LA-12411-SR
Status Report

UC-802
Issued: December 1992

Status Report on ESF-Related Prototype Testing

Compiled by
R. D. Oliver
H. N. Kalia

Contributing Organizations
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
Sandia National Laboratories
US Geological Survey

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545

CONTENTS

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES
(concluded)

LIST OF TABLES

This report was prepared prior to the change in ESF configuration from two shafts to two ramps. The report refers to the two shaft ESF. Current plans are to maximize the use of mechanical methods of excavation whereas the two shafts were to use controlled drill and blast methods of excavation. The prototype tests performed and the planned prototype tests described are however, consistent with tests to be performed in two ramp ESF to characterize Yucca Mountain.

STATUS REPORT ON ESF-RELATED PROTOTYPE TESTING

Compiled by

R. D. Oliver and H. N. Kalia

ABSTRACT

This report provides information on the Prototype Testing performed in the G-Tunnel on the Nevada Test Site by the Yucca Mountain Project from April 1988 to November 1989. The Testing Program was implemented to ensure that the Exploratory Shaft Facility (ESF) tests can be completed in the time available and to develop instruments, equipment, and procedures so the ESF tests can collect reliable and representative site characterization data. This report summarizes the ESF prototype tests and presents preliminary results.

1.0 INTRODUCTION

The US Department of Energy (DOE) is preparing to conduct an investigation of the Yucca Mountain area, located approximately 200 km (100 miles) northwest of Las Vegas, Nevada, to determine the site's suitability for a repository to isolate high-level nuclear waste from the accessible environment. The investigation must provide sufficient geologic, geochemical, hydrologic, and other geotechnical information to enable a decision to be made regarding the site's suitability for a repository. Characterization of the site requires numerous measurements of rock properties and determination of the presence of surface and subsurface water and its rate and direction of movement. Because information derived from such measurements will be the basis for assessing the site's suitability to isolate nuclear waste for at least 10,000 years, characterization studies must use the best available technology.

In preparation for actual site characterization activities directed and managed by the Yucca Mountain Project (YMP or Project) Office, the Project performed a prototype testing program to ensure that tests planned for obtaining site characterization data would perform as expected. The purpose of the prototype testing program was to prepare to meet the technical objectives of the site investigation.

Description of Prototype Testing

Prototype testing involved a series of activities that fell within two broad categories. Most of the tests were performed to develop and test the effectiveness of methods and equipment. These tests are precursors for very similar tests that will be performed during site characterization, either in the Exploratory Shaft Facility (ESF) or on the surface. Other prototype tests did not have a corollary test planned during site characterization, but rather, were used to perform preliminary evaluations of equipment or test methods to assess their usefulness for subsequent applications.

Prototype testing activities were conducted under Project-approved quality assurance (QA) requirements and procedural controls. A major product of the prototype testing program is a technical procedure, or set of procedures, that would be followed in the site characterization process. The prototype testing program provided the opportunity for site investigation personnel to become thoroughly familiar with the test equipment and procedures before they are used at Yucca Mountain.

The prototype testing program was conducted in several locations. The majority of tests related to investigations planned for the ESF at Yucca Mountain used the G-Tunnel Underground Facility (G-Tunnel) below Rainier Mesa on the Nevada Test Site (NTS), where investigators had access to both welded and nonwelded tuffs similar to those that underlie Yucca Mountain (Figures 1.1-1 and 1.1-2). The G-Tunnel was approximately 381 m (1,250 ft) below the surface and provided lithostatic loading (i.e., the weight of

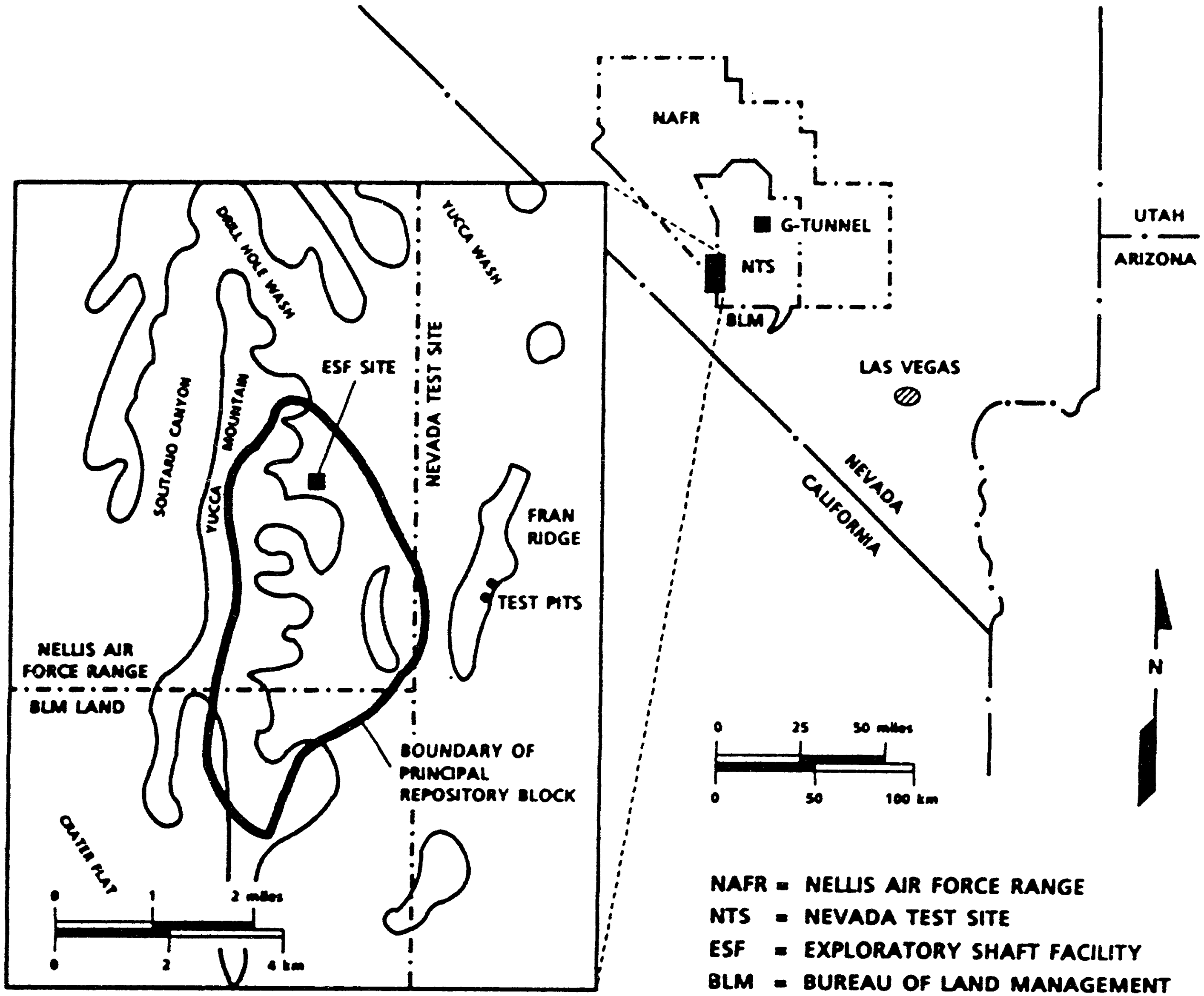


Figure 1.1-1. Location maps showing NTS, G-Tunnel, Fran Ridge Test Pits, ESF, and Boundary of Principal Repository Block.

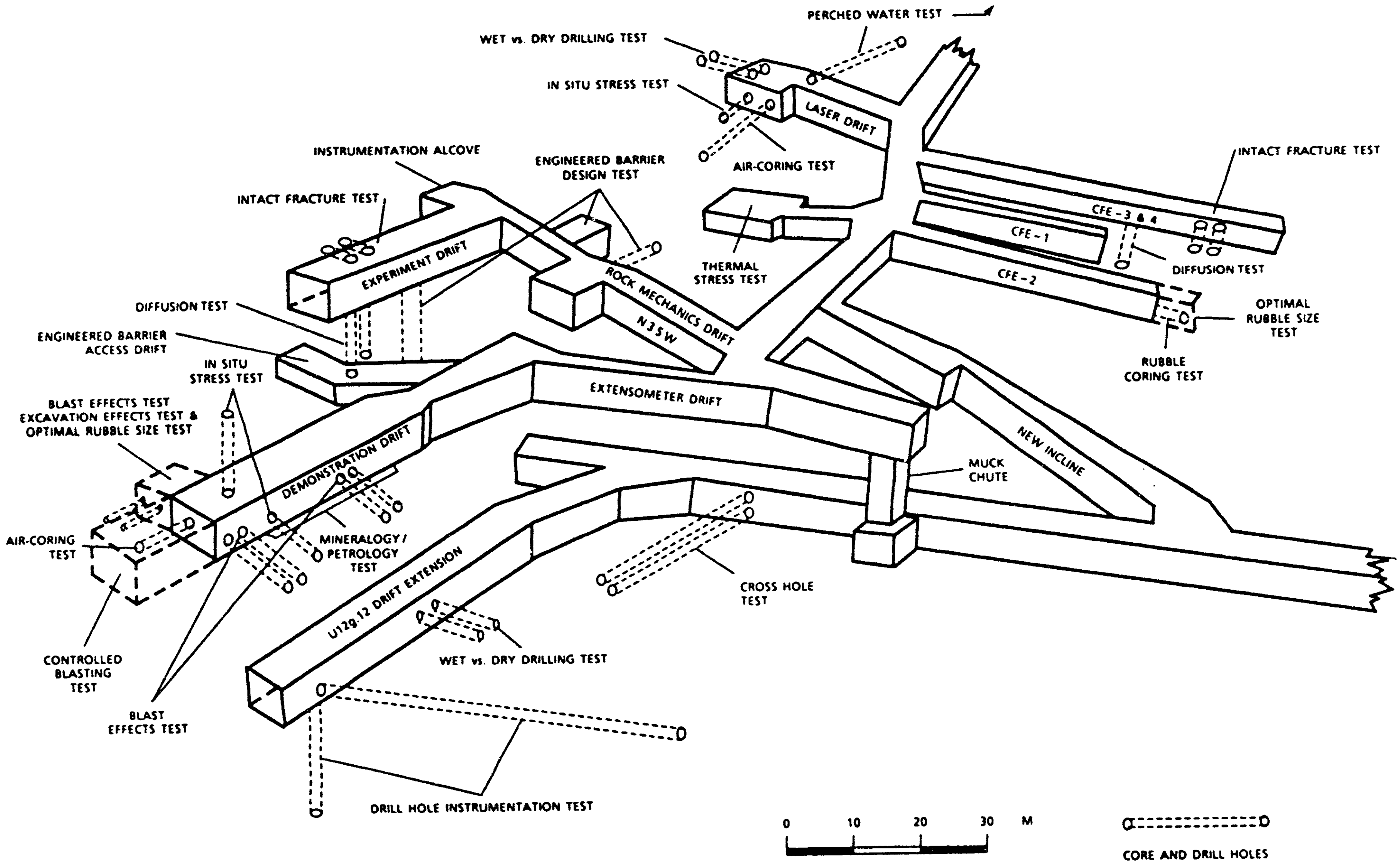


Figure 1.1-2. Layout of G-Tunnel Underground Facility and prototype tests.

the overlying rock column) and stress conditions comparable to those at similar depths in the ESF. One prototype test was conducted in a test pit located on the east flank of Fran Ridge; other prototype tests were conducted in laboratories at investigators' institutions.

Groups Involved

Prototype testing was conducted by the same Project participant organizations that are scheduled to conduct the actual characterization of the Yucca Mountain site. These organizations include the US Geological Survey (USGS) in association with the US Bureau of Reclamation (USBR) and Lawrence Berkeley Laboratory (LBL), Sandia National Laboratories (SNL), Lawrence Livermore National Laboratory (LLNL), and Los Alamos National Laboratory (Los Alamos). Field support was provided by Reynolds Electrical and Engineering Co., Inc. (REECo), Fenix and Scisson of Nevada (FSN), and Holmes and Narver, Inc. (H&N). Prototype-testing activities related to planned underground tests at Yucca Mountain were coordinated by Los Alamos on behalf of the Project.

Development of Prototype Testing Program

Los Alamos is responsible for coordinating the development and implementation of the Exploratory Shaft (ES) tests. This responsibility includes providing reasonable assurance to the DOE that estimated costs for testing are valid and that the testing program can be accomplished successfully. One way that could minimize the risk of failure of testing and increase confidence that the costs estimated for ES testing are realistic is to conduct a prototype testing program under simulated ES conditions. Los Alamos requested that all ES principal investigators review their test proposals; identify all tests or test elements that needed to be prototyped; and prepare investigation plans, with applicable QA documentation, for Los Alamos and DOE review.

Los Alamos recommended that the near-term ES testing activities focus on the development and implementation of prototype tests needed to properly prepare for ES testing. The principal investigators (PI) were requested to prepare separate investigation plans and QA Level Assignments (QALA) for each proposed prototype test. The investigation plans were to be submitted to Los Alamos for technical review, and both the plans and QALAs were to be submitted to the DOE Project Office for QA review and approval.

Upon receipt of the approved prototype investigation plans, Los Alamos requested through the Project Office that FSN develop estimates for the cost of NTS support (equipment, materials, manpower, and G-Tunnel services) and develop a schedule for performing the G-Tunnel work. The schedule was continually refined to reflect constraints such as available resources, other planned G-Tunnel activities, and available space.

This document provides a description of ESF prototype tests and will provide the preliminary results. Detailed reports on the tests performed by various organizations and participants shall be reported by the respective participant. This report is prepared in four sections. Section 1.0 provides the introduction; Section 2.0 contains purpose and objective and a summary level description of the prototype tests; Section 3.0 provides management and organizational structure; and Section 4.0 contains a description of each prototype test, including purpose and objective, support required, test program, historical perspective and background, evolution of test design, conduct and results of tests, and future activities.

Status

The prototype test program has demonstrated significant achievements in areas essential to the implementation of site characterization. Air coring has been shown to be a viable, time-efficient, and cost-effective method for drilling or coring holes in densely welded tuff in a mine environment.[1] Furthermore, related studies have shown that dust hazards associated with air coring can be controlled through equipment and procedures.[2] Significant developments were achieved in other tests, primarily in the refinement of equipment and procedures.

A status report was issued in October 1989[3] that summarized prototype testing activities. Not all the planned tests could be completed. Prototype testing in the G-Tunnel was halted in December 1989 because of reduction in the Project budget and the change in schedule for the start of the ESF.

2.0 PURPOSE AND OBJECTIVES

Purpose of the Test Program

Protection of the waste isolation capability of the Yucca Mountain site during construction of, and experimentation in, the ESF requires that alteration of the hydrologic characteristics of the rock surrounding the ESF be minimized. Furthermore, testing in the ESF must produce accurate, reliable data and must proceed efficiently to allow successful completion of the tests during a restricted time schedule.

The purpose of the prototype testing program was to ensure that the site characterization tests would perform as expected and would generate high-quality data while minimizing the impact on the waste isolation capabilities of the site.

Objectives of the Test Program

There were four overall objectives of the prototype testing program. These major objectives were

- to evaluate the suitability of the test relative to two questions:
  (1) did the test activity provide the types of data that were required and
  (2) were the test methods and equipment suitable for use in the environment of application (generally the ESF);
- to evaluate the methods and equipment that will be needed to perform ESF construction and surface-based or ESF testing;
- to develop procedures that will be followed subsequently during site characterization; and

- to train the personnel that will be needed to conduct testing during site characterization.

