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Study Plan for
Study 8.3.1.15.1.5

Excavation Investigations

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EXCAVATION INVESTIGATIONS STUDY PLAN

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ABSTRACT

Three experiments constituting the Excavation Investigations Study Plan (i.e., access convergence, demonstration breakout room, and sequential drift mining) have been designed to provide a data set to assess repository excavation performance and help to validate the rock mass constitutive models that will be used to predict deformational behavior of the ground around the excavated openings of the Exploratory Studies Facility and of the proposed repository. Each of these experiments is designed to facilitate the analyses that will be performed to validate the models.

The access convergence experiment will provide displacement data to compare with the predicted rock mass response to excavation. The range of access convergence rates and magnitudes of the in situ stress state will be established at a minimum of three stations located at different depths with varying geological and geomechanical characteristics. Measurements of the rock mass response to the tunnel boring machine gripper pad loading will be made throughout the Exploratory Studies Facility.The ramp design criteria will be evaluated to ensure that ground support loads do not exceed design specifications.

Information gathered during the demonstration breakout room experiment will investigate the performance of drifts in high-lithophysal welded tuffs. The orientation will coincide with that defined for the underground facility, with some possible modifications based on observed geological and geomechanical characteristics. This experiment will assess the effect of certain local geologic variations (i.e., fracture characteristics and lithophysae content) on the design of the repository-size openings and will be used in a preliminary evaluation of support requirements and excavation efficiency in high-lithophysal rock mass conditions. Results will be used to continue the assessment of constitutive models that will be evaluated in detail with results from the sequential drift mining experiment. Samples will be collected for laboratory tests described in other study plans to determine the characteristics of the intact rock and fractures. The demonstration breakout room will also provide an underground location for conducting experiments discussed in other study plans that are intended to evaluate the in situ state of stress, modulus of deformation, mechanical strength, and thermal response of welded tuffs with varying geological and geomechanical characteristics.

The sequential drift mining experiment is designed to enhance the data base available for validating the rock mass constitutive models that will be used to predict deformations and stresses around the underground openings and assess the stability of the underground facility in support of the license application. The excavation of a repository-size drift will be closely monitored to determine displacement magnitudes in the stress-altered region, which will be compared with predictions based on analyses performed using the rock mass constitutive models. The results will also be used

for evaluating the preliminary design concepts related to ground support requirements and excavation efficiency.

The tunnel boring machine rock mass modulus and compliance experiment is intended to provide the first information on the response of a realistically large volume (up to tens of meters) to applied loads. The experiment will provide data for evaluation of the rock mass constitutive models that will be used to predict deformations and stresses around underground openings in support of the license application. The data will also be used to evaluate design assumptions related to ground support requirements.

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1.0 Introduction

This study plan describes one series of in situ experiments intended to (1) provide some of the data for assessing the validity of the rock mass constitutive models that will be used in the repository design process and that will support the license application, and (2) demonstrate constructibility and long-term stability of full-scale openings. Data from other studies, both laboratory and in situ, will complement the excavation investigations data set. This combined data base is expected to provide the information required to develop and evaluate the constitutive models that will be used to predict the rock mass deformational behavior resulting from repository construction and waste emplacement activities.

The approach that has been adopted to understand and predict the mechanical response of the rock mass to the conditions imposed by repository excavation and waste emplacement is to employ progressively more complex numerical models (e.g., Morland, 1974; Thomas, 1980, 1982; Chen, 1986, 1987; and Blanford et al., 1987), which contain an improved understanding of rock mass deformational processes, during continued analyses for repository design, performance, and safety. These models attempt to incorporate those features (e.g., joint characteristics) that are likely to exert a significant influence on the types of overall deformational behavior so that important phenomena are identified and eventually defined in a manner that permits reasonable bounds to be placed on their magnitude. As these models are exercised and as experimental data are obtained, additional insight into the mechanics of rock mass deformational processes is gained. Careful variation of the geometric considerations that may influence the model (e.g., boundary conditions, fracture spacing, etc.) and the constitutive properties of the model can also help to identify the mechanics of the overall system and provide an understanding of the critical factors to include in a numerical model of a fractured rock mass.

1.1 Objectives of the Excavation Investigations Study

The experiments discussed in the excavation investigations study compose one element in the approach that has been adopted to develop and validate the models required to confirm the repository design. The primary objective of these experiments is to obtain an adequate data base that can be used to continue to develop and eventually validate the rock mass constitutive models used to predict deformational behavior (i.e., displacements and stress distribution). The experiments also provide an evaluation of constructibility and stability of repository-size openings. The rock mass mechanical models will be combined with a thermal model to predict the thermomechanical response of the underground openings to repository excavation and waste emplacement and to help develop an adequate design for stabilizing the underground facility.

Three experiments [access convergence, demonstration breakout room (DBR), and sequential drift mining] are designed to provide a data set that will be used to assess repository performance and help to validate the rock mass constitutive models developed for predicting the mechanical behavior of repository-size openings (Table 1-1). Each of these experiments is designed to facilitate the analyses that will be performed in the validation effort. All three experiments will be conducted in, or adjacent to, the main access, the main test level inside the underground facility, or the Calico Hills drifting.

TABLE 1-1. SUMMARY OF ACTIVITIES ASSOCIATED WITH EACH EXPERIMENT DISCUSSED IN THE EXCAVATION INVESTIGATIONS STUDY PLAN (SCP Section 8.3.1.15.1.5)

Experiment	Activity
Access Convergence	In Situ Stress Measurements Estimate of Stress-Altered Region Liner Contact Pressure Measurements Rock Mass Response Measurements
Demonstration Breakout Room	Drift Convergence Magnitude Measurements Drift Convergence Rate Measurements Estimate of Stress-Altered Region Excavation Efficiency Estimate
Sequential Drift Mining	Drift Convergence Magnitude Measurements Drift Convergence Rate Measurements Estimate of Stress-Altered Region Excavation Efficiency Estimate Water Permeability Measurements

The access convergence experiment will provide data to compare with the predicted response of the rock mass and ground support during and after excavation. A range of access convergence rates and magnitudes and the in situ stress states will be obtained at a minimum of three stations located at different depths with varying geological and geomechanical characteristics. An evaluation of the access design criteria will be performed to ensure that ground support loads do not exceed design specifications.

Information gathered during the DBR experiment will be used to investigate the performance of repository-size drifts constructed in high-lithophysal welded tuffs. The approximate location of the DBR will be determined using borehole data available before the start of access construction. The optimum orientation will coincide with the primary orientation defined for the underground facility (SNL, 1987) with some possible variations based on observed geological and geomechanical characteristics. This experiment will assess the effect of certain local geologic variations (i.e., fracture characteristics and lithophysae content) on the design of the repository-size openings and will complete a preliminary evaluation of support requirements and excavation efficiency in high-lithophysal rock mass conditions. Results will be used to continue the assessment of constitutive models that will be further evaluated with results from the sequential drift mining experiment. Samples will be collected for laboratory tests described in other study plans to determine the characteristics of the intact rock and fractures. The DBR will also provide an underground location for conducting experiments discussed in other study plans that are intended to evaluate the in situ state of stress, modulus of deformation, mechanical strength, and thermal response of welded tuffs with varying geological and geomechanical characteristics.

The sequential drift mining experiment is the primary experiment designed to enhance the data base required for validating rock mass constitutive models. These models will be used to predict deformations and stresses around the underground openings and assess the stability of the underground facility in support of the license application. The excavation of a repository-size waste emplacement drift will be closely monitored to determine displacement magnitudes and rates in the stress-altered region, and the information will be compared with predictions made using the rock mass constitutive models. The results will also be used for evaluating the preliminary design concepts related to ground support requirements and excavation efficiency.

Other measurements and observations that will complement the data base developed with this study plan and that will be used in the model validation process emphasize those factors that influence the large-scale mechanical behavior of the rock mass (Table 1-2). These measurements and observations will be used to describe the geological and geomechanical characteristics of the access and drifts in the Exploratory Studies Facility (ESF); characterize the mechanical properties of the rock mass, intact rock, and fractures; calculate the in situ state of stress; and provide a data base for validating the thermal model used to predict the rock mass thermal response. The information obtained in these study plans will collectively provide the basis for the predictive capability necessary to design stable underground openings that require minimal maintenance during the repository operational period.

TABLE 1-2. STUDY PLANS THAT WILL PROVIDE DATA TO SUPPORT MODEL VALIDATION EFFORTS AND IMPROVE THE UNDERSTANDING OF DEFORMATIONAL PROCESSES ASSOCIATED WITH FRACTURED ROCK

Study Plan	Description
8.3.1.4.2.1	Characterization of the vertical and lateral distribution of stratigraphic units within the site area
8.3.1.4.2.2	Characterization of the structural features within the site area
8.3.1.15.1.3	Laboratory determination of the mechanical properties of intact rock
8.3.1.15.1.4	Laboratory determination of the mechanical properties of fractures
8.3.1.15.1.6	In situ thermomechanical properties
8.3.1.15.1.7	Rock mass mechanical properties
8.3.1.15.1.8	In situ design verification
8.3.1.15.2.1	Characterization of the site ambient stress conditions
8.3.1.17.4.8	Stress field within and proximal to the site area

1.1.1 Use of Excavation Investigations Study Results

The principal information requirements for resolving preclosure issues related to repository design center on the question of adequate support for the underground openings. The design and support of these openings are dependent on the rock mass characteristics, the in situ stress state, and the geometry of the openings (Hardy and Bauer, 1991). With the exception of a part of the access convergence experiment, the excavation investigations experiments will be performed within specific intervals of the Topopah Spring Member containing the range in rock characteristics expected to represent the characteristics encountered throughout the repository block (Nimick et al., 1988). The predominant fracture orientation within the Topopah Spring Member is vertical, and fracture density is greatest within the densely welded portion of the Topopah Spring Member (Spengler et al., 1984). Some experiments are planned for a portion of the Topopah Spring Member that has a lithophysae content expected to range up to 24%, the maximum that is currently expected within the repository horizon (Nimick et al., 1988).

The vertical component of the in situ stress is expected to be governed by the lithostatic load calculated at any specific depth. Horizontal components of the stress state are controlled largely by the lithostatic load, tectonic effects, and elastic properties of the rock mass. The magnitude and orientation of the three principal stress components will be evaluated during the in situ testing program. Variations in the state of stress associated with the underground openings can result from the geometry of the openings, heating of the rock by the emplaced waste or test equipment, and occasional man-induced or natural seismic events. The stress-altered region associated with underground openings constructed by blasting consists of both the blast-damaged zone and stress redistribution zone, which may overlap depending on several variables including rock mass characteristics and blasting techniques. In mechanically excavated openings the stress redistribution zone will occur without a blast-damaged zone. The radial extent of the blast-damaged zone can extend from a few tenths of meters to in excess of one meter from the perimeter of the opening depending on local rock characteristics and the mining method employed (Holmberg and Persson, 1980). The stress redistribution zone may contain rock that has been stressed both elastically and inelastically and whose distribution will vary depending on the shape, orientation, and distribution of the openings and variations in the strength and deformability of the rock mass. Induced stresses in this zone are generally considered negligible beyond three opening diameters from the perimeter (St. John, 1987). The undisturbed in situ stress state must be known or estimated before the stress changes resulting from excavation can be estimated.

1.2 Rationale and Justification for Information To Be Obtained

1.2.1 Resolution of Performance and Design Issues

Performance allocation has been used to establish appropriate issue resolution strategies for design and performance objectives in the Yucca Mountain Project Issues Hierarchy. A general discussion of the performance allocation approach is provided in Section 8.1 of the SCP, and issue resolution strategies for each site program are provided in SCP Section 8.3.1.

Sections 6.4 and 8.3 of the SCP provide a detailed discussion of the approach that will be used in the design of the underground openings. This discussion is amplified in the YMP Drift Design Methodology (Hardy and Bauer, 1991). This approach emphasizes the need to ensure that openings associated with the underground facility will remain usable throughout the retrieval period (SCP Sections 6.4.8-6.4.10). The ability to predict displacement magnitudes and to estimate the limit and nature of the stress-altered region is fundamental to our ability to ensure the retrieval of waste for up to 50 yr. after emplacement begins and to demonstrate that an underground facility can be constructed in welded tuff using reasonably available technology. The assessment of stability that will be used initially involves meeting applicable health and safety standards using empirical design guidelines, which are then checked by mechanical, thermal, and thermomechanical analyses to assess their adequacy. The ground control strategy concept (Hoek and Brown, 1980) establishes some limiting value on the amount of displacement and induced stress that cannot be exceeded during construction for the proposed design of the underground opening. This design approach then uses Tunnel Index methods (Barton et al., 1974; and Bieniawski, 1976) to establish the initial ground support system requirements. These methods are then supplemented with a monitoring system to assess the effectiveness of the support system selected and, with boundary element and finite element calculations, to predict changes in stress and displacement resulting from thermal effects.

