6 of the SCP. SNL documents related to the QA program include: QAP 1-3 Quality-Related Work Stoppage QAP 1-4 Resolution of Quality Assurance Disputes DOP 2-2 Study Plans Requirements DOP 2-3 Work Plans DOP 2-4 Analysis Control and Verification QAP 2-7 Qualification of Quality Assurance Program Audit Personnel DOP 2-9 Preparedness Review

TABLE A-1

NQA-1 CRITERIA FOR STUDY 8.3.1.15.1.3
AND IMPLEMENTING DOCUMENTS AND PROCEDURES
(continued)

NQA-1 Criteria #	Documents Addressing These Requirements	
3. "Design and Scientific Investigation Control"	Since this study is a scientific investigation, the following QA implementing procedures apply:	
	DOP 2-1	Task Definition Statements
	DOP 2-2	Study Plan Requirements
	DOP 2-3	Work Plans
	DOP 2-4	Analysis Control and Verification
	DOP 3-2	Software Quality Assurance Requirements
	DOP 3-3	Analysis Definition Requirements
	DOP 3-10	Routine Calculations
	DOP 3-12	Peer Reviews
	DOP 3-13	Independent Technical and Management Reviews of Documents
	DOP 3-16	Interface Interactions
	DOP 5-2	Technical Procedure Requirements
	DOP 6-2	Reviewing, Approving, and Issuing Technical Information Document
	QAP 10-1	Surveillance Requirements
	DOP 11-1	Experiment and Equipment-Test Procedure Requirements
	DOP 11-2	Requirements for Experiment and Equipment-Test Logbooks

TABLE A-1

NQA-1 CRITERIA FOR STUDY 8.3.1.15.1.3
AND IMPLEMENTING DOCUMENTS AND PROCEDURES
(continued)

NQA-1 Criteria #	Documents Addressing These Requirements	
4. "Procurement Document Control"	DOP 4-1	Procurement Document Requirements
	DOP 7-1	Procurement Planning
	DOP 7-2	Evaluation for Acceptance of Purchased Items or Services
5. "Instructions, Procedures, and Drawings"	The activites in this study are performed according to the Experiment Technical Procedures described in this Study Plan and the QA administrative procedures referenced in this table for criterion #3.	
	DOP 5-1	Procedure Format and Content Requirements
	DOP 5-2	Technical Procedure Requirements
	DOP 11-1	Experiment and Equipment - Test Procedure Requirements
6. "Document Control"	DOP 3-17	Preparing Technical Information Document
	DOP 6-1	Document Control System Procedures
	DOP 6-2	Reviewing, Approving, and Issuing Technical Information Documents
7. "Control of Purchased Material, Equipment, and Services"	DOP 4-1	Procurement Document Requirements
	DOP 7-1	Procurement Planning
	DOP 7-2	Evaluation for Acceptance of Purchased Items or Services

TABLE A-1

NQA-1 CRITERIA FOR STUDY 8.3.1.15.1.3
AND IMPLEMENTING DOCUMENTS AND PROCEDURES
(continued)

NQA-1 Criteria #	Documents Addressing These Requirements	
8. "Identification and Control of Materials, Parts and Samples"	DOP 3-8	Reference Information Base Change Process
	DOP 3-11	Requirements for Submitting Data to the YMP Site and Engineering Properties Data Base (SEPDB)
	DOP 11-3	Requirements for Interaction with the Data Records management system
	DOP 8-1	Sample Identification and Handling Requirements
9. "Control of Special Processes"	Not applicable to this study since no special processes in the sense intended by NQA-1 are involved in this study.	
10. "Inspection"	Not applicable to this study.	
11. "Test Control"	Not applicable to this study.	
12. "Control of Measuring and Test Equipment"	DOP 12-1	Measuring and Test Equipment Control
	DOP 8-1	Sample Identification and Handling Requirements
	DOP 13-1	Identification, Handling, Shipping, and Storage of Items
14. "Inspection, Text and Operating Status"	Not applicable to this activity since no hardware is generated by this activity	
15. "Nonconforming Materials, Parts or Components"	Not applicable to this study.	
16. "Corrective Action"	QAP 16-1	Corrective Action
	QAP 16-2	Deviation Reporting

TABLE A-1

**NQA-1 CRITERIA FOR STUDY 8.3.1.15.1.3
AND IMPLEMENTING DOCUMENTS AND PROCEDURES
(continued)**

NQA-1 Criteria #	Documents Addressing These Requirements
17. "Quality Assurance Records"	DOP 17-1 Records Management System
18. "Audits"	Not an activity under this study.

Table A-2

Summary of Documents Related to Quality Assurance for This Study Plan

QAP 1-1	Quality Assurance Program Plan Control
QAP 1-3	Quality-Related Work Stoppage
QAP 1-4	Resolution of Quality Assurance Disputes
QAP 2-5	Training and Familiarization Procedures
QAP 2-7	Qualification of Quality Assurance Program Audit Personnel
QAP 10-1	Surveillance Requirements
QAP 15-1	Nonconformance Control and Reporting
QAP 16-1	Corrective Action
QAP 16-2	Deviation Reporting
QAP 18-1	Quality Assurance Audits
DOP 2-1	Task Definition Statements
DOP 2-2	Study Plan Requirements
DOP 2-3	Work Plans
DOP 2-4	Analysis Control and Verification
DOP 2-6	Qualification and Certification of Project Personnel
DOP 2-9	Preparedness Review
DOP 3-2	Software Quality Assurance Requirements
DOP 3-3	Analysis Definition Requirements
DOP 3-8	Reference Information Base Change Process
DOP 3-10	Routine Calculations
DOP 3-11	Requirements for Submitting Data to the YMP Site and Engineering Properties Data Base (SEPDB)
DOP 3-12	Peer Reviews
DOP 3-13	Independent Technical and Management Reviews of Documents
DOP 3-16	Interface Interactions
DOP 4-1	Procurement Document Requirements
DOP 5-1	Procedure Format and Content Requirements
DOP 5-2	Technical Procedure Requirements
DOP 6-1	Document Control System
DOP 6-2	Reviewing, Approving, and Issuing Technical Information Documents
DOP 7-1	Procurement Planning
DOP 7-2	Evaluation for Acceptance of Purchased Items or Services
DOP 8-1	Sample Identification and Handling Requirements
DOP 8-2	Operation of the SNL NWRT Department Samples Library
DOP 11-1	Experiment and Equipment-Test Procedure Requirements
DOP 11-2	Requirements for Experiment and Equipment-Test Logbooks
DOP 11-3	Requirements for Interaction with the Data Records Management System
DOP 12-1	Measuring and Test Equipment Control
DOP 13-1	Identification, Handling, Shipping, and Storage of Items
DOP 17-1	Records Management System
DOP 17-2	Operation of the SNL NNWSI Project Data Records Management System (DRMS)