Objectives of Individual Tests

Each test addressed topics such as developing sampling procedures, developing methods to be used for site characterization studies, and evaluating techniques or equipment for their applicability to construction or testing at the surface or in the ESF. As part of the prototype testing to develop methods for use during site characterization, tests were further subdivided into geomechanical, geologic, geochemical, or hydrological subcategories, that depended on the focus of the testing. Although the grouping summarized above provided a framework to logically categorize the tests, there was considerable overlap among some tests, and other tests did not fit neatly into any category. Each test and the specific objectives of the test are briefly described below. Detailed descriptions are provided in Section 4.0.

Underground Geologic Mapping

This test develops methods to characterize and describe the geology of subsurface environments. Activities conducted as part of this prototype test included the development of equipment and test methods for application of photogrammetric techniques to the mapping of geologic features on the excavated surfaces of shafts and drifts associated with the ESF. The major objectives of this prototype test were to develop photogrammetric mapping methods, equipment, and data-reduction techniques for application to shafts and drifts; test alternative mapping methods that would serve as back-ups in the event of temporary breakdown of the photogrammetric equipment; and develop formal procedures and train personnel in their use. Prototype mapping was conducted underground in the G-Tunnel to simulate conditions in the drifts of the ESF and in open surface pits that simulated conditions in the exploratory shafts.

Mineralogy/Petrology Studies

This prototype test was performed to determine the methods, time, and effort that would be required to collect and document rock samples gathered from Yucca Mountain. These samples would be used to determine the stratigraphic variability of the host rock, the alteration and transport history of the underlying tuff, and the mineralogy of fractures and faults in local tuffs. The primary objective of this prototype test was to determine how to perform sample collection activities in the ESF that would provide both representative materials and examples of features of special interest.

Evaluation of Effects of Wet and Dry Drilling on In Situ Hydrologic Conditions

Drilling-induced alteration of in situ hydrologic conditions of the rock matrix surrounding boreholes could have a significant effect on hydrologic experiments performed in or near boreholes, on instrumentation installed in the boreholes, and on geophysical logging. The objective of this test was to determine how air and water, when used as drilling fluids in tuffaceous rocks, affected the in situ hydrologic conditions of the rock matrix surrounding the borehole.

Drill-Hole Instrumentation

Development of borehole instrumentation that can be installed rapidly and in a well-coordinated manner would allow instrumentation installations sequenced with construction operations and would capture data that closely approximate preconstruction conditions. More importantly, the response of the hydrologic conditions to the influence of the ESF construction activities would provide invaluable data on the dynamic response of the unsaturated zone to changes in hydrologic boundary conditions.

The major objectives of this prototype test were to develop methods for installing instrumentation in boreholes that will ensure both hydrologic continuity with the surrounding tuff and isolation of instrumentation from portions of the borehole remotely located from the measuring location; to develop techniques for verifying the accuracy of instrumentation; and to provide in situ calibration of that instrumentation.

Blast Effects

The prototype blast effects test was specifically designed to measure stress and vibrational disturbances resulting from controlled blasting and to assess the impact of these blast effects on instrumentation to be used for hydrologic investigations near the construction. This investigation would examine the potential for damaging the instruments and core holes during blasting and would explore ways to improve performance through changes in instrument design and test procedures. The investigation would also create procedures and criteria to assess blast damage on site structures and equipment located near the excavation.

Cross Hole, Pneumatic, and Hydraulic

Several ESF tests are proposed for measuring the hydraulic properties of the rock units surrounding the ESF openings. These tests are designed to identify the likely paths for water flow along the contact between hydrogeologic units that have contrasting hydraulic properties and to measure hydraulic properties of faults or fault zones. The objective of this prototype test was to develop a standardized test system, for both hydraulic and pneumatic tests, that could be used in the ESF cross-hole tests.

Tracer

Fluids would be used during construction of and testing in the

ESF. Tracers added to liquids or gases used in hydrologic testing can provide a means of distinguishing among many possible sources of those fluids. The objective of this prototype test was to identify a suite of nonreactive, nontoxic chemical tracers that could be used to tag all liquids used during ESF construction and operations and during hydrologic testing.

Excavation Effects

The objective of this test was to develop, refine, and qualify the ability to measure stress changes and consequent permeability changes that occur in rock adjacent to a drift as it is being excavated. The test evaluates whether the instruments are sufficiently rugged to survive the blast accelerations, whether the instrument holes themselves would survive the blast effects, and whether modifications to the test design would be required to ensure successful measurements in the ESF.

Optimal Rubble Size

The objectives of this prototype test were to determine whether large fragments of rubble would have a center volume that was not altered significantly by the blasting process and whether the unaltered zone could be air-cored in the laboratory to obtain a plug sample for hydrochemical and isotopic pore water analyses. These activities were closely associated with the previously described prototype test for pore water extraction and would also support the ESF mineralogy and petrology sampling effort.

Intact Fracture

This prototype test was used to develop the methods and procedures necessary to retrieve minimally disturbed intact-fracture core samples. These samples were used to establish and document the laboratory methods and technical procedures for characterizing fluid flow, chemical transport mechanisms, and other properties of fractures. The major objectives of this test were to (1) evaluate and modify, as necessary, the equipment used for obtaining intact-fracture samples and conducting laboratory testing; (2) develop methods for preserving fracture integrity throughout the collection and preparation of samples; and (3) evaluate the effectiveness of the proposed laboratory testing for hydrologic characterization of the fractures.

Percolation

This prototype test was conducted to design the needed experimental apparatus to monitor liquid water and tracer movement through a large block of fractured, welded tuff. The test will evaluate the feasibility of isolating a large fractured-block test bed underground and installing instrumentation and calibration techniques to characterize flow in that test bed. The development of technical procedures and collection of flow data for comparison to model calculations is also planned.

Bulk Permeability

Prototype testing was necessary to design an experimental apparatus to measure bulk permeability and to ascertain the feasibility of conducting air permeability tests at a variety of scales within fractured, welded tuff. The primary objectives of this test were evaluation of instrumentation techniques at in situ stress levels and comparison of data to model calculations.

Perched Water

This prototype test developed methods for characterizing perched water zones that may be encountered during construction of the ESF. The objectives of this test were to investigate and develop methods for measuring rates of seepage of perched water into a shaft or drift, measuring hydraulic heads within a perched zone, collecting representative water samples, and conducting aquifer tests within the perched zone.

Dry Coring of Rubble

During site characterization in the ESF, rock samples will be required for determining pore water chemistry. It must be demonstrated first, however, that the techniques for obtaining the rock samples do not affect the results of the water analyses. The general objectives of the rubble coring test were to develop a coring technique that has an insignificant effect on the pore water chemistry of the sample rock, to identify and assess problem areas, and to determine the approximate costs and time required for dry coring rubble samples. The primary objective was to obtain, modify, or develop a coring machine that would produce smooth, unbroken cores of appropriate size that were not heated excessively during coring.

Pore Water Extraction

The purpose of this prototype test was to establish the feasibility of extracting pore water from unsaturated, welded and nonwelded tuff by using triaxial and uniaxial compression equipment. The equipment was used to squeeze water and gas from rock pores so that the fluids could be analyzed for chemical composition. The pore water-extraction experiments planned for the ESF would be part of a broader category of site characterization activities that would be performed to determine the properties of the host rock and the fluids it contains.

Controlled Blasting

This investigation will describe close-range blast pulses and stress responses generated by controlled blasting methods during mining in the host rock. The objectives were to provide a controlled source blast that could be used to evaluate the effects on instrumentation and to develop a technique to measure the extent of blast damage.

Thermal Stress

Thermal stress testing would be performed during site characterization activities to evaluate the effects of heat loads on drift stability in the repository and to provide data to validate models used to predict the thermomechanical behavior of the rock mass. The objectives of this prototype test were to develop and refine the approach, methods, and equipment and to train personnel to conduct thermal stress tests.

In Situ Stress

To assess the geomechanical properties of rock at Yucca Mountain, tests were planned in the ESF to characterize in situ stresses. The test was being performed at G-Tunnel on the Nevada Test Site where the stress state and environmental conditions to be encountered during the prototype test should be similar to those in the ESF testing. The objectives of this prototype test were to evaluate the field procedures and instrumentation and to compare alternative methods for determining in situ stresses under conditions similar to those expected in the ESF.

Diffusion

This test proposed for the ESF will measure the rate of solute diffusion into water-filled (or partially filled) pores of the tuffs in the unsaturated zone at Yucca Mountain. In situ measurements of diffusion can be used to derive diffusion coefficients for use in performance assessment calculations. The objectives of this prototype test were to ensure that all aspects of the proposed test methodology were viable and to prepare and issue the required technical procedures.

Evaluation of the Engineered Barrier System

Testing will be conducted in the ESF to gain an understanding of the near-field effects of heating and cooling a rock mass around a simulated waste package. The prototype test was conducted before the ESF testing in order to validate and refine the test design, equipment, and methods. The primary objective of the prototype engineered barrier test was to evaluate the technical feasibility of defining the hydrologic and thermomechanical behavior of the near-field (within a few meters [a few tens of feet]) rock mass during a heating and cooling cycle.

Air Coring

The diverse nature of the ESF testing will require the drilling of several different types of holes. The most recent compilation showed that more than 300 holes, totaling more than 3 km (10,000 ft) of cored hole, are specified to support ESF testing requirements. Within the prototype air coring test, the process of air coring was evaluated as a substitute for water drilling in the ESF because the use of air as the circulating medium eliminated the potential for introducing water into the drilled formations. The objectives of the prototype air coring test were to develop air coring into a viable cost- and time-effective technique, to refine the technique for application to the specific needs of the ESF testing program, and to train the personnel needed to perform the drilling.

Dust Hazards Associated with Air Coring

Air coring could create a significant health hazard to investigators and workers because of the increased generation of airborne dust that would normally be reduced by a drilling fluid such as water. Consequently, the test of dust hazards was conducted to determine if the air contaminants created during air coring could be sufficiently controlled using available dust control and collection equipment, to ensure compliance with health and safety standards. The objectives of this test were (1) to evaluate the potential exposure of workers and investigators to airborne silica, zeolite fibers, and nuisance dusts so that the proper controls (engineering controls, administrative controls, and physical protection devices such as respirators) could be incorporated into procedures for projects involving air coring at the ESF; and (2) to evaluate the effectiveness of commercial dust-control equipment attached to the drilling apparatus during air coring.

Radon Emanation

Radon, which may be released as a gas from tuffs in the ESF, decays to radioactive particles that may pose a health hazard if they are inhaled. Investigations to quantify the rate of radon emanation from the repository host rock mass would be conducted in the ESF primarily to assess the potential hazard to workers. The objective of this prototype test is to determine the relationship between airflow and radon concentration in drifts. Test procedures and equipment for measuring the rate of radon emanation in the ESF will be developed.

Vertical Seismic Profiling

For site characterization, a series of boreholes will be drilled and instrumented to gather data for various studies. One such study involves the use of vertical seismic profiling (VSP) to characterize fractures and other subsurface discontinuities. Through computer analysis, characteristics such as fracture spacing and orientation may be inferred. Successful completion of this prototype test would mean that VSP can be accomplished efficiently during site characterization activities and that the data generated are adequate for the intended purpose. Major activities in this testing program included solving logistical problems associated with the seismic equipment, such as ensuring that the large vehicle-based vibrators can gain access to the site to be vibrated; site preparation; removing the casing from the borehole; and evaluating the data gathered to refine the seismic profiling techniques.

Equipment and Instrument Development and Demonstration

The activities in this prototype test were intended to provide information on the adequacy and reliability of equipment and instruments planned for use in the ESF. Evaluation and demonstration tests were conducted on high-pressure flat jacks, multiple-point borehole extensometers (MPBX), remote convergence-monitoring equipment, anelastic strain recovery (ARS) equipment, and hydraulic chain saws. Field operation and installation procedures were developed, and personnel were trained.

Rock Mass Response Experiment in the G-Tunnel

This prototype test activity demonstrates the feasibility of large-scale shear testing and large-scale multiaxial compression testing in the underground environment. The objective of this test is to evaluate joint characteristics and typical rock mass response under experimental test conditions. Measurements will include compressive and shear strengths and strains. Test deployment procedures will be developed, and instrument installation and calibration techniques will be finalized.

3.0 CONDUCT OF TEST PROGRAM

Managerial methods and procedures were developed to ensure consistency among the various prototype tests. Furthermore, this management of the tests ensured that the testing program was carried out properly within the guidelines and under the direction of the YMP Office, that tests received adequate funding and support, that the objectives of the tests were achieved, and that the schedule of testing facilitated the efficient completion of all testing activities. The sequencing of tests was crucial because some tests provided needed input to other tests, such as samples or data.

As the Project ESF test manager, Los Alamos manages the prototype testing program and, in this capacity, is responsible for

- conducting readiness reviews of each test before its implementation;
- mediating conflicts in test schedules and related problems among the PIs and participating organizations;
- determining if the results of the prototype tests demonstrate a readiness to implement the ESF testing program and making a recommendation to the Project Office on the state of readiness;
- monitoring prototype test activities;
- coordinating interactions among PIs and interfaces with the Nevada Test Site Office (NTSO) and its support contractors;
- issuing weekly and monthly summary reports on the overall status of the prototype testing program;
- transmitting guidance and direction from the YMP management to the PIs; and
- ensuring that the evolving requirements of the YMP are reflected in the prototype testing program.

The methods developed and refined to manage the prototype test program will be used to ensure systematic and comprehensive management of the site characterization studies in the ESF and on the surface. Specific controls that were used in management of the prototype testing included the work authorization process, readiness review process, and elements of test supervision. These controls are discussed in the following sections.

Work Authorization Process

In order to begin prototype testing, a work authorization was granted by the Project Office. The field work authorization process begins when a PI completes a criteria letter. The criteria letter and field work activity flow are illustrated in Figure 1.1-3.

The criteria letter is submitted to the Project Manager after review by Los Alamos and SNL staff. The outline for the criteria letter process is set forth in Project procedure AP-5.10Q, "Use of NTS Contractors on the NNWSI Project."[4]

The Los Alamos Test Manager Office (TMO), the G-Tunnel operator, and SNL review the criteria letter. Once approved, the criteria letter is sent to the YMPO. Approval of the criteria letter also signifies approval of the NTS work authorization to begin prototype testing. The Project Office sent a letter to the DOE at the NTS (DOE/NTSO), which stated that the work authorization for the prototype testing had been approved and that appropriate NTS contractors were to be notified. At this point, NTS contractors can begin providing the requested support detailed by the PI in the criteria letter through a drilling or mining program work order process.