Information Need 4.2.1 (SCP Section 8.3.2.4) identifies the site parameters that must be obtained to design the repository and to develop the repository operating procedures that ensure the nonradiological safety of the worker. The excavation investigations study will provide the following types of information requested by Information Need 4.2.1: (1) demonstration of construction methods with emphasis on different lithophysae abundance, vitrification, and geologic structure characteristics; (2) characterization of the exposed rock to ensure compatibility with the proposed design of the ground support system; (3) monitoring of the performance of the rock mass and ground support for different rock types and ground support systems; (4) evaluation of ground support performance with performance predictions; and (5) validation of the design models used to predict the performance of drifts and access ways.

Several parameters are required for the analysis of the underground repository (Information Need 4.4.7; SCP Section 8.3.2.5.7). In situ stress measurements will be performed as part of the access convergence experiment and in the DBR experiment as part of Study 8.3.1.15.2.1: Characterization of the Site Ambient Stress Conditions. Measurements performed during the DBR experiment will provide information on the response of the rock mass to drill and blast mining techniques and to the ground support system used. The sequential drift mining experiment will provide data on fracture density, orientation, and spacing, which are required by Information Need 4.4.7. Additionally, this experiment will enhance the data base used for the validation of models that provide a measure of the design performance. The excavation investigations study is called for specifically in SCP Section 8.3.2.5, which lists those studies required for design and performance analyses.

SCP Section 8.3.1.15 requires that in situ rock mass properties are obtained for examining the validity of extrapolating laboratory properties to in situ conditions. Additionally, observations of the behavior of underground excavations are required to evaluate the response of the welded, devitrified Topopah Spring Member (Units TSw1 and TSw2) to the excavation process and to validate the constitutive models being developed to predict the mechanical response of the rock mass. The experiments planned for the excavation investigations study will provide data that will be used to help develop, test, and eventually validate the rock mass constitutive models.

Information Need 1.11.5 (SCP Section 8.3.2.2.5) requires that the damaged zone around the drifts be adequately characterized at the time of repository closure. Displacement measurements around the periphery of the access and repository-size drifts in each of the excavation investigations study experiments will be used to delineate the extent of damage induced by excavation. Additionally, permeability and compressional velocity measurements performed in the sequential-drift mining experiment will be used to estimate the rock mass changes occurring in the stress-altered region.

1.2.2 Regulatory Requirements

This study will provide some of the information required to demonstrate compliance with several key regulations outlined in 10 CFR 60, "Disposal of High-Level Radioactive Wastes in Geologic Repositories: Licensing Procedures" (NRC, 1986). These regulations form the basis for the guidelines outlined in 10 CFR 960, "Nuclear Waste Policy Act of 1982; Final Siting Guidelines" (DOE, 1986). Performance objectives as stated in 10 CFR 60 require demonstration that (1) waste retrieval shall be feasible starting at any time up to 50 yr. after waste emplacement begins (60.111) and that (2) the overall system performance of the geologic repository shall be such as to ensure that releases of radioactive material to the accessible environment conform to applicable Environmental Protection Agency requirements (60.112). The excavation investigations experiments will contribute to a data base that can be used to refine and validate the rock mass constitutive models used to evaluate the design of the underground facility. This design is intended to permit retrievability during the preclosure period. These experiments will also characterize the stress-altered region and assess its extent so that performance assessment calculations can incorporate variations in the rock mass properties throughout this region.

The Nuclear Regulatory Commission (NRC) requires that the underground openings be designed so that operations can be carried out safely and that the option to retrieve waste is maintained (10 CFR 60.133(e)). Potentially adverse conditions outlined in 10 CFR 60.122(c)(21) and 10 CFR 960.5-2-9 include in situ characteristics and geomechanical properties that do not allow the design of underground openings that can be constructed with reasonably available technology and will remain stable through permanent closure without extensive maintenance. Displacement, in situ stress, and rock bolt load cell measurements performed in the excavation investigations experiments will be used to assess the stability of the underground openings through permanent closure. Openings will be designed to minimize deleterious rock movement and fracturing of overlying or surrounding rock, and the design of the underground facility shall incorporate excavation methods that limit the potential for creating a preferential pathway for ground water (10 CFR 60.133). Evaluation of excavation efficiency and measurements of permeability and compressional velocity planned for the sequential drift mining experiment will be used to address these regulations. A safety analysis report (SAR), which must be prepared for submittal with the license application, will contain a description and assessment of the proposed geologic repository operations area that might influence design and performance. In the SAR (10 CFR 60.21), the NRC requires that "analyses and models, which will be used to predict future conditions and changes in the geologic setting, shall be supported by using an appropriate combination of methods such as field tests... which are representative of field conditions, monitoring data, and natural analog studies." This report will also document the geomechanical properties and conditions including pore pressures and ambient stress conditions (10 CFR 60.21). In addition, the SAR will provide an analysis of the performance of the major surface and subsurface design structures, systems, and components to identify those that are important to safety. Some of the information required to perform this analysis will be provided by measuring in situ stresses, monitoring loads in the ground support system, and assessing the extent of the stress-altered region around an opening.

The performance of major design structures that are required in 10 CFR 60.21 may affect the proposed shape and stabilization methods for varying rock conditions. The construction of repository-size drifts will be used to demonstrate that stabilization in welded tuffs having varying lithophysae content and fracture densities is feasible. The requirement for minimizing the potential for deleterious rock movements and fracturing (10 CFR 60.133) are addressed by the estimates of the stress-altered region and excavation efficiencies, which provide supporting information on minimizing this potential. Adverse rock conditions that require complex engineering measures must be defined as required by 10 CFR 60.122.

A requirement of 10 CFR 60.21 states that in situ field tests must be performed to support the analyses and models used to predict future conditions. Some of these predictions for Yucca Mountain will be made using the constitutive models for rock mass mechanical behavior that will be assessed using data collected in the excavation investigations experiments. Developing excavation techniques that limit the potential for creating preferential pathways for radionuclide transport (10 CFR 60.133.f) will be addressed using data obtained to define the extent of the stress-altered region. Permeability measurements obtained during the sequential drift mining experiment will be used to address, in part, 10 CFR 60.134.b, which requires the use of materials and emplacement methods that reduce radionuclide transport through existing pathways.

2.0 Rationale for Excavation Investigations Study

Three experiments are planned for the excavation investigations study that will emphasize monitoring the response of the rock mass to the excavation process. Each of these experiments is described in Section 3.0 of this study plan. The access convergence and DBR experiments are approaching the final design stages, which may be modified as in situ data from the ESF construction become available. The sequential drift mining experiment will be modified as information is obtained from the other two experiments during construction of the ESF. The primary emphasis in each of these experiments is to measure rock mass displacements, which will be used in validating the models and calculating the various parameters needed to describe the characteristics of the underground openings (e.g., stress distribution, convergence rate, and magnitude). The techniques planned for this study plan (Section 3.0) emphasize the use of multiple-point borehole extensometers (MPBXs) and tape extensometers, which have been widely used and readily accepted by the mining and rock mechanics communities for monitoring rock mass response during and after construction of underground openings (e.g., Bieniawski and Maschek, 1975; Franklin, 1977; Brady and Brown, 1985; and others).

2.1 Rationale and Justification for Excavation Investigations Experiments

2.1.1 Model Validation

The primary objective of the excavation investigations study is to obtain a data base that will be used in the development and validation of the constitutive models for predicting the deformational behavior of the rock mass in response to stresses induced by excavation and thermal loading. Although these three areas (i.e., data collection, model development, and model validation) are closely related, the rationale presented in this study plan emphasizes the collection of data to support the latter areas and only briefly summarizes, with appropriate references, the model development effort and the validation process. All three activities will be performed in accordance with Sandia National Laboratories (SNL) YMP Quality Assurance Implementing Procedures.

Recent attempts to model the response of the rock mass to excavation and to estimate the measured displacements have had limited success (Heuze et al., 1981a; Heuze, 1984b; Butkovich, 1985; Butkovich and Patrick, 1986; Morgan et al., 1985; Munson and Fossum, 1986; and Wawersik and Morgan, 1987). Discrepancies between measured and calculated closure rates in bedded salt at the Waste Isolation Pilot Plant (WIPP) suggest that the models used to predict closure do not fully encompass the physical phenomena controlling closure in salt. Wawersik and Morgan (1987) identified several conceivable sources of error that may contribute to the discrepancies between measured and predicted convergence values. Some of these sources of error include (1) differences between the thermomechanical behavior of salt core in laboratory tests and of salt masses in situ, (2) errors in generalizing one- and two-dimensional axisymmetric thermomechanical measurements on salt to three dimensions, (3) omission of immediate plastic strains, (4) inaccuracies in stratigraphic idealization, and (5) incorrect descriptions of transients and history effects.

Similar comparisons performed in fractured granitic rock at Climax also show significant disparities between predicted and measured closure trends and magnitudes (Heuze et al., 1981a,b; Heuze, 1984b; Butkovich, 1985; and Butkovich and Patrick, 1986). The predictions at Climax indicate horizontal and vertical closure of the drifts and lateral expansion of the pillars. Field measurements indicate lateral contraction of the pillars and inconsistent drift closure data. The apparent discrepancies between the measured and calculated closure rates at both WIPP and Climax demonstrate the difficulties of obtaining reasonable concurrence between the measured and calculated rock mass response and of identifying and accurately representing the physical phenomena that control rock mass deformation. The staged, iterative experimental and modeling approach presented in this study and the approach to model development discussed in Sections 6.4.2 and 8.3.2 of the SCP are intended to provide the capability to make acceptable *a priori* predictions that accurately reflect the nature and magnitude of fractured rock mass deformational behavior.

Both empirical and numerical modeling approaches will be used to predict the rock mass response to excavation in jointed, welded tuff. Empirical approaches rely on rock mass classification methods, which are based on experience, to predict stability and to design ground support systems. This approach does not, however, take into account the effects of heat.

The numerical modeling methods are founded on constitutive laws that mathematically describe the physical processes of fractured tuff deformation. The models currently being considered approximate the mechanical response of the rock mass as an elastic, elastic-plastic, compliant jointed medium or discrete blocks (SCP Sections 6.4.10 and 8.3.2; Thomas, 1980, 1982; Chen, 1986, 1987; Blanford et al., 1987). These models will incorporate an understanding of the physics of the deformation process to provide a quantitative assessment of the stress state and the displacements resulting from both mechanically and thermally induced stresses. Thus the numerical models provide insight into the underground design that is not possible using empirical techniques alone.

A linear elastic constitutive model has been used to approximate the measured deformation of densely welded, jointed tuffs in G-Tunnel (Zimmerman et al., 1986). In this application the elastic constants that serve as input parameters to the model were modified to account for the fractured rock mass and to provide a reasonable approximation of the measured deformation. The ubiquitous joint model (Thomas, 1980) has also been used to evaluate the state of stress in jointed, welded tuff. This model incorporates an elastic-plastic joint shear behavior and assumes a single dominant fracture orientation and spacing. This assumption may restrict the application of this model to specific areas of the underground facility characterized by extensive, regularly spaced fractures. The compliant joint constitutive model (Thomas, 1982; Chen, 1986, 1987; Blanford et al., 1987) incorporates a continuum-based technique to average the discontinuous displacements across fracture planes within a representative elementary volume and a constitutive description based on the linear elastic behavior of the matrix material and nonlinear normal and shear behavior of the joints. In the compliant joint model, material properties are required for both the matrix and the fractures. The model is formulated in three dimensions, but is currently limited to two-dimensional implementations in finite element codes, orthogonal joint sets (Chen, 1987), or multiple joint sets (four maximum) of arbitrary orientation (Blanford and Key, 1988), and noninterfering block responses. Data obtained from G-Tunnel (Zimmerman et al., 1987; 1988) and from Yucca Mountain will be used in an attempt to minimize these restrictions and improve the capability of this model to describe multiple joint sets with variable orientations and characteristics.

The experiments planned in this study emphasize measurements in planar geometries that are more easily modeled by two-dimensional codes and can be used to evaluate the physics controlling the deformational behavior of the rock mass. Some measurements will be incorporated into the sequential drift mining experiment to provide a limited data base for exercising the three-dimensional components of the numerical models. The In Situ Thermomechanical Properties Study (Study Plan 8.3.1.15.1.6) will include a heated room experiment that emphasizes the collection of displacement measurements that should provide a sizable data base for comparison with the results of numerical simulations in three dimensions and provide a detailed comparison between the two- and three-dimensional approximations. The model validation process, discussed in Sections 6.4.2, 8.3.2, and 8.3.5.20 of the SCP, is intended to ensure that the mathematics underlying the software is a correct representation of the physical process or processes. The formal validation process includes a series of steps that concludes with a comparison of experimental results and analytical predictions by a peer review panel. The excavation investigations study experiments are intended to provide bounding estimates for the displacement data that will be compared with analytical predictions. This comparison will be used to assess whether the measured and predicted results are of the same trend and whether disparities between the measured and predicted data fall within the limits of the combined range of uncertainties associated with the data used as input for the calculated response and the uncertainties in the measured field data. Failure to validate the rock mass constitutive models may require that performance allocation goals be reevaluated and that additional data acquisition and characterization studies be initiated. The peer review panel is expected to provide input about the direction any additional activities should take.