Once the Project Office has granted approval for the work authorization, all related work orders and final documentation

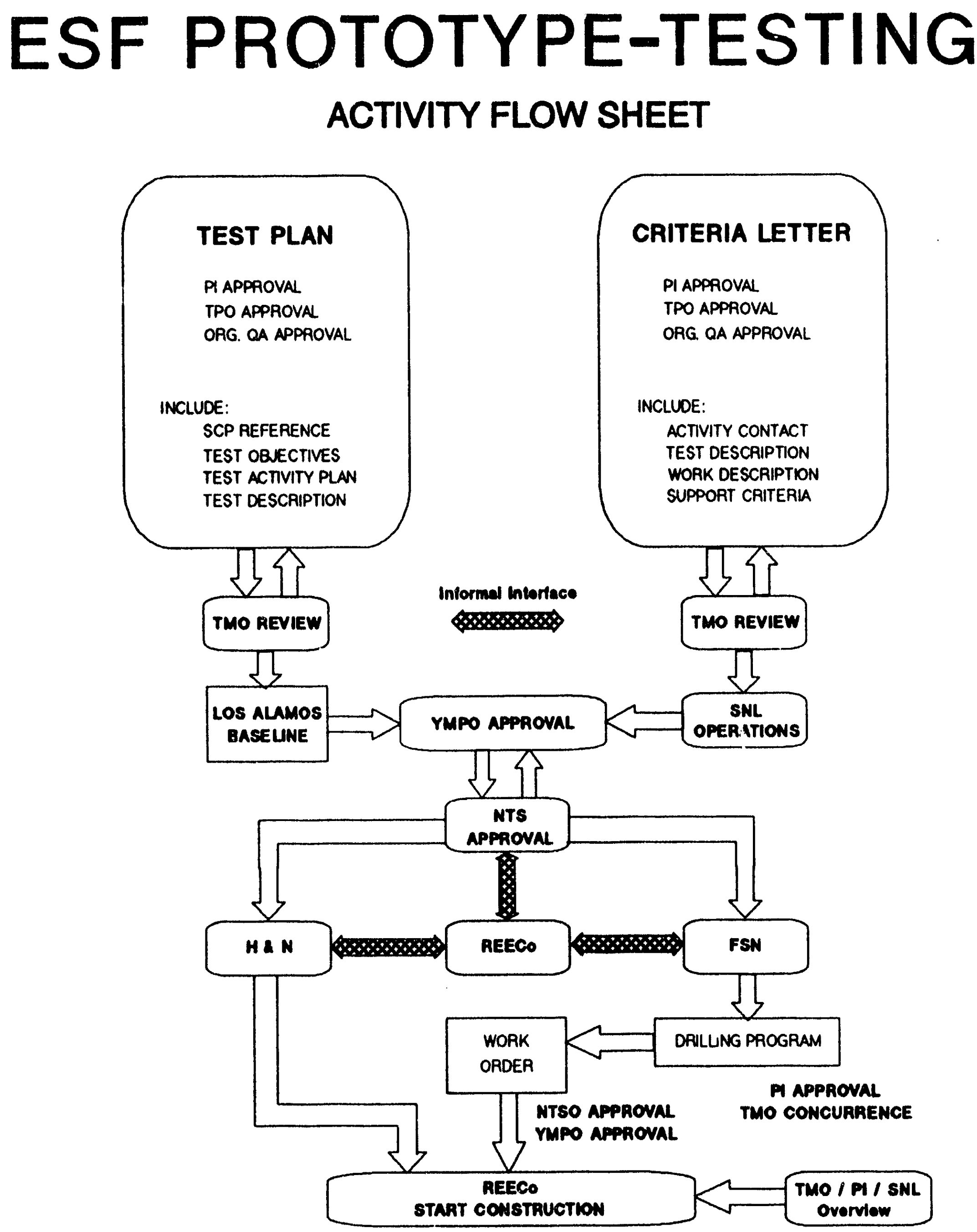


Figure 1.1-3. ESF prototype-testing activity flow sheet.

prepared by the contractors based on a criteria letter, must be reviewed by the NTSO and approved, signed, and dated by personnel authorized by the PI. Any changes the PI makes to the criteria letter or prototype test program must be approved by the DOE/NTSO. The DOE, or its designate, is responsible for informing NTS contractors of approved changes, thereby initiating changes to the work order revision process.

Readiness Review Process

Los Alamos was responsible for determining and documenting the readiness to start a field testing activity and forwarding a recommendation to the Project Office. The readiness review process took place before the actual prototype testing field work began but after the criteria letter was approved by the Project Office. A panel selected by the Readiness Review Chairperson generated a set of questions that provided the criteria used to establish "readiness." The panel and chairperson met with appropriate personnel and reviewed written documentation to answer the questions.

Test Supervision

The PI was responsible for conducting the test and direct field modifications to construction criteria that was in direct support of a test. A representative of the test manager, who acted primarily as a consultant and integrator, was onsite during construction and testing operations. Test supervision by the TMO was purposely conducted as a coordination and expediting function to maximize testing personnel's experience with construction crews, underground operations, and the general details that must be identified and resolved during field activities and testing.

4.0 DESCRIPTION OF TESTS

4.1 Underground Geologic Mapping

General Test Description

Mapping in shafts and drifts will provide a detailed description of stratigraphic, lithologic, and structural features. Mapping of fracture networks and intersections will be continuous because fracture spacing and attitude commonly vary over tens to hundreds of meters at Yucca Mountain. Mapping objectives will be met through a three-tiered approach: (1) analysis of stereoscopic photographs (photogrammetric geologic mapping); (2) continuous detailed mapping along reference lines (detailed line surveys); and (3) conventional mapping to record data not acquired by methods 1 and 2. Although the general procedures are not new, site-specific procedures are being developed.

Purpose and Objectives

Characterization of geologic features such as faults, fractures, and stratigraphy is essential to performance assessment and must be done for the entire ESF. Because the shafts and drifts of the ESF will receive lining or temporary support as they are excavated, geologic mapping must be carefully coordinated with construction activities. Once shaft lining is in place, no additional mapping is possible, and temporary lining in drifts has to be removed before mapping can be done. The mapping procedure must be conducted rapidly to minimize delays and their resultant cost to construction but must also accurately acquire necessary data and be reproducible. Photogrammetry, combined with detail line surveys and minimal conventional mapping, satisfies these needs. Equipment and procedures tailored to the mapping needs of the Project must be developed and tested before shaft construction begins.

The purpose of the prototype test is to develop methods and equipment to ensure that geologic mapping will be efficient and produce accurate, reproducible results to prescribed limits. Major objectives of this prototype test are to

- develop mapping methods, equipment, and data-reduction techniques for application to shafts, drifts, and similar exposures;
- test supplementary mapping methods that will provide additional and backup data;
- develop formal procedures; and
- train personnel.

Support Required

The prototype shaft and drift tests require support from H&N for surveying, from Pan Am for photography, and from REECo for construction. Support from contractors provides an opportunity to exercise both their activities and the interfacing between them and Project participants.

Test Program

The objectives of geologic mapping in the ESF will be met by a three-tiered approach to mapping: (1) analysis of stereoscopic photographs (photogrammetric geologic mapping); (2) continuous detailed mapping along reference lines (detailed line surveys); and (3) conventional mapping of features not obtainable by methods 1 and 2.

Detailed Test Description

This prototype test is designed to emulate mapping operations planned for the ESF. Stereoscopic photographs will be taken of all exposed surfaces in shafts and walls and crown of all drifts as mining of the ESF progresses; floors and working faces will not be mapped unless anomalous geologic features are exposed. Geologic maps will include discontinuities—such as faults, fractures, and breccia zones—as well as lithology and stratigraphy. The maps will be prepared from stereoscopic photographs using close-range photogrammetry and direct observation.

Stereophotography and in situ mapping of shafts and drifts will be done between mining operations. Close-range photogrammetry will provide continuous data in shafts and drifts. In shafts, detailed in situ measurements will be made of geologic features along detailed line surveys approximately 2 m (6 ft) apart in ES-1 and approximately 15 m (50 ft) apart in ES-2. In drifts, detailed line surveys will be done continuously along one wall. Other line surveys may be obtained as required at significant changes or special geologic features.

Geologic mapping requires a significant amount of time. The time will be minimized (from 8 h per round to 2 h per round, or 2-m (6-ft) interval) by using photogrammetry. This 2-hours-per-round requirement will allow mapping up to three 2-m (6-ft) rounds per shift, i.e., 6 h to map three rounds, or 6 m (18 ft).

The data obtained photogrammetrically are then combined with data obtained from in situ mapping. In situ mapping consists of detailed mapping of every geologic feature—such as lithology and fractures—along a reference line. The location, attitude, and fracture characteristics—such as aperture, filling materials, and roughness—are recorded. These data are then stored in a data file for specific and statistical analysis.

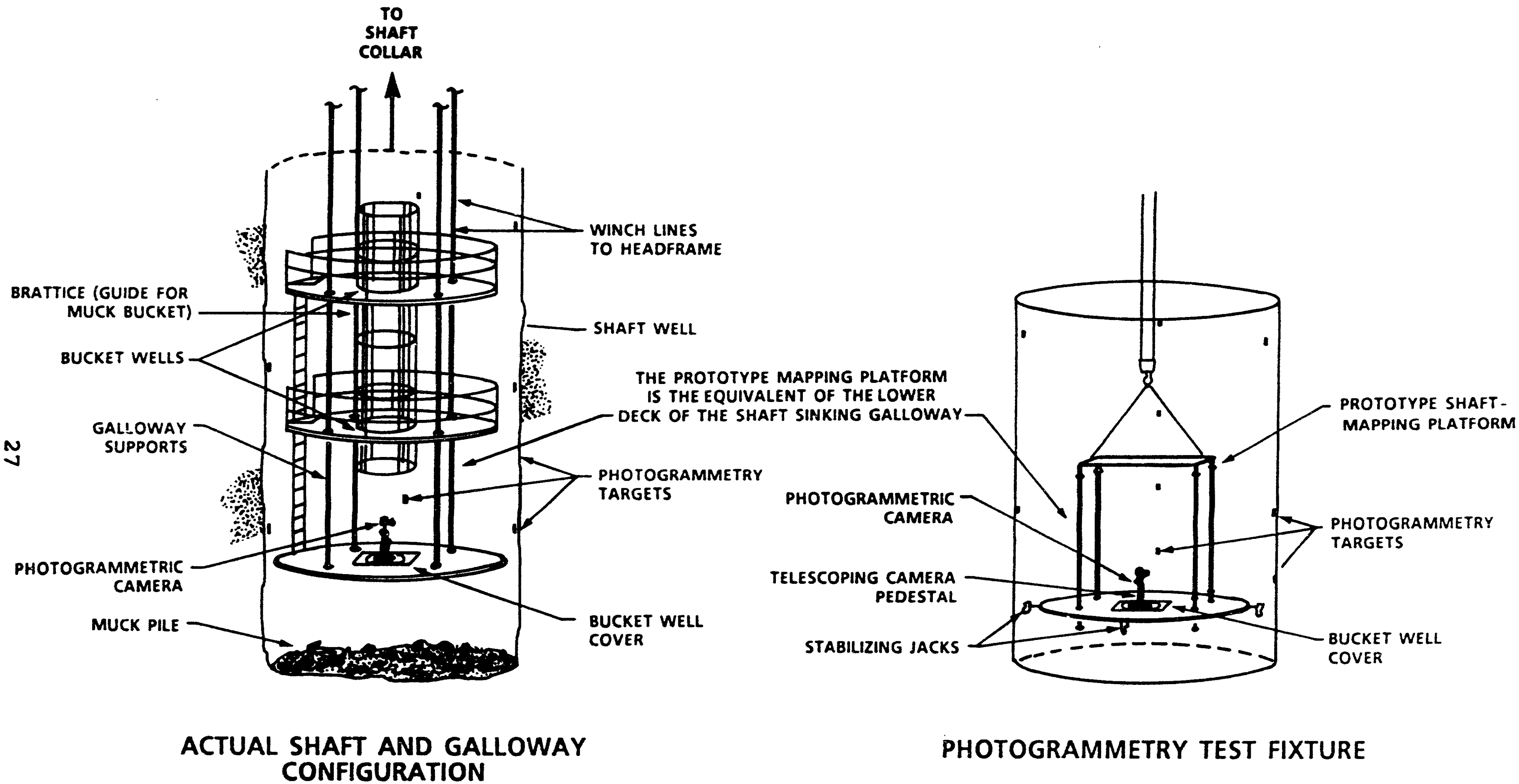
The data obtained photogrammetrically and in situ are then made available to users as data files and as full-periphery geologic maps and cross sections generated by the analytical plotter. The data are also presented as statistical plots such as histograms and stereoplots.

Three major prototype-testing activities are developing equipment, methods, and technical procedures for shaft mapping, drift mapping, and development of photogrammetric laboratory methods and technical procedures. The mapping equipment and procedures proposed for use in the ESF, and subsequently in the potential repository, have been used before but have not been integrated and optimized for ESF application. The mapping system will include the equipment required for orientation and support of the field equipment (such as the camera and survey equipment) and procedures, as well as the analytical plotter laboratory equipment and procedures.

The shaft-mapping system relies on a galloway (a multi-decked work platform, Figure 4.1-1, left) for a work base. The galloway is suspended in the shaft by cables that permit both moving the platform into place for activities at the shaft bottom and hoisting the platform upward and out of the way for blasting activities. The bottom deck of the galloway is being designed to function as both a construction and mapping deck. The major design consideration for the lower deck is a relatively unobscured field of view for the camera and a mount for the mapping pedestal.

The mapping pedestal mounts in the center of the platform (and therefore the center of the shaft) and is the mount and reference point for subsequent shaft photography, surveying, and mapping. The mapping process consists of the following seven steps: (1) cleaning the walls with an air/water mist, (2) locating photogrammetric control targets, (3) sampling, (4) photography, (5) surveying, (6) detail line surveying, and (7) conventional sketch mapping.

The drift-mapping system relies on a reference rail aligned parallel to the drift centerline (Figure 4.1-2). The reference



November 30, 1989 12:47 PM
FIG 4.1-1 LS07126(03)

Figure 4.1-1. Schematic of shaft, galloway (left), test fixture, and prototype shaft-mapping platform (right).