2.1.2 In Situ Monitoring of Rock Mass Performance

The primary objective of any underground excavation design is to use the rock mass itself as the principal structural support material and minimize the need for additional ground support (Hoek and Brown, 1980). To achieve this objective it is necessary to minimize the effects of the excavation process on the surrounding rock and to develop an understanding of the geological and geomechanical characteristics of the rock mass. An understanding of the effects of excavation on the in situ stress state and the interaction of the underground support system with the redistributed stresses is necessary to develop an underground facility that will remain serviceable throughout the required operational period.

Monitoring the behavior of underground excavations during and after the construction process is the most reliable means of developing an understanding of the behavior of the rock mass for the design and construction of underground structures (Bieniawski and Maschek, 1975). Information obtained during a monitoring program will be used to check the validity of the assumptions, conceptual models, and rock mass properties used in design considerations. Additionally, this information will contribute to worker safety by providing data to detect excessive ground deformations or loads imposed on the repository support elements. Time-dependent deformational behavior resulting from possible long-term physical or chemical changes may influence the stability of underground excavations. Monitoring programs can be used to identify these time-dependent changes if they occur, so that appropriate remedial programs can be developed.

The observational method (Peck, 1969), which emphasizes field observations of the performance of structures, is central to the general practice of geotechnical engineering. Brady and Brown (1985) summarize the types of measurements generally incorporated in a monitoring program associated with the construction of an underground facility. This program emphasizes two basic physical responses, displacement and pressure, that are then used to calculate forces and stresses using available numerical models and estimated material properties. Bieniawski and Maschek

(1975) have shown that convergence magnitude and rate measurements are important parameters for predicting the adequacy of underground support systems.

The in situ stress state that exists in an undisturbed rock mass is related to the weight of the overlying strata and the geologic history of the rock mass. An underground excavation will disturb the in situ stress field and may induce stresses that exceed the rock mass strength, leading to failure or instabilities manifested as gradual closure, rock falls, slabbing, spalling, and, in the worst case, even rockbursts (Hoek and Brown, 1980; Hoek, 1977). In order to minimize the uncertainty associated with calculating induced stresses, the undisturbed in situ stress state must first be determined (Hoek and Brown, 1980). Although the stress distribution around an isolated underground opening in a linear elastic, homogeneous, isotropic material is independent of the size of the opening, the stability of an opening in a jointed medium is still largely contingent on the ratio of the excavation size to the representative size of the blocks composing the rock mass. Thus, although the theoretical stress level may remain constant as the size of the excavation increases, the likelihood of stability of the opening decreases. This emphasizes the significance of a detailed geologic characterization program that is integrated directly with the geomechanical testing program.

A number of other factors can influence the distribution of the stress state and, hence, possibly the stability of the underground facility. The shape, orientation, and distribution of the openings can have a significant effect on the induced stress distribution as can the size, shape, and distribution of the pillars and geologic structure (Hoek and Brown, 1980). Each of these factors must be considered when defining the expected induced stress state so that the response of the rock mass can be adequately predicted and a design for the underground facility that ensures stability can be developed.

A detailed geologic characterization study is a fundamental component of any in situ monitoring program. Wilder et al. (1982) suggest that the geologic characteristics of the rock mass are possibly the most significant factors that influence MPBX measurements. This may be particularly true in fractured rock, where measurements may be influenced by joint closure and rigid block rotation and/or translation. Zimmerman et al. (1987; 1988) performed convergence measurements in welded tuffs located in G-Tunnel using a tape extensometer and MPBXs. Convergence magnitudes along a 30-meters-long, repository-size drift varied by a factor of two, which they attribute, in part, to variations in local geology. Detailed geologic characterization studies are required at each geomechanical measurement station within the access or drift to enhance the interpretation of data. Standard mapping or photogrammetric techniques should be employed to map the access and drift walls; cores and instrumentation holes will be examined to delineate variations in the rock characteristics and to select borehole instrumentation locations.

Franklin (1977), Pratt et al. (1979), Brady and Brown (1985) and others have described the requirements for a monitoring system that will help to ensure safety during the construction phase and check the assumptions used in the underground design. The type of monitoring program developed for a particular geologic medium depends largely on the characteristics of the rock mass and the objectives of the construction project. In each project, however, measurements are usually obtained with several different types of instruments that are capable of providing the information required to achieve the stated objectives. An integral part of any instrumentation program is the incorporation of a suite of instruments that are capable of obtaining redundant measurements to enhance data interpretation and to ensure that data will be obtained despite potential instrument failure.

Two types of basic physical responses, displacement and pressure, are measured in most monitoring programs (Brady and Brown, 1985) and have been incorporated in the excavation investigations experiments. Displacement of the rock associated with excavation of the underground structure is generally monitored using MPBXs, tape extensometers, and borehole inclinometers. Rock pressures and loads on the support system are measured or derived using borehole deformation gauges and stress meters, hydraulic pressure cells, and rock bolt load cells. Data obtained using these instruments will play a fundamental role in enhancing our understanding of the response of the rock mass to the excavation process in the underground facility.

2.1.3 Measuring of Rock Mass Modulus and Compliance During Excavation

Rock mass modulus and rock mass compliance are parameters of extreme importance to the YMP for validation of geomechanical performance assessment models and for evaluation of empirical models that describe the response of the ground support to loading. An approach to provide data to evaluate both parameters is to measure the load-deformation response of the rock loaded by the gripper pads of the tunnel boring machine during excavation of the underground openings. The large loads (up to 8 million) imposed by each gripper pad provide an ideal opportunity to conduct routine deformation modulus measurements throughout the underground facility. The size of each pad (about 24,000 square inches) allows a large representative volume of rock to be loaded during each gripper episode. The orientations of the pads and the orientation of the underground openings will allow for an assessment of the spatial variability as well as anisotropy of deformation modulus and jointed rock compliance in the underground at Yucca Mountain.

Numerous techniques have been developed to estimate the deformation modulus of jointed rock masses (e.g. Goodman et al., 1968; Hustrulid and Schrauf, 1979; Rocha, 1964; Pratt et al, 1977; Brown, 1981; and Schneider, 1967). These techniques include large-scale in situ tests such as plate loading tests, pressurized gallery tests, and flatjack tests in slots; borehole tests such as the borehole jack (Goodman jack) and dilatometers; geophysical techniques such as cross hole ultrasonics; and estimation from rock quality field surveys.

The combination of loaded area and range of applied pressure defines the volume of rock influenced by the test. Even at the high pressures used in the borehole techniques, the small loaded areas create very limited volumes of rock influenced by these tests. This can be illustrated by considering elasticity theory for pressure distributions under a square loaded foundation, which clearly show that the loads quickly dissipate with distance into the rock. Therefore, it is beneficial to either increase the loaded area or increase the applied load substantially in order to measure load/deformation response of a realistic volume of rock surrounding the underground openings at Yucca Mountain. It is important to note that although the pressures developed under the tunnel boring machine gripper pads are somewhat lower than may be required to affect complete closure of individual joints, the large volume of rock influenced provides reliable and realistic data on at least a portion of the load/deformation response of the actual rock surrounding main underground accesses for the Yucca Mountain ESF.

A limited number of laboratory rock joint compliance studies have been conducted by SNL for the YMP. Results of tests on Topopah Spring tuff have been reported by Olsson(1987). These tests were conducted on artificial rough fractures in which the shear and normal compliance were measured on both mated and nonmated fractures. The results of these tests show that at normal stress levels of up to 2 MPa (290 psi) the majority of joint closure has occurred, especially for the mated fractures. This suggests that in situ measurements of rock mass deformation modulus can capture a significant portion of the load-deformation response of TSw2 if a representative volume of rock is loaded to above about 250 psi.

Data obtained from the measurements of rock mass modulus and compliance are fundamental to understanding the response of the rock mass to excavation and can be used to evaluate the expected response of rock mass displacement measurements as they are made throughout the underground facility.

2.2 Rationale for the Location, Number, and Alternatives for Excavation Investigations Experiments

2.2.1 Number and Location of Experiments

The location of each excavation investigations experiment within the ESF has been selected to characterize the range of rock mass characteristics that are most likely to be encountered during the development of the underground facility. The geologic variability anticipated within the underground facility results primarily from changes in fracture characteristics and lithophysae content. Each reference geomechanical and geological unit within the Topopah Spring Member (Ortiz et al., 1985) above the repository level will be characterized to assess the effects of these variations on the stability of the underground openings.

The number of experiments planned in this study are considered the minimum necessary to obtain the data base for validating the constitutive models, to provide in situ geomechanical parameters in support of site characterization activities, and to monitor the performance of repository-size underground openings. Each experiment includes a series of measurement stations that will be used to evaluate the variability within the major geologic units examined.

A staged approach has been adopted for obtaining a data base for validating the rock mass constitutive models. This approach begins by obtaining data in the access convergence and DBR experiments that are located in the various geological and geomechanical units that have characteristics that may be encountered in the underground facility. These data will be used to refine the models and to perform a preliminary assessment of the effects of geologic variability on the stability of the underground openings. As data become available from these two experiments, a comparison of the measured and predicted response of the underground openings to the excavation process will be completed. As a result, the models will be revised if necessary. The primary evaluation of the rock mass constitutive models will then be performed using the data base obtained during the sequential drift mining experiment. This experiment will be performed in an area within the ESF that is expected to be representative of the geological and geomechanical characteristics expected at the repository horizon (Nimick et al., 1988). As a result of this approach, the models should, by incorporating the appropriate geomechanical parameters determined for the geological units encountered, accommodate the range of geological conditions that are expected to occur within the underground facility.

Experience gained during the excavation and stabilization of repository-size openings in the various rock types likely to be encountered underground will assist in minimizing the damage induced during the excavation of the underground facility and maximizing the efficiency of the mining process. Specific ground support requirements that exist for certain rock types or structural features need to be confirmed early in the construction phase to minimize their impacts on scheduling and budget. Performance of the underground openings needs to be evaluated in repository-size drifts that are of sufficient length to discount the effects of the termination of the opening and the effects of interaction with other underground openings. Each of these concerns requires a substantial amount of excavation, which will be performed, in part, to fulfill the objectives of the excavation investigations experiments.

2.2.2 Alternatives for Excavation Investigations Study Experiments

The staged approach described in Section 2.2.1 for obtaining data to validate the rock mass constitutive models is intended to provide an understanding of the interrelationships between geological variability and the geomechanical response of fractured welded tuffs. This understanding will be developed in an iterative manner, beginning with the experiments that evaluate the rock mass response to excavation in each major geological unit within the Topopah Spring Member (i.e., access convergence and DBR experiments) and culminating with the detailed geological characterization and geomechanical measurement program that will be performed as part of the sequential drift mining experiment. The sequential drift mining experiment will include characterization of the rock mass before excavation and monitoring of the rock mass response during and after excavation. This information will be used to evaluate the time-dependent behavior of the rock mass within a well-defined geologic setting.

Other types of experiments will supplement the information obtained by the excavation investigations experiments by providing specific types of similar data (e.g., displacement data) in other regions of the underground facility (In Situ Design Verification Study Plan; SCP 8.3.1.15.1.8). Convergence measurements will be performed within the drifts in the ESF. These measurements will be used to develop a substantial data base, containing drift convergence rates and magnitudes, obtained after the mined face has advanced beyond the measurement station location. These data may be useful for designers to establish appropriate stand-off distances and adequate stabilization techniques within these zones. The configuration of these drifts, however, will not permit instrumentation to be installed before the onset of excavation, thereby precluding the collection of data related to the initial response of the rock mass to excavation. Information of this type will be collected in the sequential drift mining experiment.

Several similar activities will be completed in each of the experiments planned for the excavation investigations study. These activities are largely related to defining the extent of the stress-altered region and to monitoring convergence rates and magnitudes. Several techniques will be used to define the extent of the stress-altered region. Variations in rock mass displacements and changes in the stress state, permeability, and compressional velocity will be used to delineate the blast-damaged zone and the stress redistribution zone. Convergence rates and magnitudes will be established using displacements obtained with MPBXs, tape extensometers, and borehole inclinometers.

The Goodman jack, used to obtain estimates of deformation modulus, is also being considered for evaluating the extent of the stress-altered region. The technique has had limited application within fractured welded tuffs and may be influenced by joint spacing. In addition, the volume of rock energized with the Goodman jack is limited and may only be used to provide profiles of relative changes in the deformation modulus. However, results from Patrick et al. (1985) indicate that a statistically significant decrease in deformation modulus occurs very near the excavation surface (<0.5 meters) in fractured granitic rock, which should correspond to the interval containing the blast-damaged zone in the underground facility. This technique will be evaluated further to establish its reliability in a fractured geologic medium before it is incorporated into any of the excavation investigations experiments.

High-frequency rock noise (acoustic emission) generated from changing stress conditions has been used to successfully monitor the structural stability of underground mining operations (Repsher and Steblay, 1985; Majer et al., 1981; Majer and McEvilly, 1985). Acoustic emission monitoring has been particularly useful in predicting rockbursts in overstressed rocks with high elastic and strength properties. Hardy (1984) and others have begun to detect and process low-level signals associated with soils and soft rocks such as salt. Application of acoustic emission in these geologic media necessitates a higher degree of monitoring system optimization and additional care in signal processing than normally required with higher energy events associated with high-stress regimes.