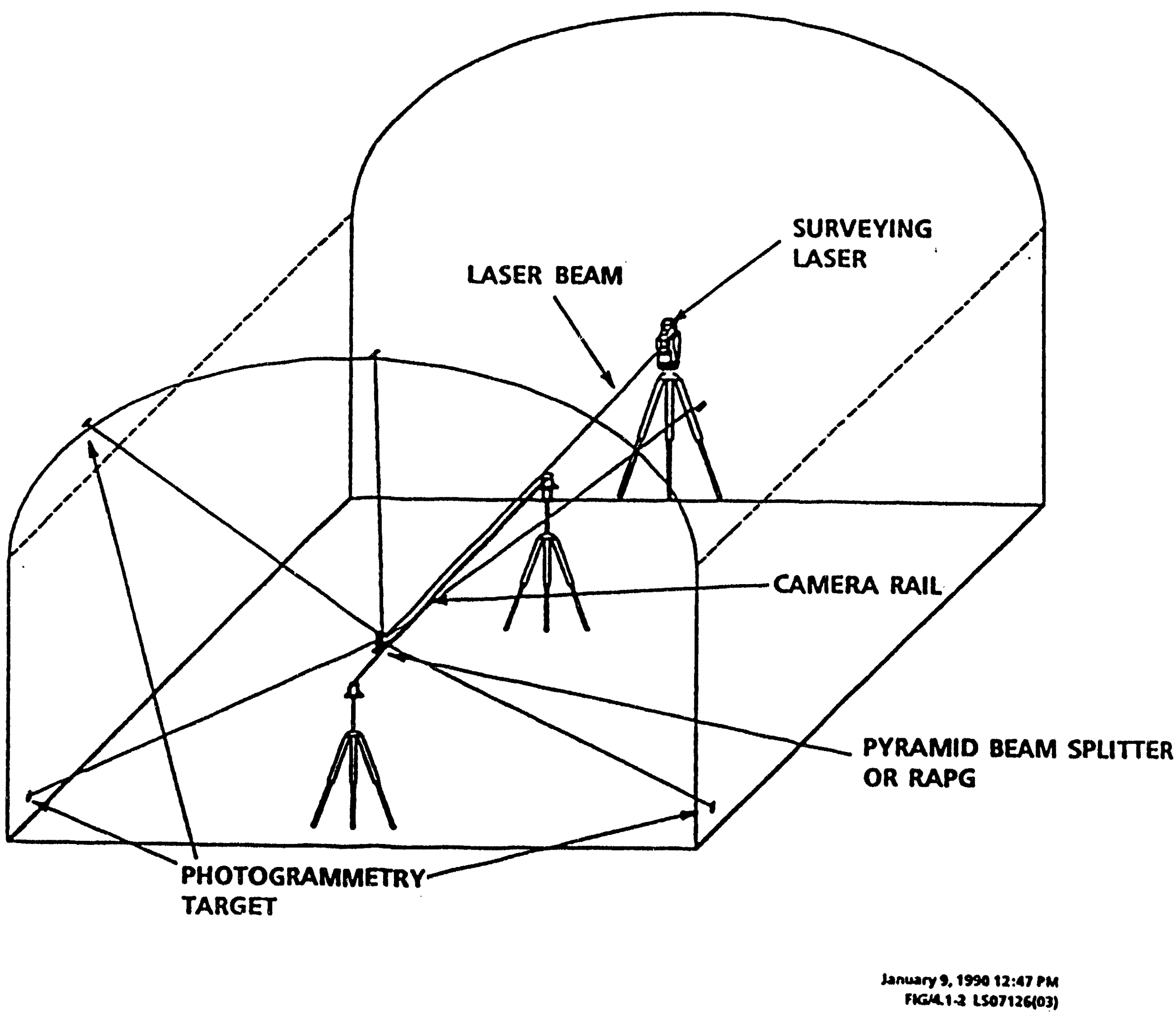


Figure 4.1-2. Diagrammatic view of the drift showing laser setup and placement of photogrammetry targets.

rail consists of a rail supported at each end by an adjustable support. The rail is aligned with a laser beam projected parallel to the drift centerline. The reference rail is the mount and reference line for subsequent drift photography, surveying, and mapping. The mapping process consists of the same steps as shaft mapping.

The photogrammetric laboratory uses the photographs to generate photogrammetric maps using an analytical plotter. The analytical plotter is a Kern DSR-11 with a dedicated MicroVAX II computer and associated peripheral equipment. Stereophotographs obtained in the excavations are mounted on plates that hold and locate several stereopairs. These stereopairs, or models, are then located spatially utilizing the surveyed locations of targets shown in the photos. The analytical plotter compensates for any camera lens aberration and can locate any point shown in the model in three-dimensional space. Because several models are located together on the mounting plates when the edge of a model is reached while viewing, the plotter automatically drives to the next appropriate model to continue viewing adjacent areas. During geologic mapping, the geologist-operator follows geologic features, such as fractures and faults, with a marker (light pip projected into a three-dimensional field of view). As the marker follows the feature being mapped, the analytical plotter digitizes, or records, the location of the light pip at hundreds to thousands of points. These points are then stored in the computer for later plotting of fracture trace locations and for calculation of geologic structural data. The digitized locations are used to calculate strike and dip, for curve fitting, and to perform statistical analyses. The photogrammetric geologic maps are integrated with the other field data for final map and data base generation.

Historical Perspective and Background

The construction of the ESF shaft and drifts will be done in "rounds," or stages. A round consists of (1) drilling, (2) loading and shooting, (3) mucking, and (4) installing supports if needed. Supports in the shafts consist of rock bolts and mesh, with concrete lining installed after approximately three rounds. Drift support consists of rock bolts and wire mesh or chain link. The only acceptable type of support installed before photography is rock bolts. Consequently, geologic mapping must be accomplished within one to three excavation cycles or rounds.

The heart of photogrammetric mapping is the analytical plotter, a computerized stereographic plotter whose advent made possible the photogrammetric geologic mapping of complex-shaped excavations at close range, while simultaneously calculating locations and structural attitudes (strikes and dips). All mapping and structural data are stored digitally, which allows further analysis. Because of the high degree of accuracy of an analytical plotter, accuracy of mapping is limited only by the accuracy of control surveys. Geologic photogrammetric mapping is considerably more accurate and faster than conventional mapping and is applicable to inaccessible areas.

Traditional geologic mapping of excavations consists of conventional sketch mapping, photomosaic mapping, or a combination of the two. These methods have several drawbacks, and the major disadvantage is the approximate eight hours required per round. The combination of close-range photogrammetry, detail line surveys, and minimal sketch mapping results in approximately two hours per round needed for mapping. In addition, photogrammetric mapping was chosen for mapping the ESF for the following reasons:

- Speed: The geologist is not compelled to spend critical (and expensive) time underground measuring and sketching fractures and other geologic features. Instead, geologic features are traced in the photogrammetric lab.

- Accuracy: Photogrammetry's accuracy greatly exceeds that possible with conventional sketch mapping under normal conditions. Prototype testing has shown that mapping with the analytical plotter can be accomplished to an accuracy of ±2 mm (±.125 in.). In practice, the accuracy is limited only by the survey accuracy.
- Reproducibility: Conventional sketch mapping is somewhat subjective and depends on the training, background, and mood of the geologist doing the mapping. Because most of the fracture tracing will be done by photogrammetry operators-geologists and then edited by field geologists, photogrammetric mapping should be less sensitive to operator bias. Also, as long as the photos remain intact, the conditions under which a map is originally constructed can be exactly duplicated. This allows a reviewer to view the rock just as the person who first made the map.
- Expandability: Because the data base is developed primarily from photographs, photos can be revisited at any later date for mapping in greater detail or for re-examination of any section of the excavation.

Evolution of Test Design

Prototype testing has proven that this overall concept of field data collection and data processing is appropriate. The testing has also shown that the actual testing of equipment and procedures is necessary to adapt equipment and procedures to the particular job. Most equipment has gone through one phase of modification, and some equipment has gone through several modifications. Prototype testing has also been invaluable in developing and testing procedures for ESF mapping.

Conduct of Test

Prototype testing of shaft mapping is being conducted in the laboratory and in the Fran Ridge test pits. All testing was to be done in the test pits, but because of permit requirements and schedule constraints, some of the testing was done in the laboratory. A photogrammetric test fixture (Figure 4.1-1) was constructed in the Denver laboratories of the USBR. The fixture provides a calibrated test field for development of specialized software for production of geologic and topographic maps of the shaft from stereophotographs. Photogrammetric control targets were placed on the interior surface of the shaft and accurately surveyed. Stereophotographs were taken of the walls and then processed by the analytical plotter to generate maps accurate to 2 mm (1/8 in.). The software developed with this fixture will be used to generate geologic maps of the exploratory shafts at Yucca Mountain. H&N personnel participated in the testing by providing the control target location survey.

A prototype shaft-mapping platform simulating the lower deck of a galloway was also tested in the test fixture (Figure 4.1-3).

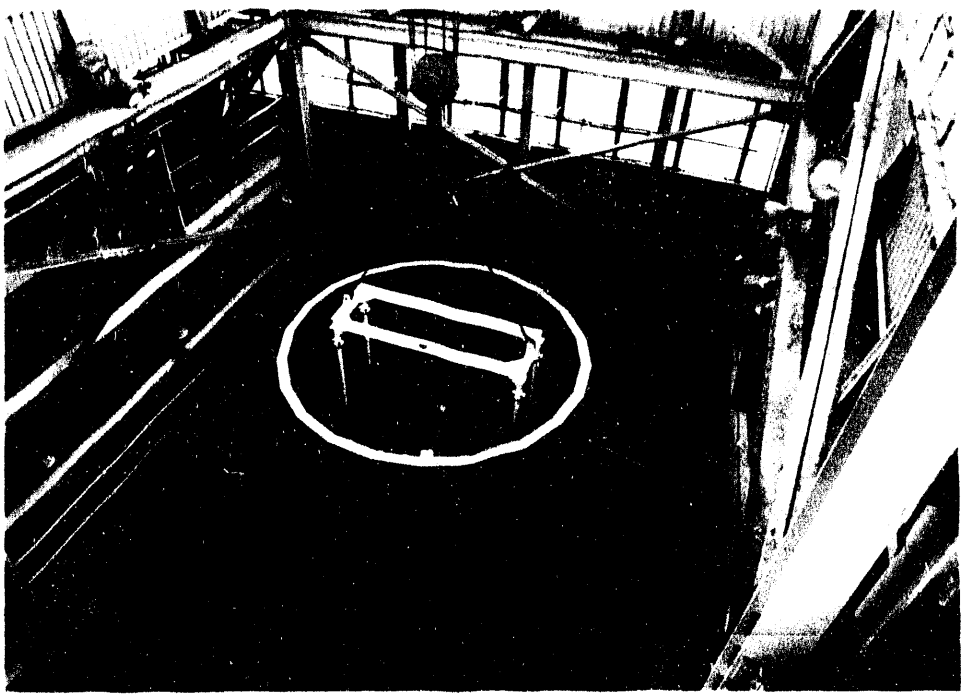


Figure 4.1-3. Prototype shaft-mapping platform.

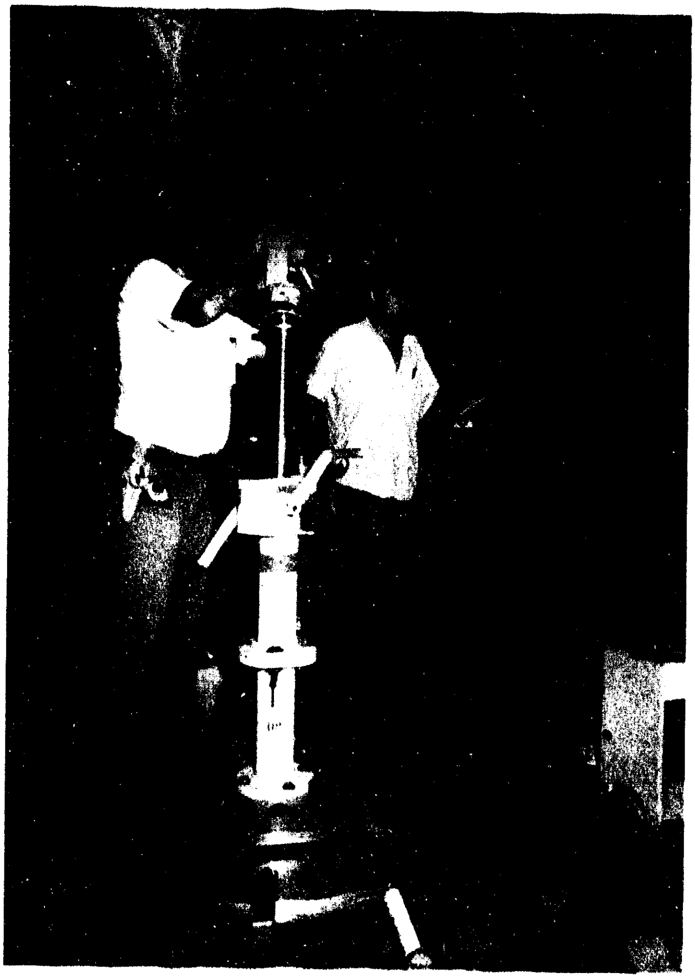


Figure 4.1-4. Prototype shaft-mapping pedestal and camera.

The platform was raised to the appropriate elevations in the test fixture for installation of control targets, photographing, and surveying using the prototype shaft-mapping pedestal camera (Figure 4.1-4). The centering and leveling base was modified as a result of this testing. The prototype shaft-mapping platform was modified to meet the safety requirements for an actual work platform. The platform is now at the Fran Ridge test pits on the NTS ready for the next phase of prototype testing.

Detailed line survey testing in the Fran Ridge test pits has provided information needed to develop equipment and specific data necessary for writing both shaft- and drift-mapping technical procedures. Photographic equipment and techniques were developed and tested. Flash mounts were modified for use with the proposed ESF equipment. A laser pointer has been developed to locate individual features intersecting the line survey. A tape measure stretched across an outcrop or exposure is the traditional method for locating features.

Prototype testing of drift mapping was done in the demonstration drift of the G-Tunnel (Figure 4.1-5). Several episodes of testing have provided the necessary data for development of mapping equipment, methods, and procedures. Testing

Figure 4.1-5. Prototype drift-mapping equipment in the G-Tunnel.

involved various aspects of the mapping procedure, including wall-cleaning techniques, photography, and surveying techniques. Prototype testing began with removal of chain-link fabric from the crown of the demonstration drift. This was done in 15-ft sections because of safety concerns. Each exposed section of tunnel was cleaned with the air/water blowpipe, photogrammetric control targets were glued to the walls and surveyed, and the area was stereophotographed and then conventionally mapped. After completion of sketch mapping, the chain link was reinstalled and another section of fabric was removed. While this operation of mapping 457 cm (15 ft) at a time approximated the routine during construction, the procedure greatly added to the time required for completion of testing because survey, photographic, and miner support personnel had to be present for several days.

An air/water blowpipe was used to clean the tunnel walls of dirt and debris (Figure 4.1-6). Air pressure and water flows were monitored during seventeen individual cleaning episodes and the air/water ratio varied to test the effectiveness of various mixes.

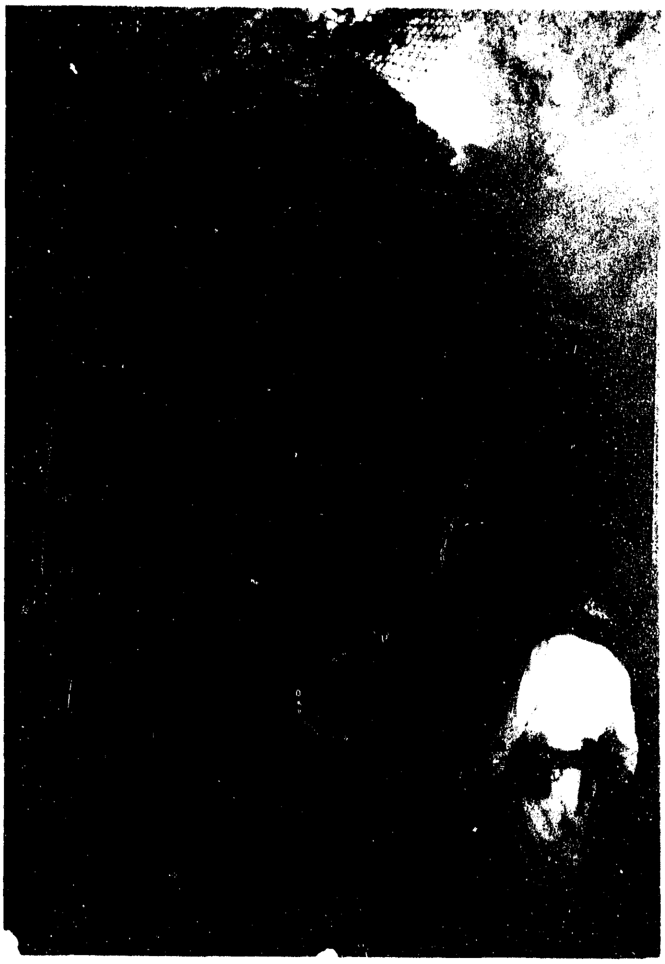


Figure 4.1-6. Cleaning of driftwalls in the G-Tunnel with air/water blowpipe.

A 7.6-l/min (2-g/min) flow at 620 kPa (90 lb/in.^{2}) proved to be the best mix for effective wall cleaning, with the least amount of free water introduced into the tunnel. At the 7.6-l/min (2-g/min) flow, most of the water used in the operation became mist, with only a fraction remaining on the tunnel wall or accumulating in the invert. The mist temporarily produced foggy conditions in the tunnel, which is not expected to be a problem in the ESF because of the ventilation system planned for that facility.

A long portion of the drift, which was 5 m (16.4 ft) long, was photographed as a test section for photogrammetry. Ninety-two 7.6 cm (3 in.) by 12.7 cm (5 in.) plastic survey targets were glued to the rock surface. The targets were located three-dimensionally using first-order surveys. The number of targets installed in this test section was intentionally about three times that normally placed for photogrammetry. This density of control points allowed determination of the optimum number of control points required for normal geologic mapping. Photogrammetric models will be assembled using all of the points in this test section and then subsequent models built using progressively smaller numbers of points. The reduction of accuracy will be determined by comparison with the test bed accuracy.

An additional 20 m (65.6 ft) of the demonstration drift was photographed using five to seven targets per 2-m (6.6-ft) round. The entire section was mapped using conventional sketch mapping techniques at a ratio of 1:10.

Plastic, 7.6 cm (3 in.) by 12.7 cm (5 in.), orange and white standard survey targets proved unsatisfactory because of alignment problems in the analytical plotter. New targets with black circles on a white background were developed and tested. The stiffness of the new targets makes them easy to glue onto irregular rock surfaces, and the matte finish permits numbering with indelible ink. A plastic hemisphere has been developed to facilitate gluing targets onto irregular surfaces while maintaining proper alignment with the camera.

The walls were photographed in stereo using the Rollei photogrammetric camera mounted on the pivoting camera mount (PCM; Figure 4.1-7). Click stops at the optimum angles allowed the

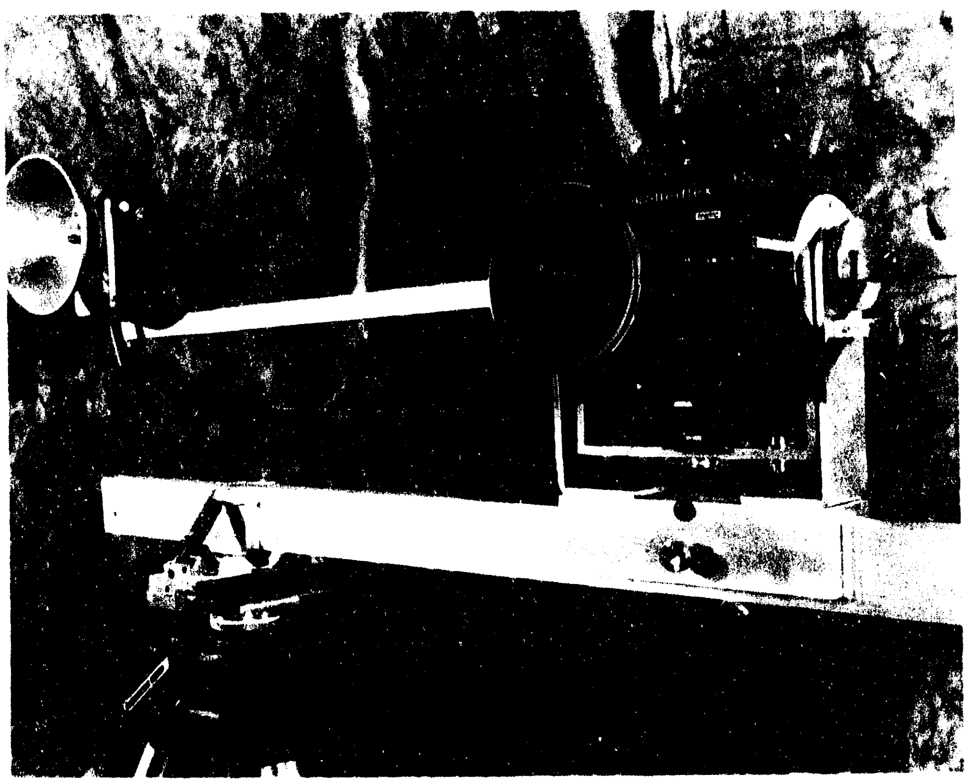


Figure 4.1-7. Stereo photogrammetric camera and pivoting camera mount.

camera to be quickly rotated from one position to the next. Flash strobes were manually positioned during photography (this required a minimum of two people). Optimal configuration was determined, and the PCM was modified to include strobe arms attached directly to the pivot of the mount. This modification of the PCM avoided the tangling of flash cords when the camera was rotated and allowed one person to handle the photography.

Photogrammetric targets were located by first-order surveys in the 5 m (15 ft) length of drift for the photogrammetric test section. Some work was performed with a right-angle prism goniometer (RAPG) and a pyramid beam splitter (PBS) for comparison of results with the target location from the first-order surveys. The remainder of the targets were located by second-order surveys.

The surveyors had some problems with the prototype RAPG and PBS in trying to obtain precise readings. This was due, in part, to flex in the reference rail and tripod supports. The PBS, tripod mounts, and reference rail were redesigned to improve stability and shorten setup time.

The possibility that rock at the ESF is magnetic and the large amount of steel underground used in excavation support and mining equipment make measurements based on a magnetic compass unreliable. Methods of determining bearings geometrically using a goniometer were tested. In addition, a hand-held gyrocompass was developed and tested.

Prototype testing of the photogrammetric laboratory functions consists of utilizing data generated by the shaft and drift field testing to develop and test plotter software, to test data base and map generation software, to test hardware, and to develop procedures. Accomplishments to date consist of the following:

- Installation of the Kern SDR-11 analytical stereoplotter, the DEC MicroVAX 11/VAXstation II GPX cluster, and the graphics editing workstation is complete.
- Installation of commercial support software, including operating system and data base, is complete.
- Installation of the geographical information system and the analytical plotter operating system is approximately 90% complete.
- Application software for multimodel orientation and fracture orientation measurement is complete.

- Translation of data collection to data storage and data base application design are under way.
- A camera calibration frame has been completed and software development for calibrating cameras is under way.

In summary, equipment and procedures for geologic mapping of shafts and drifts have been developed and tested. Equipment for shaft mapping is still in the prototype stage, additional testing is required. Equipment for drift mapping is essentially complete. Dress rehearsals of shaft and drift mapping must still be completed. Photogrammetric laboratory equipment installation and some software are complete, although a major portion of the software must still be tested and modified. The implementation of quality assurance for the software is under way, but a major effort is still required.

Test Activity Results

Prototype shaft-mapping testing has produced the following major results:

- A photogrammetric test fixture was constructed in the Denver USGS laboratories. The fixture provides a calibrated test field for development of specialized software that produces geologic and topographic maps of the shafts from stereophotographs. Photos from these tests are being used to develop the procedures and software for shaft mapping in the ESF.
- The use of a prototype shaft-mapping platform in photogrammetry-stereophotography testing has resulted in the modification of shaft-mapping equipment and procedures.
- Detailed line survey testing in the Fran Ridge test pits has provided information needed to develop equipment and

the specific data necessary to formulate technical procedures for both shaft and drift mapping.

- The rock at the ESF is possibly magnetic. This possibility, coupled with the large amount of steel used underground, makes measurements based on a magnetic compass unreliable. Methods for determining bearings geometrically using a goniometer were tested. In addition, a hand-held gyrocompass was developed and tested.

Prototype drift mapping has produced the following major results:

- Prototype testing of drift mapping was done in the demonstration drift of G-Tunnel. Testing involved various aspects of the mapping procedure, including wall-cleaning techniques, photography, and surveying techniques.
- Several episodes of testing have provided the necessary data for development of mapping equipment, methods, and procedures. The only further testing anticipated to complete the drift phase is a dress rehearsal utilizing equipment fabricated from final designs using the proposed technical procedures.
- The blowpipe was very effective in cleaning the tunnel walls while introducing a minimum of free water into the tunnel. Water-air flows were optimized and techniques tested.
- Methods of determining bearings geometrically using a goniometer were tested. In addition, a hand-held gyrocompass was developed and tested.
- Several adhesives were tested and one selected to fasten photo targets to the excavation walls.

- The PMC was redesigned to stabilize and locate the camera and flash units at the proper orientations for stereophotography.
- Tripods and reference rail mounts were modified to increase stability for both surveying and photography and a stronger reference rail was designed and tested.
- A PBS and RAPG were developed to expedite photogrammetric target installation and surveying.
- Final design of drift-mapping equipment was completed.
- A camera calibration frame was completed and software development for calibrating cameras is under way.
- Equipment for the photogrammetric laboratory was installed and tested.
- Data derived from G-Tunnel testing was used to develop and test photogrammetric mapping in the laboratory utilizing an analytical plotter.
- Major portions of the analytical plotter and data base software were developed, installed, and tested.

Future Activities

Future activities will include the following:

- Shaft prototype testing must be completed. Although part of the prototype shaft mapping has been done in the laboratory mapping fixture, major portions of the testing remain to be done in a test pit.
- Dress rehearsals of shaft and drift mapping are necessary to finalize test equipment and procedures. Final design drawings of mapping equipment must be completed and the equipment fabricated and tested.

- Software design and testing must be completed. Significant portions of the analytical plotter and database-related software are complete, but integration of the separate portions into the final mapping system must be completed and tested.

4.2 Mineralogy/Petrology

General Test Description

The prototype mineralogy and petrology tests were performed to determine the methods, time, and effort required to collect and document rock samples to ensure adequate sampling and sample traceability. When the ESF is mined, samples will be collected and documented, using procedures developed during this test, for use in QA Level I characterization activities. ESF samples will then be used to determine the variability of the Topopah Spring tuff, the alteration and transport history of both the Paintbrush tuff (which includes the Topopah Spring Member) and the underlying Calico Hills tuffs, and the mineralogy of fractures and faults.

As a consequence of this prototype activity, a number of samples of the host rock and samples of specific features are being collected. These samples are used to develop and test procedures for analyzing material that will be removed from the ESF.

Three subtests were planned to be performed under the prototype sample collection test; all will be performed at locations other than the ESF but will result in procedures to be used at the ESF. These subtests include the following:

1. Samples of the Topopah Spring member were collected from an outcrop in Solitario Canyon along the lateral and vertical exposure of this tuff. These prototype samples were used to determine the optimal number of samples and distribution required to achieve representative sampling. The prototype samples were also used to develop and verify chemical and other tests that will be used to determine rock characteristics. These samples will be analyzed to determine the stratigraphic variability of the host rock.
2. The muck pile at the Fran Ridge test pits will provide

rubble containing both representative rock and pieces containing features of special interest, such as fractures. This prototype test will compare the results of examining special features exposed in rubble with results of examining similar features exposed in the walls of the test pit.

3. Samples of special features, such as fractures, and oriented samples will be removed from the walls of the Fran Ridge test pits and the prototype shaft, if it is constructed. As originally conceived, this subtest also included sampling of fractures in G-Tunnel in conjunction with USGS/USBR prototype wall-mapping activities. This subtest activity has been dropped because of the near absence of fracture fillings in G-Tunnel. Samples of gels will be collected from fractures in N-Tunnel, and a simulated gel-sample collection is planned for the prototype shaft. The time required to identify, measure, orient, remove, and document these samples is noted, and changes to draft sampling procedures and projected sample requirements are made as needed. The logistics of fracture sample collection at the Fran Ridge test pits and the prototype shaft are compared with the time required to collect and document similar features from the muck pile.

Purpose

The primary purpose of the Mineralogy/Petrology test was to determine the methods and time that will be required to take samples in the ESF that will provide both representative materials and examples of features of special interest. It is recognized that the time available for in situ mapping and sampling during construction of the ESF will be limited. However, samples from muck removed from the ESF will be readily available and will provide a significant potential resource for defining geologic characteristics. This prototype test will provide information to optimize the number of in situ samples required to provide a control on information collected from rubble samples. This is of particular importance with regard to characterizing fractures or other special features intersected by the ESF excavation. This prototype test will also provide an opportunity to formalize interfaces between the USGS, the USBR, and other Project participants involved with mapping and sampling. For site characterization work, all samples must be documented as required for QA Level I work. A secondary purpose of this test is to collect samples that are used in other tests. Some samples are being used to develop methods to assess the variability of the Topopah Spring tuff. The study of gel samples collected for this test contributes general background information to the alteration-history site characterization activity.

Objectives

The objectives of the Topopah Spring/Solitario Canyon outcrop sampling subtask are to

- identify 25 or more sampling locations that are about 3 m (10 ft) apart vertically and staggered laterally to cover the exposed face, including faults;
- determine a sample-removal technique for 200-g (7-oz) samples;
- work out a sample documentation method;
- develop and verify analysis procedures; and
- determine the smallest sample size representative of the potential host-rock stratigraphy.

The objectives of the Fran Ridge muck pile sampling task are to

- determine the time, optimal sample size, and handling procedures necessary to select representative bulk rock samples, samples of fracture mineralogy, and other special features; and

- work out a sample documentation method.

The combined objectives of the Fran Ridge test pit, prototype shaft, and underground sampling task are to

- determine time requirements and procedures for sample orientation, marking, and removal;
- determine optimal sample size;
- identify suitable equipment for these procedures;
- determine the accuracy and precision of orienting equipment; and
- work out a sample documentation method that preserves all relevant information.

Support Required

The Topopah Spring/Solitario Canyon sampling subtask required support from the USGS and from FSN in performing field collection work.

The muck pile sampling subtask for the Fran Ridge test pits required coordination with, and support from, the USGS and USBR, who are in charge of the blasting, coring, and sample-removal operations at that site. USBR personnel map the walls and specific features of interest. The equipment used is developed and constructed by the USBR. The work is described in the USGS/USBR shaft wall-mapping test. Muck removal will be done by REECo.

If a YMP decision is made to construct a prototype shaft, the mineralogy/petrology test will include activities similar to those planned for the Fran Ridge test pits, as well as realistic tests of sampling and sample distribution procedures. Exact responsibilities have yet to be determined, but it is anticipated that the activities will involve USGS, USBR, REECo, and sample management facility personnel.

The underground sampling subtest has now been reduced to gel sampling in N-Tunnel and does not require coordination with, or support from, the USGS or USBR. A mining inspector might be needed to accompany the investigator during sampling, depending on applicable safety requirements. The investigator might also be incidentally accompanied by a FSN geologist involved in Defense Nuclear Agency (DNA) activities. All samples collected specifically for the prototype test are to be removed by the investigator, but previously collected samples from other investigations might be studied as well.

Detailed Test Description

The upper two-thirds of the Topopah Spring crops out in Solitario Canyon, which makes it an easily accessible location to sample for variability. Representative 200-g (7-oz) samples will be divided into successively smaller subsamples, down to 2 g (.07 oz) in order to determine the smallest size that is still representative of the original sample and the scale of variation. The number of samples required and the frequency of samples to be taken in the ESF to characterize the complex, faulted host rock will be determined from the analyses performed on subsamples. The analysis techniques—x-ray diffraction, x-ray fluorescence, neutron activation analysis, and other model petrographic methods—will be developed and verified for this tuff. Documentation methods for QA Level I work will be developed and tested.