The acoustic emission technique has been considered for monitoring rock mass stability in the DBR and sequential drift mining experiments. Low-level acoustic emission events may occur in the facility after the ground support system is installed. The intensity and number of acoustic emission events caused solely by the redistributed stress field is not expected to provide a sufficient data base to augment the other excavation investigations study activities planned. Unless the stress conditions induced by the orientation of the underground facility can be greatly increased without introducing a thermal source or unless time-dependent deformation processes related to physical or chemical changes are occurring, the acoustic emission technique has very limited application in the excavation investigations study experiments.

Petite seismique has been used by a number of investigators to determine the field deformation modulus of the in situ rock mass (Schneider, 1967; Bieniawski, 1978; Heuze et al., 1981b; Zucca, 1984) in a number of different rock types. The petite seismique technique involves energizing the rock mass to create a shear wave and then recording the signal at some location up to tens of meters away. The dominant frequency of the recorded shear wave is measured, and the modulus calculated using an empirical relationship developed by Heuze et al. (1981b). This technique is relatively inexpensive and easy to perform and incorporates a large volume of rock. However, the work by Zucca (1984) indicates that the characteristics of the source, the path length, the frequency response of the rock mass, and the attenuation effects with increasing distance between the source and receiver must be well-defined to provide a high degree of confidence in the reproducibility of the results. As this technique continues to be developed, it may have definite applications in the sequential drift mining experiment and provide useful data to compare with the modulus of deformation measurements made in the rock mass mechanical properties study. However, at the present time, the use of petite seismique is not planned because of the uncertainties discussed above.

The in situ stress state is required to design stable underground openings. Overcore stress measurements will be performed as part of the access convergence experiment and in the DBR as part of the characterization of site ambient stress conditions study. Zimmerman and Vollendorf

(1982) present test results and summarize the problems encountered with the use of this technique in fractured welded tuff. Other techniques available for determining the in situ stress state include the anelastic strain recovery method, which uses oriented core to predict the in situ stress (Teufel, 1981), and hydraulic fracturing (Warpinski et al., 1981) that is performed in boreholes with a packer system. The anelastic strain recovery method has not been performed in welded tuffs, although measurements performed in nonwelded tuffs (Teufel, 1981) indicate that strain relaxation is uniform with time and that strain orientations may provide an accurate determination of the direction of the principal horizontal in situ stress.

A limited amount of hydraulic fracture data has been obtained in fractured welded tuffs. Results from Rainier Mesa presented by Warpinski et al. (1981) indicate that natural fractures in the welded tuffs caused significant offsets in the induced fractures, resulting in severe fluid loss. Results presented by Stock et al. (1985) indicate that after the initial shut-in pressure, preexisting fractures in Yucca Mountain welded tuffs were reopened rather than new fractures created. Additionally, difficulties in determining the exact orientation of the induced fractures reduced the level of confidence in the determined value of the least horizontal stress. Requirements to limit the amount of fluid injected into the rock mass surrounding the ESF and the difficulties encountered in interpreting this type of data in fractured and unsaturated welded tuffs will preclude using hydraulic fracturing as part of the excavation investigations study.

2.3 Constraints on Excavation Investigations Study

2.3.1 Potential Impact on the Site

The potential impacts related to the construction of the ESF on the site are discussed in Section 8.4 of the SCP. No additional impacts on the site are expected as a result of the experiments conducted in this study. Only a minimal amount of excavation is required for the excavation investigations experiments as compared to that required for the ESF. The proposed measurement stations in the access convergence experiment require little or no additional excavation. The DBR and sequential drift mining experiments will require specific excavations, but in both experiments the amount of material extracted is very small. The permeability measurements conducted as part of the sequential drift mining experiment require a minimal amount of water that will be regulated and monitored to limit any impact on the site. No other impacts on the site should occur as a result of the experimental work planned in this study.

2.3.2 Repository Simulation and Scale of Phenomena

The model validation process requires that a representative volume of rock be subjected to experimental conditions approaching or exceeding those expected in the underground facility. Ideally, these conditions will result in stress levels and displacements that exceed the maximum anticipated for the repository while monitoring the rock mass response during the model validation process. Repository-size (cross-sectional dimensions) excavations will be used in the excavation investigations experiments to approximate the conditions anticipated in the underground facility. The exact dimensions will be determined as the design for the underground facility proceeds. However, in an effort to increase the induced stresses and measurable displacements in welded tuffs with subvertical to vertical fractures, the widest repository-size opening will be used in the DBR and sequential drift mining experiments. The length of the drift in the DBR experiment will be designed so that the midsections of the drifts will be subjected to stress levels that approximate those envisioned for the underground facility under ambient temperatures without being influenced by other excavations or by end effects resulting from the termination of the rooms (Costin and Bauer, 1988). Repository-size drifts will also be used in the sequential drift mining experiment to evaluate the response of the rock mass to the excavation process. The length of the drifts (approximately six times the width) is adequate to minimize end effects, and the spacing between the access drift and instrumentation drift will be selected so that displacements meet or exceed those expected in the underground facility.

Variations in the rock mass thermal response will be evaluated using experiments planned in the In Situ Thermomechanical Properties study. Temperature-dependent conduction appears to be the dominant heat transfer mechanism for unsaturated tuff (Zimmerman et al., 1986). The rock mass thermal responses from the heat source will be analyzed separately from the mechanical responses and input into the mechanical analyses to calculate the thermomechanical response (SCP Section 8.3.2). Experiments planned in the In Situ Thermomechanical Properties and Excavation Investigations study plans are expected to simulate the major types of thermomechanical behavior that are likely to occur within the repository.

2.3.3 Time Available for Model Validation Considerations

The primary data collection period for each of the excavation investigations study experiments is scheduled to occur over a period ranging from a few weeks to several months. A limited number of measurement stations in this study may, however, be used for long-term monitoring. The relatively short duration of each of the experiments should preclude any impacts on other ESF construction or experimental activities, although the iterative process employed to validate the mechanical models could possibly result in delays that may impact project schedules.

The model validation effort consists of an iterative process that begins with the collection of in situ displacement data and data obtained from interrelated study plans (Table 1-2), continues with a comparison of the calculated and measured displacement results, and concludes with consultation and concurrence by an established peer review panel (SCP Section 8.3.2.1.4.3). Several factors may contribute to delays in the validation process that could significantly impact project schedules. In the sequential drift mining experiment, displacement data will be obtained in the instrumented drift at several stations during and after the excavation process. Vertical displacement data will be analyzed and compared for each of the measurement stations to assess whether characteristic data have been collected for estimating representative displacement values for the entire drift. If these representative values cannot be determined, additional geologic characterization studies and an assessment of the adequacy of the instrumentation type and placement will be required before comparing the measured results with the results predicted using the mechanical model. If the lack of uniformity is attributed to instrumentation drift or calibration problems, then additional calibrations will be performed, and an assessment of the vertical displacements will be repeated. If the results indicate that significant geologic complexity exists, then additional detailed geologic characterization will be required. After establishing representative measured displacement values, a comparison will be made between the measured and calculated values. The results of this comparison will be used by the peer review panel to determine whether the comparison of results are valid using the guidelines in SCP Section 8.3.2.1.4.3.

2.3.4 Differentiation of Stress-Altered Region

In openings constructed by drill and blast methods, the stress-altered region consists of the blast-damaged zone and the stress redistribution zone. In controlled blasting, the blast-damaged zone is generally limited to a radial distance of a few tenths of meters to possibly a meter from the perimeter of the opening (Holmberg and Persson, 1980). In mechanically excavated openings, the blast-damaged zone does not occur. Induced stresses associated with the stress redistribution zone are generally considered negligible beyond three opening diameters from the perimeter (St. John, 1987). The stress in this zone may be higher or lower than the original in situ stress depending on the shape, orientation, and distribution of the underground openings and on the initial stress tensor.

Delineating the extent and nature of the stress-altered region can have significant ramifications for modeling the mechanical, thermal, and hydrologic characteristics of the rock mass around the openings. Rocks located within the blast-damaged zone would generally have a lower modulus of deformation, a lower rock quality designation, lower compressional and shear wave velocities, and higher permeabilities (Hustrulid and Ubbes, 1982). Variations in rock mass displacements, compressional and shear wave velocities, and permeabilities that will be measured in the sequential drift mining experiment will occur as a result of the stress change associated with the stress redistribution zone. However, depending on a number of factors including localized geology, these changes may either accentuate the changes that occur in the blast-damaged zone or possibly even lead to an apparent reduction in the radial extent of the blast-damaged zone. Analyses by Costin and Bauer (1988) show that in the DBR experiment the introduction of a blast-damaged zone into the calculation increases the displacements of the excavation boundaries, lowers the stress at the excavation surface, and produces a stress peak in the rock mass located outside the blast-damaged zone. Although several different techniques will be employed in an attempt to distinguish between the effects of each of these zones on the characteristics of the rock mass around the opening, information presently available would suggest that developing these relationships in jointed welded tuffs is constrained by the available instrumentation and analytical techniques. These techniques should, however, provide the necessary data to describe the combined effects of these changes on the rock mass located within the stress-altered region.

2.3.5 Rock Mass Changes Before Instrumentation

A significant fraction of the response of the rock mass at any location to the process of excavation takes place when the advancing face is near that location. Simulations of highway tunnel excavation by Ranken and Ghaboussi (1975) indicate that 30% of the radial displacement has already occurred before the face reaches a given location and 94% has occurred by the time the face has advanced one and one-half radii beyond the location. Site-specific analyses of the exploratory shaft concept (Costin and Bauer, 1988) give similar results. Each of the experiments planned for the Excavation Investigations Study has been designed so that changes occurring in the rock mass before instrument installation are minimized.

It may not be possible to install access convergence experiment instrumentation until all of the immediate response is complete. If this is the case, the data will be useful as a demonstration of long-term opening stability rather than for model validation. However, opportunities to install instrumentation near the face will be used.

The measurements of rock mass modulus and compliance will be made routinely as the tunnel boring machine excavates the underground facility. These measurements, although within the disturbed zone of the excavations, are representative of the rock mass around all underground excavations at Yucca Mountain.

Data obtained in the sequential drift mining experiment will be collected before, during, and after the mined face advances beyond each measurement station. These data will be compared with the predictions of total displacement that are based on numerical material models to determine whether the initial displacement history measured in situ is comparable to that predicted. These comparisons will make up one component of the validation process.

2.3.6 Relationships With Other Studies

The experiments planned in the excavation investigations study will contribute to a data base that will be used to validate the rock mass constitutive models. Data from several other studies will also contribute to the data base used to validate these models. These studies will characterize the intact rock and fractures and enhance our understanding of the response of the rock mass to heating and to the excavation process. Specifically, the experiments planned in these studies (Table 1-2) will be used to improve the capability to predict the rock mass response and help to ensure stable underground openings throughout the waste retrieval period.

Changes in fracture characteristics and variations in lithophysae content can significantly alter the rock mass response to the excavation process. Results from other studies (characterization of the structural features within the site area, characterization of the vertical and lateral distribution of stratigraphic units within the site area, and fracture studies of intact rock) will characterize these changes and supplement the interpretation of data obtained in the excavation investigations study.

The stability of the underground openings is contingent upon several factors including the rock mass response to induced thermal and mechanical stresses. The in situ thermomechanical properties study experiments will be used to validate the thermal model, which will be combined with the mechanical models to predict the long-term stability of the underground facility. The in situ design verification study will monitor drift stability and the performance of the ground support systems in variable geologic conditions. These data will complement the data obtained in this study for validating the rock mass constitutive models. A detailed evaluation of excavation efficiency, which includes varying the mining techniques for different underground conditions, will be conducted as part of the in situ design verification study. This evaluation will develop a substantial data base that will supplant the limited information obtained on excavation efficiency in this study.

Results from the characterization of the site ambient stress conditions study will be used to obtain in situ stress values in several locations with variable fracture density and lithophysae content using the overcore stress and anelastic strain recovery techniques. These data will be combined with stress measurements obtained in the access convergence experiment to delineate local variations in stress within the Topopah Spring Member.

Permeability measurements performed primarily to evaluate the extent of the stress-altered region will also provide insight into the differences in permeabilities determined using air and water. These data will complement hydrologic studies planned for the ESF.

A limited amount of the in situ geomechanical data that will be obtained in the excavation investigations experiments can be used to develop and evaluate scaling relationships for extrapolating from laboratory-derived data to in situ conditions. Permeability and compressional wave velocity measurements obtained during the sequential drift mining experiment will contribute to the data base that will be used to develop these scaling relationships. Data obtained in the rock mass mechanical properties study, the laboratory determination of mechanical properties of intact rock study, and fracture studies of intact rock will be used to examine and develop scaling relationships for comparing strength and modulus of deformation parameters and to provide input parameters for exercising the models.

2.3.7 Statistical Relevance of Excavation Investigations Study Data

The experiments planned for the excavation investigations study will not provide a statistically valid data base for the in situ rock mass characteristics of the Topopah Spring Member. However, all available site characterization data will be used to locate each experiment in those intervals of the Topopah Spring Member that appear representative of the conditions expected at the repository horizon or that bound the conditions expected to be encountered. The approach to developing a statistically valid data base that has been adopted is to sample and test the major geomechanical and geological units in situ and develop scaling relationships for extrapolating from laboratory-determined values to the in situ environment. The rock mass load-deformation response measurements made from monitoring the tunnel boring machine gripper pads during excavation of the underground openings will provide a significant data base throughout the underground facility. These measurements will provide information in both spatial variability and anisotropy of the load-deformation response in all units excavated with the tunnel boring machine. A limited set of data (i.e., compressional velocities and permeability) will be obtained in the excavation investigations study to develop or extend scaling relationships that will be derived from experiments formed in the rock mass mechanical properties study and the laboratory determination of mechanical properties of intact rock study. The approach for developing scaling relationships is continuing to evolve and is discussed in SCP Section 8.3.1.15.

2.3.8 Test-to-Test Interference

Section 8.4.2 of the SCP is a discussion of the potential for interference between tests in the ESF. The excavation investigations experiments have significant standoff requirements from other activities as a result of a need for mechanical isolation from unrelated mining activities while data are being collected. Borehole permeability measurements in the sequential drift mining experiment will result in a small zone of hydrological influence. All three experiments will have small zones of geochemical influence associated with the use of grout for anchoring instruments.

3.0 Description of Excavation Investigations Experiments

The excavation investigations study is composed of three experiments that are intended collectively to provide much of the data required to validate the rock mass constitutive models. The access convergence and DBR experiments will provide the initial data required to evaluate and gradually refine the models that will be used to predict the deformational behavior and stability of the underground facility. The sequential drift mining experiment will provide a data base for a detailed evaluation of the models as part of the validation process. The design of this experiment is likely to change as data are obtained and analyzed from the other excavation investigations experiments, as a result of test integration between the in situ thermomechanical experiments (SCP 8.3.1.15.1.6) and the engineered barrier system field tests (SCP 8.3.4.2.4.4), and as the information base for the Topopah Spring Member improves as a result of other experiments performed during the construction of the ESF. Work Agreements (WAs), which will be written in conformance with SNL YMP Quality Assurance Implementing Procedures, will direct the fielding of each excavation investigations experiment.

3.1 Access Convergence Experiment

The access convergence experiment involves a group of simple measurements intended to: (1) monitor access convergence and rock mass deformation at several discrete locations, (2) measure the radial stress distribution and in situ state of stress at these locations, and (3) routinely measure the response of the rock mass to the loads imposed by the tunnel boring machine gripper pads. This information is important to demonstrate the stability of, and state of stress around, a full-scale repository opening in rock of varying quality. One of the measurement sets comprising parts (1) and (2) of the experiment will be performed in each major thermomechanical unit encountered in the ramp accesses, with special emphasis on the units in the Topopah Spring and Calico Hills formations. Where possible, primary measurement locations in each unit will be selected at least 100 meters from major structural features such as stratigraphic contacts and faults; additional stations may be installed in or near these features. The measurements will be performed in both of the repository access ramps as well as in the Calico Hills ramps. Precise locations and numbers of tests will be determined on the basis of geologic structure and complexity. Part (3) of the experiment will be performed throughout the underground facility, wherever the tunnel boring machine operates.

The response of the surrounding rock mass to the excavation process can be divided into immediate and time-dependent components. The immediate response actually begins ahead of the face and is completed a short distance behind the face. The time-dependent response can involve additional convergence and rock mass deformations over a period of days or years following excavation. Time dependent deformation histories are an important measure of opening stability and the effectiveness of ground support. Measurement of the rock mass response to the tunnel boring machine gripper pad loading will provide critical first information on rock mass modulus and compliance. This information is necessary for initial comparisons and estimates of the time-dependent deformation response of the underground openings.

Two configurations have been defined for this experiment: a standard sequence and an alternate sequence. The information from the alternate sequence is sufficiently valuable that it should be conducted if the opportunity to conduct the experiment arises during construction.

3.1.1 Standard Sequence

In the standard sequence, instruments will be installed and measurements initiated at the closest possible location back from the face. Depending on the design of the machine, it is likely to be at least several tunnel diameters from the face, in which case most of the immediate response to excavation will be lost. Because models involving time-dependent effects are not currently being considered for application in the YMP, the standard sequence will not provide data for model validation. Instead, the information obtained from this experiment on long-term response will be used to evaluate opening stability. Other experiments, most importantly the sequential drift mining test in the core area of the main test level, will study the immediate response of the excavation during mining.

The stability of the underground openings is contingent upon several factors including the rock mass response to induced thermal and mechanical stresses. The in situ thermomechanical properties study experiments will be used to validate the thermal model, which will be combined with the mechanical models to predict the long-term stability of the underground facility. The in situ design verification study will monitor drift stability and the performance of the ground support systems in variable geologic conditions. These data will complement the data obtained in this study for validating the rock mass constitutive models. A detailed evaluation of excavation efficiency, which includes varying the mining techniques for different underground conditions, will be conducted as part of the in situ design verification study. This evaluation will develop a substantial data base that will supplant the limited information obtained on excavation efficiency in this study.

If a concrete liner is necessary, linear pressure measurements will be performed by installing hydraulic pressure cells (HPCs) in the concrete liner. These cells will indicate the stress changes in the liner. The HPC stress data are combined with the MPBX deformation data to provide the essential input for evaluating the interaction of the rock and liner. The MPBX measurements associated with the mining activities provide data that can be used to assess the possible loading of the access liner by the rock mass.

If the access is unlined, load cells on rock bolts will provide an indication of support loading in place of the liner instrumentation. Rock bolt load cells that use strain gauges as the sensing units (e.g., Terrametrics Model PC-60) will be used to monitor changes in rock bolt tension that occur after installation. The load cells will be attached to mild steel rock bolts. The load cells have a capacity of 535 kN and a sensitivity of 267 N. Long-term monitoring of rock bolt tension requires that the load cells be capable of withstanding the effects of nearby blasting and be sealed to prevent water and/or dust from entering the housing of the load cell. Experience in G-Tunnel welded tuffs (Zimmerman et al., 1988) indicates that the long-term stability for the Terrametrics load cell exceeds periods of 200 days. The strain gauge circuits should be temperature compensated to minimize the effects of ambient temperature changes on the measured strains. Resistance changes resulting from varying cable lengths and connections can also influence the accuracy of the load cell measurements.

The standard sequence for the measurement of rock mass modulus and compliance using the tunnel boring machine gripper pads portion of the access convergence experiment will involve: (1) measuring the deformation of the rock mass due to tunnel boring machine gripper pad loading and (2) measuring the pressure in the tunnel boring machine gripper pad hydraulic rams during loading. The deformation of the tunnel boring machine gripper pads will be measured routinely using robust noninterfering wire extensometers mounted directly to the machine. Also, short MPBXs may be installed in the rock prior to gripper pad loading to measure the deformation of the rock mass directly and to provide a check or verification of the on-board instrumentation. The pressure in the tunnel boring machine gripper pad hydraulic rams will be used to determine the applied loads to the rock mass and will be made using pressure transducers installed directly into the hydraulic system. These measurements will be made routinely during operation of the tunnel boring machine.

3.1.2 Alternate Sequence

The alternate sequence will involve working in front of the tunnel boring machine. The alternate sequence will be conducted only if the opportunity to conduct the experiment arises during construction and if permission from the constructor is given. The information from the alternate sequence is sufficiently valuable that it should be conducted if the opportunity arises.

To monitor both immediate and long-term response, a sequence of measurements may be performed at each station to obtain stress and deformation information. The alternate sequence would involve (1) in situ stress measurements, (2) installing MPBXs and convergence pin stations, and (3) monitoring rock-mass deformations by measuring displacement of extensometer anchors as a function of time. The in situ stress measurements provide the boundary conditions necessary for modeling the immediate excavation response at the measurement location. The deformation measurements can be used to compare to modeled deformations at the anchor locations. If only convergence pins can be installed, these will still yield valuable information.

The convergence array would consist of 5 measurement anchor points (pins) grouted into short boreholes in solid rock near the excavation surface. The precise location of individual anchors would be dictated by interferences with other equipment in the tunnel. Changes in distances between pairs of convergence anchors would be determined with a tape extensometer on a regular basis to monitor time-dependent changes in convergence rates or magnitudes. The MPBX installation involves a number of anchors (typically 5 to 7) spaced in horizontal and vertical holes drilled radially from the excavation. The furthest anchor from the excavation serves as a reference anchor and should be three diameters from the wall, if possible, to ensure a stable reference. The spacing of the other anchors typically decreases toward the excavation, to concentrate instrumentation in the most important regions.

3.1.3 Quality Assurance Requirements

All work will be performed in accordance with the SNL Quality Assurance Implementing Procedures. The experiments will be governed by SNL Quality Assurance Grading Report 1242111, which specifies the implementing procedures that will be followed.

The access convergence work agreement will describe the operational and technical procedures required to fulfill the experiment objectives.

3.1.4 Accuracy and Precision

The accuracy and precision of the access convergence experiment data are largely contingent on the amount of convergence that occurs before instrument installation and the capability of calculating reasonable estimates of the convergence that has occurred before recording data. Finite element analyses that incorporate elastic-plastic material properties and an axisymmetric geometry (Costin and Bauer, 1988) indicate that the calculated in situ stress values will be within 20% of the actual in situ values. Approximately 60% of the total displacement associated with convergence of the access will occur before instrument installation, even if the alternate sequence is used.

The required accuracy and precision of instrumentation used to collect in situ data in a monitoring program depends largely on the intended application and expected range of results (Wilder et al., 1982). Instrumentation required for activities related to model validation must have high degrees of accuracy and precision over a relatively short operational period. Conversely, instrumentation intended for long-term monitoring applications will generally sacrifice some accuracy and precision to ensure reliability over the time intervals required. In either case, the instrumentation employed must be compatible with the intended application to help ensure that the experimental objectives are achieved.

The range of results and the equipment required for the access convergence experiment are summarized in Sections 3.1.6 and 3.1.7, respectively. The accuracy and precision of each of the instruments used in this experiment are summarized below.

The principal factors that influence the accuracy of MPBXs are (1) anchor slippage, (2) thermal expansion of the components, (3) friction acting on the rods, and (4) displacement transducer performance. Wilder et al. (1982) discuss the effect of these factors on the measurements obtained with MPBXs. Three types of six-anchor MPBXs are being considered for installation in the access convergence experiment. The response of each type is currently being evaluated based on results from G-Tunnel welded tuff (Zimmerman et al., 1987; 1988). The results of these evaluations will be used to select the most appropriate instrument type and associated anchor spacing. An IRAD Model 4500 MPBX with groutable anchors and Invar rods may be used at several measurement stations. This type of MPBX uses a depth micrometer and sonic probes to measure the rod travel distance. The second type of MPBX that may be used also has groutable anchors and Invar rods but uses a linear variable-differential transformer (LVDT) to measure displacement. A third type of MPBX, the Roctest BOF-Ex, has mechanical anchors and uses an LVDT to measure displacement. A principal advantage of the Roctest MPBX is that the components of the system can be readily removed, recalibrate, and replaced if the MPBX begins to malfunction. The sensitivity of all three units is about 0.025 millimeters. Other types of extensometers are available and may be used for special applications.

Anchor stability is crucial to the accuracy of the MPBX system. Tests performed in G-Tunnel (Zimmerman et al., 1987; 1988) have demonstrated that grouted anchors located in the vicinity of blasting operations have remained stable for periods of greater than 200 days. However, in areas of severely jointed rock, the amount of grout that is used must be closely monitored to avoid having the grout enter the fractures and alter the deformation characteristics of the rock mass.

The accuracy of the MPBX can be greatly influenced by the thermal expansion of the various components, in particular the connecting rods, at temperatures in excess of 200° C. The ambient temperature within the ESF will be less than 30° C during the excavation investigations study, with local variations of only a few degrees centigrade during the experiments. These temperatures are well below the temperature range where the nonlinear thermal expansion coefficient of Invar rods becomes a major concern.

Friction acting on the rods, often manifested by stick-slip behavior resulting in pronounced jumps in displacement data, influences the accuracy of the MPBX data. Proper alignment of the rods with the head assembly and appropriate installation procedures generally alleviate the stick-slip problem and minimize its impact.

Sinco Terrametrics Model 50 tape extensometers will probably be used to measure access convergence. This instrument has a sensitivity of 0.025 millimeters. Measurements will be obtained between anchors mounted in the access at each station. The accuracy of the tape extensometer measurements can be greatly influenced by the instability of the anchors during blasting operations that occur after the anchor has been installed, temperature effects, and variations resulting from subtle changes in procedures that may occur with different operators. The effects of each of these factors on the accuracy and precision of the tape extensometer measurements will be greatly reduced when the technical procedures are followed.