The muck pile produced from each blast round at the Fran Ridge test pits contains devitrified Paintbrush tuff that is reasonably similar to the potential host rock. Muck pile work at the ESF might need to be done under rigid time constraints; efficient and effective sample-selection practices will be needed. The time required to select both representative samples and samples that contain features of specific interest will be determined. In addition, methods of selecting samples of appropriate size, methods of handling samples, and sample documentation methods will be developed and tested.

Sample selection, marking, and collection techniques to be used in shafts and drifts of the ESF will be important, especially when information about the orientation of a sample is critical. The original in situ orientation of samples taken from the muck pile is unknown. As part of the rock wall mapping activity from the Fran Ridge test pits, rock wall features are identified, orientation measurements made if necessary, and samples removed. The time and effort to collect and document underground samples will be determined. This time and effort for collection, coupled with the increased information on the samples, will be balanced against the time, effort, and information associated with collecting samples from the muck pile.

Historical Perspective and Background

Topopah Spring tuff contains many faults and fractures that produce offsets in the unit, but there are few stratigraphic distinctions that allow observation of these offsets. Furthermore, the overlying Tiva Canyon ash flow obscures surface expression of fault movement. Therefore, estimating the stratigraphic position of this unit has proved difficult. However, the tuff is mineralogically variable and texturally stratified. These characteristics can be used to determine its position within the horizon. To keep mining operations for the potential repository within the host rock, it will be useful to know the chemical and mineralogical characteristics of the various zones within the horizon, as well as the variability of these characteristics. The direction of fault movement and amount of fault offset can be estimated by determining the characteristics of samples collected at successive levels or lateral locations. Drill core samples do not provide the opportunity to examine lateral variability of the rock because of the small diameter of the core.

Both in situ and muck pile sampling operations are being developed in Paintbrush tuff at the Fran Ridge test pits. It is hoped that samples from the ESF walls and muck pile will be larger than ordinary drill core and will therefore provide better information on the quantitative abundances of minerals in fractures, systematic variations in fracture mineral distributions, cross-cutting fracture relationships, and compositions of fault fillings. Oriented samples will provide information on directional features in the rocks pertaining to deformation and tectonism. This type of information has been used in past studies to infer the timing of alteration. The prototype collection of oriented samples from test pits will be used to evaluate the time constraints and accuracy of oriented sample collection procedures used by the USBR.

Natural colloidal gels represent a type of material whose abundance and candidate role in radionuclide transport or retardation at Yucca Mountain are unknown. Gels have been collected from fractures in zeolitized rocks in tunnels at Rainier Mesa, about 40 km (24.8 mi) northeast of Yucca Mountain. The ESF will provide an opportunity to check for the presence of gels at Yucca Mountain, and the Rainier Mesa Tunnel samples will be used to develop sample collection and study procedures.

Evolution of Test Design

The devitrified Topopah Springs tuff is variable in mineralogy and is texturally stratified, but its short-range variability is not known. Several faults have been identified, some of which are not apparent at the surface. Fractures that contain fill material and faults showing offsets appear in core material from Yucca Mountain. The repository mining activities must be confined to the identified host rock and must not penetrate the underlying vitrophyric and vitric nonwelded tuffs. Methods for estimating stratigraphic position within the host rock have not been satisfactory so far, and procedures for these estimations in granitic and sedimentary rocks are not applicable to tuffs. These problems have focused attention on the need to develop a sampling procedure that will allow stratigraphy and stratigraphic variability to be defined. A procedure on "Sample Collection of Muck from Excavations at the Exploratory Shaft Facility for Mineralogy-Petrology Studies" has been written.[5]

Conduct of Test

Samples from the Topopah Spring horizon exposed in Solitario Canyon were collected. The modal textural analysis, mineralogic analysis on thin sections, and x-ray diffraction analysis have been completed at EES-1 in Los Alamos.

Minimal sample-size analysis has shown that subsample mass has no detectable effect on sample variability, even in samples as small as 2 g (.07 oz). However, analysis for tridymite demonstrated mineralogic variability on a larger scale (several centimeters).

Drilling work at the Fran Ridge test pits has been suspended. All work at Fran Ridge test pits is on hold pending the issue of an air quality permit from the state of Nevada. No samples have been collected, and no drilling or blasting is scheduled. However, the USBR has completed construction of various mapping and sampling instruments.

Extensive laboratory work that includes petrography, x-ray diffraction, and scanning electron microscopy, has been done on a dried gel sample collected from the T-Tunnel. A gel sample from the N-Tunnel, collected during recent DNA mapping activities, has also been studied.

Future Activities

The chemical and petrographic analysis of Topopah Spring tuff will be completed. The data will be analyzed statistically to determine the necessary number and frequency of samplings in the

ESF that will be needed to characterize location in the host rock. A gel collection is being developed.

Sample collection and documentation activities are planned at the Fran Ridge test pits after an air quality permit is obtained.

4.3 Wet Versus Dry Drilling

General Test Description

The type of drilling fluid (gaseous or liquid) used in drilling the exploratory shaft may influence the in situ hydrologic conditions of the rock matrix and the resulting core samples of the tuff. The effects of drilling fluids on the in situ hydrologic conditions of the formation in the unsaturated zone at Yucca Mountain must be known before any borehole testing is conducted in the ESF. Alteration of in situ hydrologic conditions of the rock matrix surrounding the boreholes could have a significant impact on hydrologic experiments performed in or near the boreholes, on instrumentation installed in the boreholes, and on geophysical logging. Examples of alteration of hydrologic conditions include the introduction of biologic organisms or changing the chemistry of interstitial water. To minimize the possibility of contaminating an area in which an unsaturated-zone hydrologic test is to be conducted, the extent of drilling fluid penetration in the rock matrix and fractures must be accurately estimated. These estimates can be accomplished, in part, by providing data to be used in structuring appropriate unsaturated-zone hydrologic models. The USGS will supervise the drilling of boreholes in G-Tunnel. Laboratory testing will be conducted at the USGS Unsaturated Zone Testing Laboratory. Hydrologic models will be developed by the Denver office of the USGS.

Purpose and Objectives

The purpose of this test is to determine how air and water used as drilling fluids in tuffaceous rocks affect the in situ hydrologic conditions of the core samples and the rock matrix surrounding the borehole. The effects of drilling-induced changes in the in situ hydrologic conditions and on the response of the rock to geophysical logging and borehole equipment will also be examined.

Test data will be used to calibrate and validate a set of numerical hydrologic models that will be constructed to quantitatively simulate and predict results of ESF tests. Therefore, the test will determine whether air and/or water are suitable drilling fluids for the ESF boreholes. Specific objectives for this test are to

- measure the rock matrix and hydrologic properties of core samples collected from the boreholes;
- determine the amount of water penetration from wet drilling fluid into the rock matrix and the extent of drilling fluid movement along fractures that intersect the borehole;
- determine how drilling fluids affect the response of tuff to borehole instrumentation and geophysical logs;
- compare the results obtained from wet- and dry-drilled boreholes to determine how the drilling fluids affect the ambient hydrologic conditions of the formation;
- provide empirical data that can be used to calibrate and validate the hydrologic models;
- evaluate quantitatively the expected limits of uncertainties of hydrologic model predictions based on statistical characterization of the input hydrologic property data set; and
- assess the application of the hydrologic models to the drilling and coring of boreholes to be used in the ESF.

Support Required

The NTS contractors were required to support the test objectives. The contractor provided support in both construction and testing. Construction support entailed the drilling of four test boreholes, surveying of borehole collar locations, and transporting of samples to the testing facility. The contractor designated a person dedicated to testing activities. Testing support from the NTS included testing of the

- electrical supply,
- video camera tagging equipment,
- caliper logging equipment, and
- personnel for technical assistance.

Test Program

Detailed Test Description

This prototype test entails a sequence of field, laboratory, and hydrologic-modeling activities. The field activities involve the coring of two pairs of horizontal boreholes in a rock type similar to the type that will be encountered at the ESF. One pair of boreholes will be drilled into a fractured, welded tuff, and the second pair will be drilled into a nonwelded tuff. Of each pair of boreholes, one will be cored using a dry method (air) and the second will be cored using a wet method (water). Air and water are used as circulating fluids in the drilling process. The circulating fluids remove drilled material (cuttings) from the borehole, cool the drill bit, and return samples to the surface. The volume of water and air used in the drilling of the boreholes is closely monitored and recorded. Core samples are taken for laboratory tests, which are described below. When the boreholes have been completed to total depth, a series of logging experiments are conducted to measure in situ conditions. Standard geophysical logging techniques and television techniques are used.

A neutron moisture meter is used to measure volumetric water in surrounding rock. Boreholes to be used for fractures and other rock property determinations are inspected using downhole television equipment. Caliper logging is used to determine locations in boreholes for setting packers that are used for installing borehole sensor instruments.

Borehole sensor instrument packages are then emplaced at locations selected by using the logging information. The purpose of the sensor equipment is to determine ambient background moisture and temperature conditions and to monitor the change of these conditions over time. Each borehole has three downhole instrument sensor stations. Following the determination of ambient conditions, particle density, bulk density, and porosity are determined using these data; volumetric water content and percent saturation may be calculated.

Laboratory activities consist of the measurement of rock sample properties and of experimental analysis of these rock samples. Laboratory measurements of in situ water saturation and moisture potential conditions are made on samples taken from the core recovered from each borehole. Samples are analyzed to estimate statistical parameters and to develop statistical characterization for the hydrologic properties used in the hydrologic models. A sequence of imbibition (i.e., the tendency for a rock to absorb a fluid) and moisture-release experiments is performed on selected samples to provide data for comparison of laboratory samples, geophysical logs, and borehole sensors in both welded and nonwelded tuffs. The instrumentation packages installed in the core holes were similar to those described in Section 4.4, Drill Hole Instrumentation. Moisture-retention-characteristic curves are developed to provide information in modeling and to determine the accuracy of water content measurements from cores at ambient conditions. Saturated and unsaturated hydraulic conductivities are determined using centrifuge techniques. If hydrologic models are determined to be sensitive to thermal conductivity and heat capacity, further testing for those properties is conducted.

The hydrologic model is designed to predict the simultaneous storage and flow of liquid water, water vapor, pore gas, and heat in the near-field environment of each borehole and is also designed to simulate cross-hole effects between each pair of wet- and dry-cored boreholes. The models are designed for air and water drilling in welded and unwelded matrices. The field and laboratory data gathered will help in building and validating the hydrologic models. These models will be calibrated with respect to rock matrix properties by using the measured in situ saturation and moisture potential data and the results of the laboratory imbibition and moisture release experiments. A critical feature in the hydrologic modeling will be to determine the effect that fractures have on fluid (air and water) movement and loss. Another aspect important to the modeling portion of this test is to analyze the effects that the wet-drilling method may have on the air-drilled boreholes. Observed fracture properties in the fractured welded tuff unit, together with the amounts and rates of water lost to the fractures during the wet-coring operations in this unit, are used to calibrate the models with respect to the fracture hydrologic properties. Validation of the models is acceptable if model predictions of test results agree with observed results within acceptable limits.

Historical Perspective and Background

It has long been recognized that drilling operations affect both cored samples and the rock matrix surrounding the borehole.

To minimize the impact of drilling on the matrix and core samples and to avoid contamination of any formation water, investigators conducting hydrologic tests in the ESF have requested that air be used as the circulating fluid when drilling in the unsaturated zone. It was determined that tests were needed to evaluate the effects of wet and dry circulating fluids on the hydrologic properties of core samples and the rock matrix surrounding boreholes drilled in the unsaturated zone.

To evaluate the effect of the drilling fluids, a test plan was prepared that would use data obtained from the laboratory analysis of core samples, borehole geophysical logging, and in situ borehole instrumentation. This combination of data-gathering activities was chosen because it provides information on the influence of drilling fluids on the hydrologic properties of the rock matrix surrounding the boreholes and core samples. This approach would also provide data on the response of the rock matrix after the completion of drilling.

Evolution of Test Design

This test was initially conceived to settle a difference of opinion between PIs working in the unsaturated zone in the ESF and engineers working on ESF design and construction planning. The engineers did not believe that drilling with water would adversely affect hydrologic tests conducted in ESF boreholes. The USGS was assigned the task of devising a prototype test that would provide data on wet and dry drilling. The wet- versus dry-drilling test began as a simple comparison of test results from wet- and dry-drilled boreholes. Later, a hydrologic modeling component was added to the test plan. The final version of the test is a combination of wet and dry coring, with sample collection and analysis, borehole geophysical logging, in situ testing and monitoring, and hydrologic modeling of the test results.

Conduct and Results of Test

Four core holes have been drilled successfully: two with air and two with water as the drilling medium. The neutron logging procedure was revised for safety consideration. Television and neutron moisture logs were performed successfully in the four holes. Core samples were collected and analyzed. Hydrologic data were collected, and preliminary analysis suggests there are significant differences in the hydrologic effects of wet versus dry drilling. Hydrologic modeling is in the development stage and is yet to be completed. The prototype test has demonstrated the viability of many of the test procedures.

One wet-drilled core hole was inadvertently drilled so that it intersected one of the previously drilled dry holes. All damaged instruments were repaired or replaced within 48 hours. The experience derived from this accident provided some very useful information and may enhance understanding of the differences between wet- and dry-drilling methods. The test was completed, and the equipment was removed from the G-Tunnel.

Future Activities

New drilling equipment has been recommended,[1] and the coring procedures are being revised.

4.4 Drill Hole Instrumentation

General Test Description

The unsaturated zone at Yucca Mountain, extending from the surface to more than 300 meters (900 ft) below the emplacement elevation, provides the principal natural barrier to radionuclide migration from the potential repository to the accessible environment. A thorough description of the moisture status and related hydrologic characteristics that govern unsaturated flow is thus a major element of the site characterization work proposed for the ESF. Water flow in the unsaturated zone, through both the porous matrix and fractures, is governed by gradients in the total energy potential (water potential) of the water held in the tuff. The magnitude of the total energy potential is influenced by the temperature, pressure, and water content of the tuff. Specialized instrumentation is needed for measurement of the components of the energy potential resulting from each of these three factors.

This prototype test will design, develop, and test, under laboratory and field conditions, instrumentation for the measurement of water potential in the unsaturated zone. The instrumentation will be designed for placement in the range of borehole sizes and configurations proposed for use in the ESF.

Purpose and Objectives

Construction of the ESF will undoubtedly alter the hydrologic characteristics of the unsaturated zone, both due to the physical disturbance associated with shaft and drift construction and to the gradual evaporation of water from the tuff into the ventilated air space in the ESF. Expedient and well-coordinated installation of borehole instrumentation immediately following construction of all or a portion of the ESF will capture data representing a close approximation of preconstruction conditions. More importantly, the response of the hydrologic conditions to the influence of the ESF will provide invaluable data on the dynamic response of the unsaturated zone to changes in hydrologic boundary conditions. This information is an essential part of the performance-assessment calculations that will be done as part of the license application process. Thus, it is essential that the instrumentation installed in the boreholes function properly because operational failure could result in the irretrievable loss of valuable data. Thus, the overall purpose of this test is to develop and test instrumentation for measurement of unsaturated zone properties in the tuff surrounding the ESF. This equipment, and the procedures for its use, must be operational before construction of the ESF is initiated. The specific objectives of this test are to

- develop methods for installing instrumentation in boreholes to ensure both hydrologic continuity with the surrounding tuff and to isolate the instrumentation from portions of the borehole that are remote from the measuring location and
- develop techniques for in-place calibration or verification of the accuracy of the instrumentation.