The accuracy of the U.S. Bureau of Mines BDG depends on a number of factors including gauge sensitivity as a function of temperature, bridge input and output voltage, bridge offset as a function of temperature, and gauge thermal expansion coefficient (Wilder et al., 1982). Laboratory testing in engineered materials has yielded highly accurate deformation measurements of 0.002 millimeters with a sensitivity of 0.001 millimeters. Gauge sensitivity and bridge offset are subject to long-term drift, which is greatly influenced by localized test conditions at the transducer. The magnitude of drift is not predictable and must be controlled by periodic recalibration.

Stress changes are primarily calculated from deformation data; therefore, accuracy depends on the knowledge of rock properties (Young's modulus, Poisson's ratio, and thermal expansion coefficient) and the degree to which the rock mass behaves as a linear elastic and isotropic medium. Errors in calculating stress changes are directly proportional to the errors involved in selecting the appropriate rock modulus, where the scale of changing rock characteristics (e.g., fracture spacing and orientation) are often the most important variables influencing the magnitude of the stress change. Thus a thorough understanding of the geology at each measurement station, using borehole surveys in combination with data obtained from Study 8.3.1.4.2.1, Characterization of the Vertical and Lateral Distribution of Stratigraphic Units Within the Site Area, is essential to minimize the errors in the stresses calculated with the BDG.Additionally, it is important to overcore each borehole gage to measure the rock modulus using a biaxial gage.

Terrametrics/Glotzl Concrete Stress Cells, Model B 10/20 or a comparable unit with similar characteristics, will be used to monitor the access liner stress. The reported accuracy of the HPC is 10 kPa with a maximum stress recording capability of 30 MPa. Variations in temperature can inadvertently influence the stress measurements, although within the expected ambient temperature range, these errors should be within the range of accuracy of the HPC. Other errors may result from the orientation of the HPC relative to the liner or an inappropriate matching of the HPC with the material stiffness of the liner.

Pressure transducers for use on the tunnel boring machine gripper pad rock mass modulus and compliance measurements can be obtained with a range of 0.035-69.0 MPa and an accuracy at least 0.1% full scale. These transducers will be installed directly into the hydraulic system controlling the gripper pad movement and loading. The operating temperature range for some standard transducers is -40°C to +130°C. Shock and vibration resistance is estimated at 0.05% full scale per g acceleration within the 10Hz to 2kHz frequency range.

The wire extensometers intended for use in measuring the displacement of the tunnel boring machine gripper pad during loading employ linear potentiometers with variable range and a resolution of 0.01 millimeters. These extensometers are designed for noisy and vibrating environments and are expected to yield repeatable data for this experiment.

3.1.5 Range of Expected Results

The expected range of values for each of the activities performed in the access convergence experiment (Table 3-1) has been estimated on the basis of data obtained in the welded tuff composing the Grouse Canyon Member located in G-Tunnel (Zimmerman and Finley, 1987) and laboratory data obtained from the welded tuff composing the Topopah Spring Member at Yucca Mountain (Price et al., 1985). The range and magnitude of the results are intended to satisfy the requirements for accuracy and precision outlined in Section 3.1.2 of this study plan.

TABLE 3-1. EXPECTED RANGE OF RESULTS FOR ACTIVITIES PERFORMED DURING THE ACCESS CONVERGENCE EXPERIMENT.

Activity	Parameter Measured	Estimated Range of Values
In Situ Stress Measurements	In situ stress	<10 MPa
Estimate of Stress-Altered Region	MPBX anchor displacement	0-10 mm
Convergence Magnitude	Displacement	0-10 mm
Convergence Rate	Displacement/time	0-2 mm/yr.
Liner Contact Pressure	Liner stress	<15 MPa
Rock Mass Modulus	Modulus	4-16 GPa

3.1.6 Equipment and Design Requirements

Requirements for the access convergence experiment are outlined in the "Exploratory Studies Facility Design Requirements Document" (DOE, 1992) and will be documented in the access convergence Work Agreement. Instrumentation, equipment, and material requirements are summarized in Table 3-2.

TABLE 3-2. SUMMARY OF EQUIPMENT, INSTRUMENTATION, AND MATERIAL REQUIREDFORTHEACCESSCONVERGENCEEXPERIMENT.

Item	Description
Tape Extensometer	Rated sensitivity of 0.025 mm
Multiple-Point Borehole Extensometer	Rated sensitivity of 0.025 mm
Borehole Deformation Gauge	Rated sensitivity of 0.001 mm
Hydraulic Pressure Cell	Rated sensitivity of 10 kPa
Wire Extensometer	Rated sensitivity of 0.01mm
Pressure Transducer	Rated sensitivity of 70 kPa

3.1.7 Analyses of Field Measurements

3.1.7.1 In Situ Stress Measurements

The analysis of overcoring measurements will be performed using the equations developed by Panek (1966). In this analysis, the three borehole diameter measurements provide a data set that can be used for the solution of three simultaneous equations, giving stresses in the plane perpendicular to the measurement borehole. Stresses in other directions can be obtained by drilling appropriately oriented boreholes.

3.1.7.2 Estimate of the Stress-Altered Region

The extent of the stress-altered region will be estimated using the relative displacements measured between each of the MPBX anchors, the cumulative displacement of all of the anchors, and the total convergence measured between the three sets of MPBX collars and convergence anchors. The radial distance at which the relative displacements between anchors approaches zero will be used to approximate the limits of the stress-altered region. A demonstration of different MPBX anchor types has been completed in G-Tunnel welded tuff (Zimmerman et al., 1987; 1988) to assess whether a larger number of anchors or more closely spaced anchors should be used. The difference between the cumulative displacement measured with the MPBX anchors and the total access convergence measured between sets of convergence anchors or MPBX collars will also be used to estimate the extent of this region. The difference between the convergence magnitudes calculated using these techniques can be ascribed to at least three factors: (1) convergence of the rock mass occurring beyond the last anchor installed 15 meters away from the rib; (2) if the excavation is constructed by blasting methods, displacement of the blast-damaged zone, which may not be measured with the MPBX anchors; and (3) differential movement associated with fractures or an asymmetrical rock mass response on either side of the access. Minimal differences between these values will significantly increase the level of confidence in the estimate of the extent of the stress-altered region.

3.1.7.3 Access Ground Support Analyses

If a concrete liner is required, the overall liner/rock analyses provide data that will be used by the designers to assess the adequacies of the liner's design as it responds to the potential relaxation in the surrounding rock. Pressure measurements obtained within the liner as the surrounding rock relaxes can be extrapolated to predict equivalent stresses at the surface of the liner by using elasticity theory as it applies to thick-walled cylinders (Timoshenko and Goodier, 1951). The displacements at the liner/rock interface should be compatible with the measured stress changes as long as the liner acts like a liner elastic structural unit, and the liner and rock are well bonded. Numerical methods with appropriate non-linear material models can also be used for analysis if elastic assumptions are not justified.

3.1.7.4 Rock Mass Modulus and Compliance Measurements

The rock mass modulus and compliance will be evaluated using data obtained from the tunnel boring machine gripper pad loading and unloading.

It is important to note the similarities between the test geometry presented for the rock mass modulus and compliance measurements and the geometry of the borehole or Goodman jack. The solution to this problem has been extensively studied (Goodman et al, 1968; Heuze, 1984a; Heuze and Amadei, 1985). The applicability of the solutions to the borehole jack geometry for use in the tunnel boring machine rock mass modulus and compliance measurements will be evaluated. It is expected that numerical simulations will be required to identify tunnel boring machine gripper specific correction factors for the borehole jack modulus equations presented in the referenced sources. The solutions developed specifically for the tunnel boring machine gripper pad geometry will be used to evaluate the field data as it is acquired. Modifications to the developed solutions may be necessary as site-specific data are collected during construction of the underground openings. Also, two- and three-dimensional numerical simulations of rock surrounding the underground excavations may be required using available continuum and discrete block finite element models.

Additional data that will be required for complete analysis of rock mass modulus and compliance include site-specific joint and inhomogeneity information in the region directly under and surrounding the gripper pad locations. These data will be used for comparisons with rock quality field surveys being conducted by SNL under the In Situ Design Verification Study (SCP Section 8.3.1.15.1.8). It is also suggested that additional confirmatory tests such as drift surface seismic and limited borehole techniques be conducted at selected tunnel boring machine gripper locations. These techniques, having been verified by comparison with the tunnel boring machine results, can be used to evaluate rock mass modulus and compliance in regions not constructed using the tunnel boring machine.

3.1.8 Representativeness of Results

The measurement stations selected for the access convergence experiment are intended to assess the variations in geomechanical characteristics that are likely to be encountered in a vertical profile within Yucca Mountain. Specifically, measurement stations will be selected to sample the high lithophysae (15 to 20% lithophysae content) interval of the Topopah Spring Member and the densely welded tuff interval, containing $< 10\%$ lithophysae, to assess variations in in situ stress, convergence rates and magnitudes, variations in ground support loads imposed by differing geology, and the extent of the stress-altered region. Variations in the in situ stress state will be evaluated for differing geologic horizons that compose the reference geological and geomechanical units within the ESF. These data will be combined with stress data obtained in the characterization of the site ambient stress conditions study to evaluate the effects of geologic variations at a specific depth with the changes in stress attributed to varying depths representative of the Yucca Mountain repository location. Fracture characteristics are likely to vary between geologic horizons and with changes in the lithophysae content. The data obtained should represent the fracture conditions encountered elsewhere in the ESF but may differ markedly from those areas where faulting is pervasive.

The measurements of rock mass modulus and compliance using the tunnel boring machine gripper pads will be performed throughout the mechanically excavated openings at Yucca Mountain. These measurements will provide data in all rock units penetrated by the tunnel boring machine and will, as the excavations change direction, provide data on both the spatial variability and potential anisotropy of rock mass modulus and compliance. These data are therefore expected to be representative of rock mass modulus and compliance throughout the underground facility.

3.1.9 Performance Goals and Confidence Levels

The performance allocation process has identified the performance goals and confidence levels required to resolve the key issues addressed by the excavation investigations study experiments (Information Needs 1.11, 4.2, and 4.4; and Investigation 8.3.1.15). These goals and confidence levels are summarized in Table 8.3.1.15-1 of the SCP.

As discussed in Section 8.3.1.15 of the SCP, the required confidence levels for geomechanical parameters require a minimum number of measured samples for each measured property. The minimum number of samples required to satisfy the confidence level is always larger than the number of in situ tests that will be conducted. Thus the values obtained from the in situ experiments will serve as guidelines that will be used to examine the validity of extrapolating the laboratory-derived values to in situ conditions. If these extrapolations do not appear valid, then the performance goals will need to be reevaluated, and an approach that relies more heavily on either field or laboratory data will possibly be adopted.

3.2 Demonstration Breakout Room Experiment

The DBR experiment will be conducted in a repository-size room located ~~in~~ the high-lithophysal zone of the Topopah Spring Member. The configuration of this experiment may be changed in response to modifications in the design of the ESF or as a result of in situ data obtained during ESF construction. The room will most likely be connected to the north ramp at a depth of about 160 meters. The precise depth will be determined at the time of the experiment and will be based on observation of the rock quality encountered. The orientation of the DBR will most likely coincide with the orientation established for the underground facility, with some possible modifications depending on the dominant fracture orientation and in situ stress conditions. The DBR will be repository-size, with the opening dimension comparable to the widest opening planned for the underground facility, in an attempt to increase the measurable displacements around the perimeter of the underground opening. The length of the DBR will be approximately six times the width. Measurements obtained in the midsection of these rooms are not expected to be influenced by end effects resulting from the ESF opening or the drift face (Costin and Bauer, 1988). Drift convergence will be evaluated during the excavation and stabilization process to delineate differences in the rock mass response as a result of varying geologic characteristics. The repository-size drifts will also be used for other in situ experiments (e.g., overcore stress, anelastic strain recovery, plate loading, mechanical strength, and laboratory study of intact rocks) that relate directly to the design of the underground facility.

Eleven measurement stations, beginning nominally 11 meters from the beginning of the drift, will be located at approximately 2.4-meter intervals at the DBR location. Each of these stations will be instrumented with drift convergence anchors and rock bolts with attached load cells. At five measurement stations, six MPBXs will be installed (one in the floor, one in the roof, and four in the ribs). Each MPBX will contain at least five anchors located at nominal one meter intervals from the perimeter of the opening. A sixth reference anchor will be located a minimum of 15 meters from the perimeter of the opening in rock that has not been altered by the excavation process.

During the mining operation, rock bolts will be installed in each of the rooms using a pattern designed to maintain stability. The ground support requirements will be determined on the basis of experience developed from mining other welded tuff locations, using both analytical and empirical techniques described in the "Drift Design Methodology" (Hardy and Bauer, 1991). At each measurement station, the appropriate instrumentation will be installed, and measurements will be initiated to determine displacement magnitudes, variations in support loading, and the extent of the stress-altered region. Drift convergence measurements will be made using tape extensometers at each station, while the MPBX measurements are performed at the stations. Estimates of the extent of the stress-altered region will be made using the MPBX data.