Support Required

The development of the instrumentation systems and the means for proper deployment in boreholes will be conducted primarily in a laboratory environment. Construction of a horizontal and a vertical borehole in the G-Tunnel will be required for field testing of designs that would be successful in the laboratory.

Detailed Test Description

Work on this prototype test was divided into three phases: engineering design, laboratory testing, and field testing. The engineering design phase will define the kinds of instrumentation needed, identify specific candidate instrumentation, and develop detailed requirements for deployment of the instrumentation. The laboratory testing phase will use a simulated borehole for evaluating the performance of candidate instrumentation systems. Finally, promising candidates will be installed in boreholes in both welded and nonwelded tuff in the G-Tunnel.

The water potential of an unsaturated porous medium consists of the sum of four components: the matrix (or capillary), temperature, pressure, and gravitational potentials. Direct measurement of the temperature and atmospheric pressure in the pores of the medium allows evaluation of those two components. The gravitational potential is computed from the known elevation of specific point in the medium. The matrix component results from adhesion of water to the interior surfaces of the pores. Direct measurement of the matrix potential by equilibration with a water column is possible only at water contents very near saturation.

For water contents relatively near saturation, the measurement of matrix potential will rely on heat dissipation blocks that have been previously calibrated against known water potentials. As the water content (and therefore, the water potential) of these dissipation blocks increases, applied head is dissipated more rapidly. However, for lower water contents, measurement of the matrix potential must rely on the physical relationship between the matrix potential and the relative humidity of the air in the pores or fractures of the tuff. The relative humidity of the pore or fracture atmosphere can be measured directly using thermocouple psychrometers. However, as the water content (and therefore, the relative humidity) decreases from saturation, the magnitude of the matrix potential increases exponentially. Thus, a small change in the relative humidity corresponds to a relatively large change in the matrix potential, which mandates considerable accuracy in the measurement of the relative humidity. Because of long-term drift in the calibration curves for all instrumentation (thermocouple psychrometers in particular), recalibration of the sensors during the course of the test will increase confidence in the data collected. Calibration methods will thus be an important feature of this test.

In practice, thermocouple psychrometers are calibrated directly against water potential in a environmentally controlled sample chamber in the laboratory. The calibration data are then used to determine the water potential of the tuff surrounding the borehole. However, the measurement is extremely sensitive to spatial and temporal variations in temperature. Furthermore, the relative humidity sensed by the psychrometer must be in equilibrium with the relative humidity of the pores in the surrounding tuff. This test will investigate various means for ensuring that equilibrium.

For all three measurements of temperature, pressure, and matrix potential, this test will use simulated boreholes in a laboratory environment. Various borehole geometries will be used to represent a variety of normal and abnormal (but expected) bore-hole conditions. Various packing and stemming systems will be tested to investigate placement and removal methods. Similarly, the design for in-place calibration for all sensors will be tested.

The instrumentation systems tested (and modified as needed) in the laboratory simulations will be installed in boreholes penetrating both welded and nonwelded tuffs in the G-Tunnel. Primary objectives of the field testing are to gain experience with instrument deployment, to test methods for instrument removal where necessary or appropriate, and to evaluate the effectiveness of in-place recalibration of instruments.

Historical Perspective and Background

Instrumentation of the type designed for deployment in boreholes drilled from the ESF for measurement of water potential has historically been used for monitoring of relatively shallow soil zones. Placement and removal of the instrumentation under these conditions is relatively simple and inexpensive, and most studies that involve measurement of water potential have relied on large numbers of sensors to minimize the importance of any one installation. There is much less experience with application of this instrumentation to relatively deep boreholes in solid rock, such as the tuffs at Yucca Mountain. In addition, this type of instrumentation has most commonly been used at ambient temperatures that may be substantially less than those temperatures expected at depth in Yucca Mountain (in excess of 50° C). The significantly higher cost (compared with applications in soils) of each installation and the limited number of boreholes that will be instrumented substantially increase the need to have high confidence in all the collected data.

Because of the range of water contents expected in the tuffs at Yucca Mountain, the location at which the components of the water potential are measured must be carefully isolated from other measurement locations. Slight changes in temperature, pressure, or relative humidity that might result from air movement within an open borehole must be avoided. Thus, either inflatable packers or solid fill (stemming) material must be used to isolate individual sections of a borehole where measurements are taken.

Removal of an instrument package from a borehole would allow verification of the calibration of the sensors. However, inflatable packers may not provide the desired instrument isolation and will not provide for hydraulic continuity between the instrument and the tuff. This hydraulic continuity is essential for successful use of the heat dissipation blocks. Stemming materials may therefore be needed for some applications. Various stemming materials and placement methods will be evaluated by this test, and the advantages and disadvantages of each identified.

Removal of the instruments from stemmed boreholes could damage the instruments, thus no calibration check would be possible. Further, removal of the instruments during the course of the ESF tests would disrupt the hydrologic conditions surrounding the borehole. Equilibration following reinstallation of instrumentation would cause significant loss of data. Thus, a critical component of this prototype test is the development and testing of in situ calibration methods for all instrumentation.

Downhole recalibration of temperature sensors will rely on insertion of precalibrated sensors into the borehole through a specially designed access tube. Similarly, pressure transducers can be calibrated in place by exposing them to a pressure source from outside the borehole through an access tube. Both these recalibration methods will use calibration chambers in the instrument package in which the in situ and calibration sensor are isolated from the environment of the tuff during calibration.

The physical size of both heat dissipation blocks and thermocouple psychrometers, as well as a need for assured hydraulic continuity with the tuff, may prevent their recalibration by insertion of precalibrated instruments. An alternative approach will consist of the withdrawal of a sample of air and measurement of the relative humidity external to the borehole. This method requires careful control of temperatures in the access tube to avoid condensation that would deplete the water content of the withdrawn air, which would invalidate the calibration.

Conduct of Test

To date, proposed packer and instrumentation systems have been tested in simulated boreholes in the laboratory. Simulated conditions surrounding the borehole included highly fractured material and rubble zones, such as those associated with the base of some tuff units. Horizontal and vertical access holes have been constructed at the G-Tunnel, and the instrumentation systems were installed. Following a several-week period of equilibration, the collection of data to evaluate the effectiveness of the instruments and the recalibration system was initiated. Test data were gathered, and the instrumentation was removed from the G-Tunnel.

Future Activities

The evaluation of data collected in welded and nonwelded borehole locations in the G-Tunnel will continue. Instrument life expenditure tables will be developed, and equipment improvements will continue. Procedures for installation and in situ calibration will be revised and developed as necessary.

4.5 Blast Effects

General Test Description

A large number of hydrologic tests using downhole instrumentation will be performed during ESF construction. The prototype blast effects test was designed to evaluate the effects of blasting and mining on test instrumentation installed nearby.

The investigation will involve two phases: field studies to be conducted in the G-Tunnel drift and supporting laboratory work to be conducted at the USBR test facility. Based on results of the two phases, the instruments will be protected against vibrational damage resulting from blast-induced shock loads. Investigators may provide this protection in either of two ways—by modifying the initial instrument designs or by developing special operating procedures. Prototype testing will allow instrument designers to protect the instrumentation before starting planned hydrologic tests in the ESF.

In the G-Tunnel drift, prototype instrumentation methodology and equipment tests, such as the prototype blast effects test, will be conducted for use in the ESF investigations. Rock materials in the G-Tunnel drift are lithologically similar to Yucca Mountain tuffs.

Five other investigations will use instruments developed during the blast effects test to monitor rock properties while underground mining is conducted nearby. These investigations are the

- cross-hole test in the G-Tunnel drift (Section 4.6);
- drill hole instrumentation test in the G-Tunnel drift (Section 4.4);
- radial borehole investigation in the ESF;

- excavation effects test in the G-Tunnel drift and the ESF; and
- Calico Hills investigation associated with the ESF.

Purpose and Objectives

The purpose of the blast effects test is to use both field studies and laboratory experiments to evaluate comprehensively the vibrational and shock limits that would measurably affect the performance of instrumentation installed near an underground site where controlled blasting methods are used.

The instrumentation will include hydrologic instruments, hydraulic pressure cells, and borehole extensometers. The hydrologic instruments contain pressure transducers, thermal sensors, thermocouple psychrometers, heat-dissipation probes (blocks), internal or external solenoid valves, electrical connections and leads, and hydraulic connections and tubing. The hydraulic pressure cell consists of an expandable steel bladder encapsulated in a prefabricated concrete cylinder. The borehole extensometers consist of mechanical anchors, extension tubes, displacement transducers, and centralizers.

The objectives of the prototype blast effects test are to

- determine and describe the effects of blast-induced damage on instruments installed near blasting;
- use laboratory equipment at the USBR test facility to simulate a wide range of vibratory and shock loading effects on instrumentation needed to support field studies at the G-Tunnel drift;
- evaluate the vibration and shock limits that affect instrumentation;
- modify initial designs of hydrologic instrumentation assemblies;

- develop instrumentation calibration, installation, and data-acquisition system procedures; and
- provide shock- and vibration-resistant instrumentation that will be required for other planned G-Tunnel drift prototype tests that are proposed for ESF investigations.

Results from the field and laboratory work will be used in various ways by site investigators to protect instrumentation from blasting damage—for instance, by selecting alternate instruments, by modifying designs of the hydrologic instruments, or by developing procedures that contribute to survivability of the instrumentation.

Success in the prototype blast effects test will result in the development of hydrologic instruments capable of surviving blast-induced shock loads. The study will also lead to the development of preliminary operating criteria for installation, calibration, and monitoring of instrumentation during investigations for the ESF.

Support Required

Experimental work associated with this test will be conducted in both field and laboratory settings. The laboratory equipment is described in the Detailed Test Description section.

Test site contractors will support field activities by drilling instrumentation holes, grouting nonretrievable instrumentation in appropriate drill holes, installing collar pipes to protect collars of holes in which retrievable instruments will be installed, and installing channel irons to protect instrumentation cabling. Contractor support also includes constructing a bulkhead to protect the drift where monitoring equipment will be stored during blasting.

Detailed Test Description

The prototype blast effects test investigation will generate data describing how well hydrologic instruments will perform in a mining environment. The prototype test is specifically designed to measure shock and vibrational stresses resulting from controlled blasting. The test will also assess the impact of these blast effects on instruments to be used for investigations that employ downhole instrumentation during construction of the ESF.

The field-work phase of the study will consist of the following steps:

1. Instrumentation drill holes will be air-drilled.
2. The holes then will be surveyed with a downhole video camera. Surveys of the drill holes allow comparison of preblast and postblast hole conditions in order to assess the ability to retrieve hydrologic instruments after blasting has occurred.
3. Hydrologic instruments, which have been calibrated previously in the laboratory, will be installed in the designated drill holes.
4. The investigators will perform downhole calibrations to assess effects of the installation.
5. Once the instruments have been installed and calibrated, monitoring of the instruments will begin.
6. The blast holes will be drilled, loaded, and detonated.
7. The instrumented drill holes will be monitored during blasting. Once each blast round is completed, monitoring will be stopped and downhole calibrations of the instruments will be performed.
8. The postblast calibration drift will be compared to the time-dependent drift to assess blasting effects.

9. The instrumentation then will be removed from the drill holes.
10. The investigators will inspect and check calibration of the instruments to assess the effects of retrieving instruments from the drill holes.
11. The drill holes will be resurveyed with a downhole video camera if difficulties arise during retrieval of the instruments.
12. The instruments will be reinstalled in the drill holes, and downhole calibrations will be performed to determine reinstallation effects.
13. Monitoring of the instruments will be resumed.
14. More blast holes will be drilled, loaded, and detonated as the controlled blasting investigation room is excavated. Steps 2 through 13 will be repeated for each blast round.

The laboratory phase of the prototype blast effects test will be conducted at the USBR test facility in Denver. The test facility includes a vibration actuator, which is a 230,000-kgm (500,000-lb_m) reinforced concrete mass actuated by hydraulics that are multimountable. The actuator is capable of producing vibratory motion and dynamic loading at a 400-Hz frequency and a 225,000-N (50,000-lb_f) test force. Greater loads at low frequencies are possible, with displacements in either horizontal or vertical modes.

Other equipment items associated with this system are the control equipment, instrumentation, and a data-acquisition system. The latter includes a desk-top computer that can control both the test system and record test data. The facility also includes a modal analyzer. The analyzer is capable of determining the dynamic elastic properties of a structure (such as a rock mass) by identifying its vibrational modes.

The current laboratory testing plan is to perform laboratory vibration and shock testing, followed by instrument redesign or reselection as necessary, and then verification testing in the G-Tunnel. Additional laboratory work, if determined from field testing to be necessary, will be performed after the G-Tunnel testing is completed.

The laboratory phase of the blast effects test generally will consist of the following steps:

1. The investigators will perform proof tests of the shock and vibration equipment at the USBR test facility. This will ensure that equipment will perform as expected at the vibration and shock levels already determined from prior blasting at G-Tunnel.
2. The investigators will calibrate individual instrument components in order to establish baseline readings. At this point, the investigators will begin to learn the established calibration procedures for each individual instrument component, will begin to write new calibration procedures as required, or will modify existing procedures for each component.
3. The investigators will conduct low-level vibration testing of individual instrument components. This exercise will familiarize the investigators with the performance of the laboratory equipment and will establish procedures to be followed in later testing at higher vibrational and shock loads.
4. Based on results from low-level tests of the individual components, modifications will be made, if necessary, to the existing designs of the hydrologic instruments. Then the modified instrument package will be assembled.
5. The assembled instrument package will be calibrated. Then it will be tested at low vibrational levels only. Problems that surface from this stage of testing will be addressed at this time. If necessary, the instrument package will be disassembled and inspected, modifications

will be made, and the package will be reassembled. This process will be repeated until all problems have been resolved.

6. Additional instrument packages will be subjected to increasingly higher levels of stress until the instruments are subjected to the maximum vibrational and shock levels expected from blast-induced loads. Each problem with the instrumentation will be addressed as it arises. The same process will be followed as in the previous step until all problems are solved.

Operating procedures that will be used during investigation of the ESF will be developed during laboratory testing. The investigators will take a flexible approach to the laboratory testing phase of the blast effects investigation so that they will be able to react quickly to problems with instrumentation and monitoring equipment. During evaluation of data generated by laboratory tests (and by the field tests in the G-Tunnel drift), all applicable techniques of analysis, including statistical methods, will be applied to solving problems.

Information derived from the laboratory tests, combined with results from field tests in the G-Tunnel drift and with recommendations from the blast effects investigators, will enable instrument designers to build vibration- and shock-resistant instrument packages that will satisfy investigation objectives.

Historical Perspective and Background

Methods to control vibration and shock include reduction at the source, isolation of either the source or of the sensitive equipment, and reduction of the response of the equipment. Methods that will be developed during the prototype blast effects test, both in laboratory and in field testing in the G-Tunnel drift, will rely on methods developed by equipment manufacturers and methods that have been developed in the civil, mining, and explosives industries. These methods may include suggestions for modifying the equipment or developing procedures to ensure survival of instrumentation in a harsh mining environment.