Excavation efficiency will be evaluated qualitatively during the construction of the rooms. If blasting is employed, evaluations will include documenting the controlled blasting procedure employed (i.e., charge density and configuration, delay sequence, hole spacing, etc.) and assessing the advance rates, amount, and size of loosened blocks and the amount of overbreak and underbreak evident after each round. If mechanical excavation is employed, machine advance rates, availabilities, and utilization will be recorded. A detailed evaluation of excavation efficiency that may include varying the excavation techniques employed will be completed during the in situ design verification study (Study Plan 8.3.1.15.1.8). The MPBX, cross-drift convergence, and rock bolt load cell measurements will also be used to assess the excavation efficiency. Variations in the forces and displacements associated with the underground opening will be monitored to evaluate the degree of uniformity in the rock mass at a single station and with respect to the entire length of the DBR.

3.2.1 Quality Assurance Requirements.

All work will be performed in accordance with the SNL Quality Assurance Implementing Procedures. The experiments will be governed by SNL Quality Assurance Grading Report 1242111, which specifies the implementing procedures to be followed.

The DBR Work Agreement will describe the operational and technical procedures required to fulfill the experiment objectives.

3.2.2 Accuracy and Precision

The accuracy and precision of the DBR data is subject to the same constraints as the data obtained in the other excavation investigations experiments. The range of results and equipment required for the DBR experiment is summarized in Sections 3.2.3 and 3.2.4, respectively. The accuracy and precision of the MPBXs, tape extensometers, and rock bolt load cells in this experiment will be contingent upon the same factors as in the access convergence experiment (Section 3.1.4), and a description will not be repeated here.

3.2.3 Range of Expected Results

The expected range of values for each of the activities performed in the DBR experiment (Table 3-3) have been estimated on the basis of data obtained in the welded tuff composing the Grouse Canyon Member located in G-Tunnel (Zimmerman and Finley, 1987).

TABLE 3-3. EXPECTED RANGE OF RESULTS FOR ACTIVITIES PERFORMED DURING THE DEMONSTRATION BREAKOUT ROOM EXPERIMENT.

Activity	Parameter Measured	Estimated Range of Values
Drift Convergence Magnitude	Displacement	0-10 mm
Drift Convergence Rate	Displacement rate	0-2 mm/yr.
Estimate of Stress-Altered Region	MPBX anchor displacement	0-5 mm

3.2.4 Equipment and Design Requirements

Requirements for the DBR experiment are outlined in the "Exploratory Studies Facility Design Requirements Document" (DOE, 1992) and will be documented in the DBR Work Agreement. Requirements for instrumentation, equipment, and material requirements are summarized in Table 3-4.

TABLE 3-4. SUMMARY OF EQUIPMENT, INSTRUMENTATION, AND MATERIALS REQUIRED FOR THE DEMONSTRATION BREAKOUT ROOM EXPERIMENT.

Item	Description
Rock Bolt Load Cell	Rated sensitivity of 267 N
Multiple-Point Borehole Extensometer	Rated sensitivity of 0.025 mm
Tape Extensometer	Rated sensitivity of 0.025 mm

3.2.5 Analyses of Field Measurements

3.2.5.1 Drift Convergence Measurements

Drift convergence rates and displacement magnitudes will be determined at each measurement station using data obtained after each blast round. A cumulative record that will contain plots of displacement as a function of time, face distance from the measurement station, and distance to the last station for rock bolt placement will be used to calculate and interpret drift convergence rates and displacement magnitudes.

Drift convergence magnitudes will be determined using data obtained from the tape extensometers and the head movements of the MPBXs relative to the deepest anchor. These measurements should agree, although local variations in rock characteristics (i.e., fracture density and orientation, lithophysae content, etc.) may result in measurable differences.

3.2.5.2 Estimate of the Stress-Altered Region

An estimate of the stress-altered region will be performed using the displacement data obtained with the MPBXs and the technique discussed by Brown (1981) and summarized in Section 3.1.5.3. The limit of the stress-altered region occurs where the change in displacements between consecutive anchors approaches zero.

Data from the load cells will also be used to augment the estimate of the stress-altered region based on MPBX data. Several factors influence the force changes measured by the load cells including fracture characteristics and the time-dependent rock mass relaxation and stress changes that occur during excavation. The uniformity of the rock mass mechanical response to these factors will be used to assess the variability in rock mass characteristics that can also influence the extent of the stress-altered region.

3.2.5.3 Excavation Efficiency Estimate

Excavation efficiency in this study examines only the excavation techniques and does not address administrative and management issues such as selection of machine, the supply system and crew training. Evaluation of excavation efficiency will focus on documenting the techniques employed for excavation and the results of these techniques (e.g., advance rate and amount of overbreak or underbreak) in varying geologic conditions.

Rock bolt load cell, MPBX, and tape extensometer data obtained at the measurement stations within each DBR will also be used to assess the excavation efficiency. Variations in the forces and displacements associated with the underground opening will be monitored to evaluate the degree of uniformity in the rock mass at a single station and with respect to the entire length of the DBR. The variations measured with the rock bolt load cells will be compared with localized changes in the geologic character (i.e., fracture density and orientation, lithophysae content, etc.) and the effects of mining, evident visually, to provide a preliminary assessment of excavation efficiency. A detailed evaluation of excavation efficiency will be performed during the In Situ Design Verification Study (Study Plan 8.3.1.15.1.8).

3.2.6 Representativeness of Results

The activities performed during the DBR experiment are designed to evaluate the influence of varying geological and geomechanical characteristics on the design proposed for repository-size drifts. The lithophysae content encountered is expected to provide an upper bound to the conditions at Yucca Mountain in general (Nimick et al., 1988). The fracture density is also expected to represent conditions found in Yucca Mountain except in those areas associated with well-developed faulting. The in situ stress conditions at the upper breakout level will not represent the stress conditions at the main test level. This difference results primarily from the difference in depth between these two levels. Ground support requirements for both drifts will be developed using the same requirements planned for designing the ground support for most of the repository.

3.2.7 Performance Goals and Confidence Levels

The location of the DBR within the ESF is intended to bound the site-specific geological and geomechanical characteristics that should be encountered in the underground facility. Construction in the high-lithophysal zone will be used to demonstrate that available technology and planned ground support systems are adequate for the expected site-specific conditions.

The performance allocation process has identified the performance goals and confidence levels required to resolve the key issues addressed by the excavation investigations study experiments (Information Needs 1.11, 4.2, 4.4, and Investigation 8.3.1.15). These goals and objectives are summarized in SCP Table 8.3.1.15-1 (DOE, 1988).

As discussed in SCP Section 8.3.1.15, the required confidence levels for geomechanical parameters require a minimum number of measured values that vary with each property if the properties are sampled at random. The location of the DBR has been chosen to provide the density of lithophysae that would represent an upper bound to conditions prevalent in Yucca Mountain except in areas with well-developed faulting. By carefully selecting the DBR location using observations during access construction, the DBR results should bound the conditions expected to influence performance and help to reduce the number of large-scale tests required to achieve the needed confidence.

3.3 Sequential Drift Mining Experiment

The sequential drift mining experiment will provide an additional suite of data for model validation. Measurements performed in this experiment will be used to better define the extent of the stress-altered region. This experiment will be performed in and around three drifts located at the main test level within the ESF. The experimental design is preliminary and will be optimized using pretest analyses, experience gained in G-Tunnel, and experience from previous excavation investigations study experiments to facilitate the analyses required for model validation. Measurements will be performed to characterize the rock mass before and after the excavation of a drift using the excavation techniques planned for the repository to evaluate the effects of the excavation process on the rock mass and the radial extent of these effects away from the excavated opening.

Validation of the constitutive models is a necessary step in predicting repository behavior during the preclosure phase of the repository. The emphasis in the sequential drift mining experiment is to relate the predictions of the models to the measurements obtained during and after excavation.

This information will be used to develop design guidelines for the underground facility that can be used for the underground conditions encountered during the excavation process.

A provisional experiment plan for the sequential drift mining experiment is summarized for discussion purposes only. This plan will change, possibly significantly, as data from the other excavation investigations study experiments become available. Some planned measurements are intended to form a data base for comparison with calculations using the models in three dimensions, although the exact nature of these measurements will not be determined until the requirements for the models and the plans for the in situ thermomechanical study are finalized.

The sequential drift mining experiment will begin by excavating two drifts of appropriate size to adequately instrument the rock in the region where a third drift of repository size will be excavated. A series of holes will be diamond drilled into the ribs of the outer instrumentation drifts to characterize the rock mass associated with the center main drift before and after excavation. The first drilling station will be located approximately three drift diameters from the start of the drifts, with subsequent holes drilled at nominal 1.2- or 2.4-meter intervals. These holes will be used to characterize the rock mass to establish a reference data base for future use and to develop a three-dimensional understanding of the geology in the region around the central drift. In addition to the diamond drilling for site characterization, additional holes for overcoring stress measurements will be drilled horizontally into the future pillars between the instrumentation and main drifts. Procedures for overcoring stress measurements have been discussed earlier.

A number of different types of measurements will be made using instrumentation installed in the boreholes drilled from instrumentation drifts. Air and water borehole permeability measurements will be performed in the boreholes located in the rib of the main drift before, during, and after it is mined. Air permeability measurements will be completed to provide data to perform a preliminary evaluation of any correlation between air and water permeability measurements from the same location. At each selected interval, the straddle packers will be set and steady-state pressure injections will be made at several different pressure settings to establish a hydraulic quotient. This quotient describes the average ratio of pressure to flow rate for each interval tested. This process will be repeated at a number of intervals within each borehole to establish an average hydraulic quotient before mining the main drift. This process will be repeated during and after the mining of the main drift in each of the boreholes that have not been instrumented and the results will be compared to determine the effects of excavation on permeability. Data obtained in the other stations will be used to locate and map fracture patterns and, in conjunction with borehole televiewer observations, will be used to develop a geologic fracture model for the pillar located between the measurement stations. Overcoring stress measurements will also be made in the post-mining pillars.

Cross-borehole ultrasonic measurements will be performed using a 30-50 kHz transceiver capable of transmitting and receiving compressional waves over a one meter interval before and after mining in the boreholes that will be used to establish the hydraulic quotient. These measurements will be performed in the stress-altered region associated with the main drift. The measurements will be repeated with the transmitter and the receiver interchanged to establish directional variations in the stress-altered region that may be related to geology.

Borehole deflectometer measurements will be performed along the full length of several inclined boreholes. Small borehole angle deviations will be measured before and after the mining of the main drift to establish small-scale angle changes as a result of dilation of the rock mass into the opening of the main drift. Continuous monitoring during the mining of the main drift will be performed using MPBXs and borehole stressmeters installed in the pillars between the instrumentation and the main drifts and tape extensometer measurements obtained across the main drift between convergence anchors. MPBXs will be installed in the pillars between the drifts at each measurement station before mining the main drift. The end anchors of each MPBX will be located about 0.5 meters from the projected rib of the main drift with each successive anchor installed at nominal one meter intervals. The exact anchor locations will depend on the geology encountered in the underground facility. These anchors will be used to measure the displacement of the rib into the cavity of the main drift.

Four of the horizontal boreholes originating in the instrumentation drifts will be used for the installation of borehole stressmeters with strain gauge sensors. Each hole will be located so that one of the stressmeters is about one meter from the projected rib of the main drift and the other two are in the pillar between the drifts. The stressmeters will monitor the stress redistribution effects and the stress changes related to mining. The uniformity of the stress changes will be assessed along individual boreholes using the three borehole stressmeters and within the pillar between drifts using the data obtained from each of the boreholes. Also, in situ stress measurements will be performed ahead of the face at several locations during excavation of the main drift, using a technique suitable for the rock encountered.

Several measurement stations will be established in the main drift to monitor drift convergence while excavation proceeds. Four MPBXs will be installed at four measurement stations to augment the cross-drift extensometer measurements that will be obtained manually at each of the stations in the main drift. After the excavation of the main drift is complete, the measurements obtained in the instrumentation drifts before mining will be repeated for comparison.

3.3.1 Quality Assurance Requirements.

All work will be performed in accordance with the SNL Quality Assurance Implementing Procedures. The experiments will be governed by SNL Quality Assurance Grading Report 1242111, which specifies the implementing procedures to be followed.

The sequential drift mining Work Agreement will describe the operational and technical procedures required to fulfill the experiment objectives.

3.3.2 Accuracy and Precision

The range of results and the equipment required for the sequential drift mining experiment are summarized in Sections 3.3.3 and 3.3.4, respectively. The accuracy and precision of the MPBXs and the tape extensometers have been discussed in Section 3.1.4. The accuracy and precision of these instruments will depend on the same sources of error as in the applications discussed earlier and will not be reiterated.

Rigid inclusion borehole stressmeters with a strain gauge sensor developed by SNL (Cook and Ames, 1979) will probably be used to monitor borehole stress changes. These units have a sensitivity of 130 kPa. The calibration of the rigid inclusion stressmeters depends on several factors including the elastic properties of the media, the platen contact area, the borehole size, loading conditions, temperature, and the prestress level during installation (Wilder et al., 1982). Each of these factors can contribute to a significant amount of scatter in results performed at the same interval.

Borehole deflectometers will be used to measure angular deviations of the borehole axis, which can be summed over a period of time to provide displacement information. Precision of the deflectometers is expected to be on the order of 2 to 4 arc seconds and the resolution is 0.75 arc seconds. Temperature fluctuations, generally greater than 15° C, and zero drift can both have a significant effect on the accuracy of the angular deviations measured and subsequent displacements. The accuracy of the inclinometer is generally constrained by the orientation of the instrument at the same point in the casing.

Straddle packers connected to a flow meter and pressure gauge will be used for the fracture permeability testing. The sensitivity of the flow meter and the water flow range will be determined using G-Tunnel mining evaluation test results (Zimmerman et al., 1988). Measurements will be obtained under steady-state flow conditions at up to five pressure-flow rate steps. A detailed description of the fracture characteristics over the interval tested, performed before and after the mining of the main drift, is required to minimize the error induced by variable geology and possibly increased flow rates. The packers must be properly seated within the borehole to minimize leakage around the packer over the time interval required for the test. Experience gained from the G-Tunnel mining evaluation test (Zimmerman et al., 1988) will be used to develop the technical procedures that are required to perform the permeability measurements in welded tuffs.

3.3.3 Range of Expected Results

The expected range of values for each of the activities performed during the sequential drift mining experiment are estimated on the basis of data obtained in the welded tuff Grouse Canyon Member located in G-Tunnel (Table 3-5; Zimmerman and Finley, 1987).

TABLE 3-5.EXPECTED RANGE OF RESULTS FOR ACTIVITIES PERFORMED DURING THE SEQUENTIAL DRIFT MINING EXPERIMENT

Activity	Parameter Measured	Estimated Range of Values
Drift Convergence Magnitude	Displacement	0-10 mm
Drift Convergence Rate	Displacement/time	0-2 mm/yr.
Rib Stress Change	Stress change	<15 MPa
Estimate of Stress- Altered Region	MPBX displacements Compressional velocity Borehole angle change	0-5 mm 2-5 km/s <0.2°
Permeability	Flow rate Flow pressure	<1260 cm^3/s <1.4 MPa

3.3.4 Equipment and Design Requirements

Construction and experiment requirements for the sequential drift mining experiment are outlined in "The Exploratory Studies Facility Design Requirements Document" (DOE, 1992) and will be documented in the sequential drift mining Work Agreement. The instrumentation requirements are summarized in Table 3-6.

TABLE 3-6. SUMMARY OF EQUIPMENT, INSTRUMENTATION, AND MATERIALS REQUIRED FOR THE SEQUENTIAL DRIFT MINING EXPERIMENT.

Item	Description
MPBX	Rated sensitivity of 0.025 mm
Borehole Stressmeter	Rated sensitivity of 130 kPa
Tape Extensometer	Rated sensitivity of 0.025 mm
Borehole Deflectometer	Rated sensitivity of 2 arc seconds
Fracture Permeability Instrumentation	Rated sensitivity of 1.0 cm^3/s
Ultrasonics	Rated sensitivity of 50 m/s

3.3.5 Analyses of Field Measurements

3.3.5.1 Drift Convergence Measurements

The primary data used for the validation of the rock mass constitutive models are the drift convergence magnitude data. Displacement data will be recorded at several stations located in the main drift until excavation is completed. These data will be analyzed using the methods previously described in Section 3.2. If reasonable agreement exists between the data obtained at each station, representative values will be determined. The representative values determined for the drift displacement magnitude data will be used as the basis for comparison of the predicted convergence values with the measured values. If reasonable agreement does not exist between the displacement data obtained at the stations, additional geologic characterization studies will be performed to establish whether the lack of uniformity is a result of the geologic structure, the accuracy of convergence measurements, or a lack of understanding inherent to the models predicting displacements.

The validation process is documented in Section 8.3.2.1.4.3 of the SCP. The process consists of a series of steps that include (1) analysis of the experiment design to ensure that the experiment addresses the appropriate phenomena, (2) collection of site-specific data and material properties for model calculations, (3) completion of a pretest analysis; (4) performance of the experiment, (5) reevaluation of the pretest analysis in light of the actual work agreement, and (6) a post test comparison of the experimental and analytical results performed by a peer review panel.

3.3.5.2 Estimate of the Stress-Altered Region

Estimates of the stress-altered region will be performed in the first two experiments described in this study using drift displacement data obtained with MPBXs (Sections 3.1.7.3 and 3.2.5.2). The stress-altered region will be better defined in the sequential drift mining experiment by using several other techniques to augment the data obtained with the MPBXs. Borehole permeability measurements performed before, during, and after the excavation of the main drift will be used to obtain the hydraulic quotient. Variations in the hydraulic quotient will be compared to estimate the extent of the effects of mining on the rock mass. Analysis of cross-hole ultrasonic data obtained before and after mining the main drift will also be used to establish the effect of mining on the compressional velocities. Results from these three analyses will be compared and used to reevaluate the extent of the stress-altered region determined in previous experiments using only MPBX data.

3.3.5.3 Excavation Efficiency Estimate

The analysis of the excavation efficiency activity will be performed in the same manner as described in Section 3.2.5.3.

3.3.5.4 Air and Water Permeability Comparison

Permeabilities measured using air and water will be compared over the same borehole intervals using the equations developed by the U. S. Army Corps of Engineers (1980). These analyses will provide input to the development of rock mass constitutive relationships for the unsaturated zone.

3.3.6 Representativeness of Results

The measurement stations selected for the sequential drift mining experiment will be located in the main test facility at the main test level. The fracture density and orientation and the variation in the lithophysae content are expected to represent the site-specific conditions found within the Yucca Mountain repository block (Nimick et al., 1988). Experience and information gained in the DBR experiment will also be used to assess the effect of lithophysae on the mechanical response of the underground openings.

3.3.7 Performance Goals and Confidence Levels

The confidence levels for the model validation activities will be established by a peer review panel as outlined in Sections 6.4.10 and 8.3.2 of the SCP (DOE, 1988).

4.0 Application of Results

Sections 1.1.1, 1.2.1, and 1.2.2 discuss the manner in which results from the excavation investigations study experiments are applied to resolving regulatory requirements and the Information Needs and Investigations identified by the performance allocation process.

The data from this study will be used to address or help to resolve a number of Information Needs and Investigations identified by the Yucca Mountain Project (Table 4-1). In situ stress measurements will be integrated with other in situ measurements and laboratory data to delineate the spatial distribution of thermal and mechanical properties and ambient stress of welded tuffs (SCP Investigations 8.3.1.15.1/2). Information pertaining to the effects of the mining operation on the extent and nature of the stress-altered region, drift convergence rates and magnitudes, and stress changes will be used in Information Needs 1.11.3, 1.11.5, 4.2.1, 4.4.1, and 4.4.9 (SCP Sections 8.3.2.2.3/5, 8.3.2.4.1, and 8.3.2.5.1/9, respectively) to demonstrate that technology is available to construct repository-size rooms in welded tuffs having variable geological and geomechanical characteristics.

TABLE 4-1. INFORMATION NEEDS AND INVESTIGATIONS ADDRESSED DURING THE EXCAVATION INVESTIGATIONS STUDY.

	Information Need/Investigation	SCP Section
1.11.1	Site Characterization Information Needed for Design	8.3.2.2.1
1.11.3	Design Concepts for Orientation, Geometry, Layout, and Depth of the Underground Facility Including Flexibility to Accommodate Site-Specific Conditions	8.3.2.2.3
1.11.5	Design Constraints To Limit Excavation-Induced Changes in Rock Mass Permeability	8.3.2.2.5
4.2.1	Site and Performance Assessment Information Needed for Design	8.3.2.4.1
4.4.1	Site and Performance Assessment Information Needed for Design	8.3.2.5.1
4.4.7	Design Analysis, Including Those Addressing Impacts of Surface Conditions, Rock Characteristics, Hydrology, and Tectonic Activity	8.3.2.5.7
4.4.9	Identification of Technologies for Underground Facility Construction, Operation, Closure, and Decommissioning	8.3.2.5.9
8.3.1.15	Studies To Provide the Required Information for Spatial Distribution of Thermal and Mechanical Properties	8.3.1.15.1
8.3.1.15	Studies To Provide the Required Information for Spatial Distribution of Ambient Stress and Thermal Conditions	8.3.1.15.2

4.1 Resolution of Site Programs

Results from the excavation investigations study will provide useful corroborative data for a number of other studies. In situ experiments (SCP Section 8.3.1.15) associated with several study plans will be performed to estimate the in situ rock mass properties that will be used to examine the validity of extrapolating laboratory-determined properties to in situ conditions. Preliminary estimates of the variability of in situ properties (i.e., permeability, compressional and shear velocity, strength, etc.) at scales significantly larger than laboratory scales will improve our understanding of the scale effects on the geomechanical characteristics. These in situ properties will facilitate interpretation of results obtained in other experiments designed to validate the thermomechanical model. The scaling relationships will be used to assess the effects of excavation on results of tests performed in the stress-altered region and enhance our capability to select test locations that appear representative of the Yucca Mountain repository.

4.2 Resolution of Performance and Design Issues

The primary objective of the excavation investigations study is to develop a data base for validating the rock mass constitutive models that, when combined with a thermal model, will predict the thermomechanical response of the underground openings and help to develop an adequate design for stabilizing the underground facility. The models will be used to predict displacement magnitudes and the stress distribution induced by excavation and thermal loads. Analysis of ground support requirements will consider the in situ stress state, joint spacing and orientation, and the effects of blasting on the rock mass.

5.0 Schedule and Milestones

5.1 Durations and Relationships of Excavation Investigations Study Experiments

The experiments planned in the excavation investigations study will be performed in a progression that will permit the constitutive models to be gradually refined while proceeding with construction activities in a timely and cost efficient manner. The access convergence experiment will provide initial information on variations in the geological and geomechanical characteristics that will be encountered in the ESF. These variations will be incorporated into the models, where appropriate, to predict displacement magnitudes for a preliminary assessment of the proposed design of the underground facility. The DBR experiment will be used to demonstrate that repository-size rooms can be constructed in high lithophysae jointed welded tuffs, to exercise the rock mass constitutive models, and to provide an underground facility for additional in situ experiments. Experience gained in these two experiments will be an asset in designing and performing the sequential drift mining experiment. This experiment will be used to enhance the data base available for validating the rock mass constitutive models.

5.2 Scheduling Relative to Other Studies

The excavation investigations study experiments will be performed using the schedule proposed for the construction of the ESF. Delays related to installing instrumentation during the access convergence experiment may influence construction schedules, which may subsequently impact the remainder of the experiments scheduled in the underground facility. However, the instrumentation that will be installed during this experiment has been routinely used in numerous mining operations in the past and should not cause any unnecessary delays. Delays in the construction of the DBR could possibly impact experiments planned in other studies that will be conducted in the DBR. The schedule for the sequential drift mining experiment should not impact other studies.

5.3 Schedule

The schedule for the activities associated with the excavation investigations study (Tables 5-1, 5-2, and 5-3) is based on the initiation of these activities relative to the start of ESF construction and on the estimated duration of the activity. Delays in the start of access construction will have a commensurate effect on the activities planned in this study.

TABLE 5-1. ACCESS CONVERGENCE EXPERIMENT SCHEDULE

Activity	Estimated Time from Start of North Ramp Construction (mo)	Estimated Completion (mo)
Produce All Applicable Technical Procedures	-1	
Perform Access Convergence	5	17
Perform Post Test Analyses	8	25
Report Results of Access Convergence Test	25	31

TABLE 5-2. DEMONSTRATION BREAKOUT ROOM EXPERIMENT SCHEDULE

Activity	Estimated Time from Start of North Ramp Construction (mo)	Estimated Completion (mo)
Produce All Applicable Technical Procedures	3	
Perform Demonstration Breakout Room Testing	9	21
Perform Post Test Analyses	11	25
Report Results of Demonstration Breakout Room Experiment	25	31

TABLE 5-3. SEQUENTIAL DRIFT MINING EXPERIMENT SCHEDULE

Activity	Estimated Time from Start of North Ramp Construction (mo)	Estimated Completion (mo)
Produce All Applicable Technical Procedures	22	
Perform Sequential Drift Mining Experiment	28	30
Perform Post Test Analyses	29	35
Report Results of Sequential Drift Mining	35	40

5.4 Milestones

The Yucca Mountain Project milestones associated with the excavation investigations experiments are listed in Tables 5-4.

TABLE 5-4. EXCAVATION INVESTIGATIONS MILESTONES

Milestone Number	Description	Criteria
M686	Begin Access Convergence Testing	Letter
M688	Begin DBR Testing	Letter
M689	Begin Sequential Drift Mining Experiment	Letter
Z938	Access Convergence Experiment Data Report	SAND report
Z939	DBR Data Report	SAND report
Z940	Sequential Drift Mining Data Report	SAND report
M620	Final Report on Access Convergence Experiment	SAND report
M609	Final Report on DBR	SAND report
M627	Final Report on Sequential Drift Mining	SAND report

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