Laboratory-based vibrational or shock testing of equipment, primarily electronic equipment, has been performed for the aerospace and shipping industries in accordance with military specifications. Shaker tables were used for higher-frequency lower-amplitude vibrational loads. Shock testing machines were used to provide shock loads in tests in which either a hammer would strike the test machine or a weight would be dropped onto it from a known height. Approaches that will be used in the blast effects study will build on these methods. Other, more unique approaches, such as subjecting instrument packages to underwater explosions, will be evaluated by the blast effects investigators and will be used if feasible.

Extensive field work has been performed in the explosives industry in an attempt to reduce damage to the surrounding rock or to existing structures near a blasting site. These methods of measuring and reducing the effect of vibrations and shock impulses (e.g., decoupling of the explosive charge) will be evaluated and used in the blast effects test. Methods that take into account unique characteristics of the instrumentation packages may also be developed in the blast effects test.

Evolution of Test Design

Initial considerations for the test design drew heavily from the mining and explosives industries. Later considerations used techniques from the electronics industry. Further research will uncover additional approaches from other industries, and these will merit further investigation. After consideration, these additional techniques, approaches, and procedures will be incorporated into the study in an attempt to develop instrumentation that will survive vibration and shock loads.

A number of approaches may be feasible for ensuring the survival of the instrumentation packages. One technique is the use of waterproof polystyrene packing material inside the body of the packer string that contains the hydrologic instruments to surround the sensitive electronic equipment. The packing material, which is a classic method for protecting electronic equipment, acts as an isolator. Another technique that will be considered is the use of guide rails to hold circuit boards in place.

A difficult problem that must be addressed is how to protect electrical connections, leads, and cables that traverse the entire length of instrument packages. Any point of attachment within the instrument package will be sensitive to vibration and shock. Methods and/or procedures used to protect this vital area will continue to evolve as the prototype blast effects investigation proceeds.

The flexible approach that is being taken by the investigators will ensure that new, feasible methods will be rapidly incorporated into the test design as soon as they are discovered.

Conduct of Test

The field test activity was terminated due to the closing of the G-Tunnel following only preliminary construction activities. All test and support equipment was removed from the facility before any testing could be accomplished.

Future Activities

The field investigation phase of the prototype blast effects test will be performed when operations, equipment, and contractor services are put into final form. The start of this phase of the blast effects test depends on commencement of the prototype controlled blasting test, which will provide necessary excavation blast pulses to be used in the evaluation and design modification investigation in the prototype blast effects test.

The laboratory investigation phase of the prototype blast effects test will begin once instrumentation components are received.

The current literature search and review of calibration procedures will continue. Investigations of alternate ways to vibrate and shock-test instrument packages will also continue.

4.6 Cross hole, Pneumatic, and Hydraulic

General Test Description

Several tests are proposed to measure hydraulic properties of the rock units surrounding the ESF. These tests are designed to identify the likely paths for water flow adjacent to the contact between hydrogeologic units that exhibit contrasting hydraulic properties, to measure hydraulic properties of faults or fault zones, to develop three-dimensional bulk permeability tensors, to investigate changes in bulk permeability that result from stress redistribution associated with underground excavation activities, and to characterize the fracture network in the tuff as part of the Percolation Test in the ESF.

The tests proposed for the ESF will involve the use of two boreholes for the injection and extraction of fluids. These test methods are referred to as cross-hole tests. Cross-hole tests provide a means of evaluating the in situ hydrogeologic characteristics of the rock between the two boreholes.

Purpose and Objectives

The purpose of this prototype test is to develop a standardized cross-hole-test system to be used for both hydraulic and pneumatic tests. The system will consist of several components that include test hardware, supporting software, technical procedures, data analysis techniques, and the field-testing configurations. Developing, testing, and refining each of these components during the prototype test will increase the likelihood that the proposed ESF cross-hole-testing applications will be successfully accomplished. A standardized ESF test system will also make the conduct and interpretation of the tests more consistent among the several investigators and facilitate the comparison of results obtained from different tests. The prototype

testing, by developing or refining test equipment and methods before their application in the ESF, could avoid costly delays in construction or test implementation and avoid the irretrievable loss of data on the hydraulic effects of excavation activities that can only be gathered concurrent with construction of the ESF.
The specific objectives of this prototype test are to

- design, fabricate, and test a straddle packer system for measuring permeability values as low as 1.0×10^{-17} m/s;
- develop a field test configuration to detect lateral flow along a hydrogeologic contact, as well as methods for conducting such tests and analyzing data from these tests;
- develop a field test configuration for measuring the permeability of a known fault, as well as methods for conducting such tests and analyzing data derived from these tests;
- develop an analytical method for interpreting cross-hole gas injection tests to determine three-dimensional gas permeability tensors, as well as procedures for conducting cross hole anisotropy tests in support of the bulk permeability testing program; and
- develop formal written procedures for all cross hole-test methods to be used in the ESF cross hole-testing program.

Support Required

The tests associated with evaluation of hydrogeologic boundaries and fault permeabilities will each require two boreholes of specified depth. Three additional boreholes will be needed in support of the bulk permeability testing. Operational equipment for conducting the tests includes inflatable straddle packer assemblies, flow and pressure regulation systems for both hydraulic and pneumatic tests, and various valves, fittings, and tubing used in the flow control systems. Measurement equipment will include resistance temperature detectors (RTD), pressure transducers, thermal mass flow meters, turbine flow meters, and psychrometers for measuring relative humidity. The conduct of the tests will require the availability of water at the test locations and of high-pressure nitrogen gas cylinders. Field geologic mapping in the vicinity of the cross hole tests will be needed to define test locations before the tests.

Detailed Test Description

Cross-hole-testing techniques rely on the use of two wells or boreholes. One active borehole is used for fluid injection or withdrawal and one passive, or observation borehole, from which fluids are used to observe the response of the hydrogeologic units between the two boreholes. In saturated material, cross-hole testing commonly involves pumping one well and observing water level changes in nearby observation wells. In unsaturated material, such as that at Yucca Mountain, cross hole testing requires the injection of water or gas into the active borehole and the collection of liquid or gas (or observations of pressure changes) in the passive borehole.

A conceptual layout for the cross hole testing is presented in Figure 4.6-1. Gas or water is injected into the formation in the test interval, and the effects of that injection are measured in the observation borehole. Sensors in both holes will be used to measure fluid pressure, fluid temperature, and relative humidity.

Three types of cross hole testing will be conducted in the G-Tunnel Underground Facility (GTUF). These are cross-contact testing between a welded and nonwelded tuff unit, testing of a known fault, and fracture and matrix permeability testing in a welded tuff unit. These activities simulate testing configuration and permeability conditions that will be encountered in the ESF.

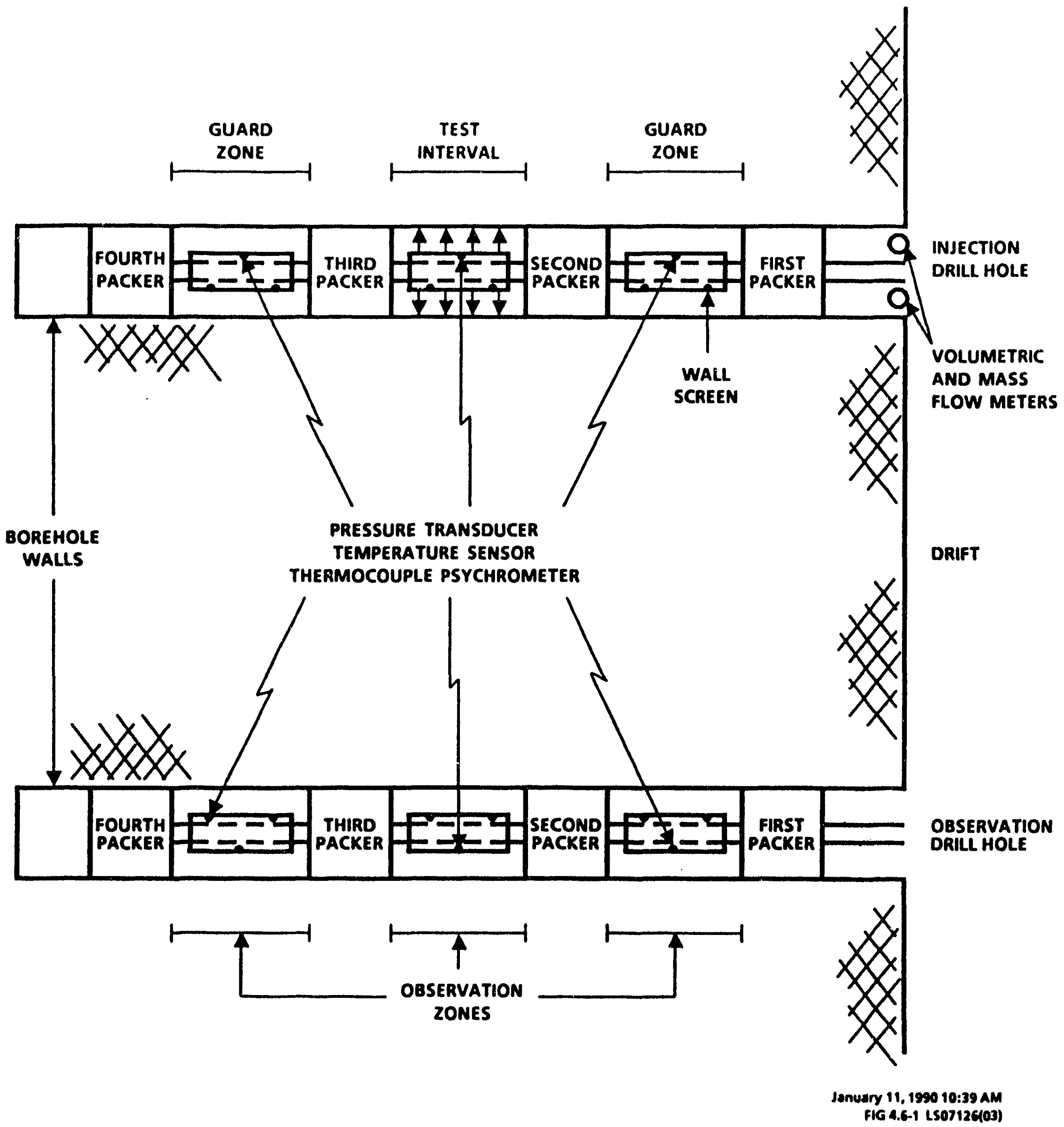


Figure 4.6-1. Conceptual layout of packer injection systems for use in cross-hole testing.

Cross-contact Testing

The test configuration for the cross-contact test in the GTUF is illustrated in Figure 4.6-2. The test configuration and location is representative of the ESF testing proposed for the contact between the Topopah Springs welded unit and the nonwelded Calico Hills tuff.

The test configuration requires the drilling (and coring) of two closely parallel boreholes on either side of the contact, parallel to the contact (and therefore, parallel to the dip of the beds). The optimal location of the boreholes with respect to the contact is determined from scoping calculations and the constraint that the testing should be completed in a 6- to 12-month period.

After the holes have been cored, they will be logged with a neutron moisture meter (to determine moisture content of the surrounding tuff) and with a video camera to view changes in lithology and to characterize fractures encountered by the borehole. The core extracted from the boreholes will be logged to map fracture characteristics, including locations, type, aperture size, presence of fill material, and characteristics of fracture walls. Samples of the core are used for laboratory measurements of hydrologic properties that include water content, water potential, porosity, water- and gas-saturated permeabilities, relative permeability versus saturation, and water potential versus saturation. These data are compared with similar information obtained from the cross-hole testing and are used to interpret the results of that testing.

The cross-contact test is actually two series of individual testing operations. The first test series evaluates fracture locations within both boreholes, using gas flow and pressure measurements. The second test series consists of water injection

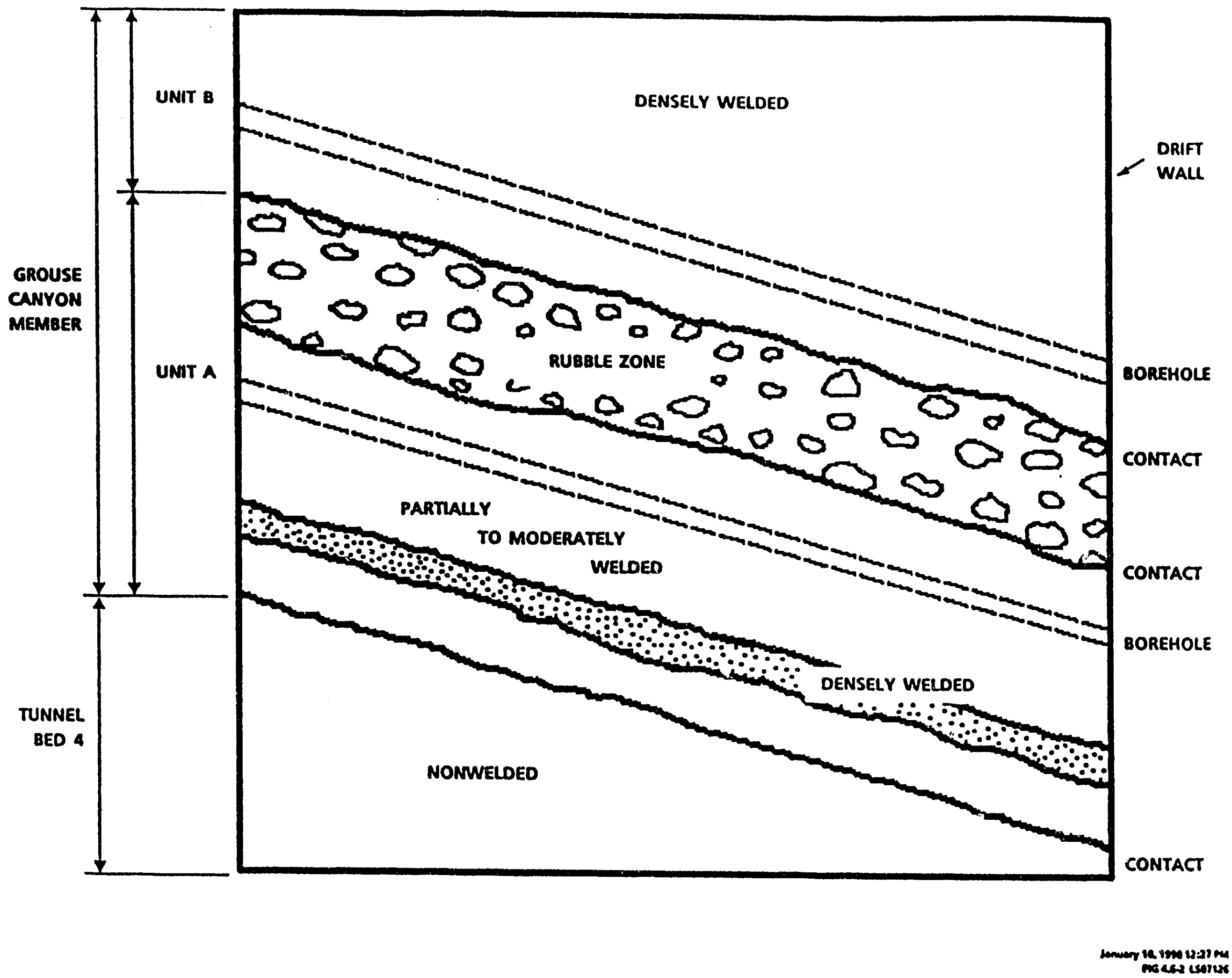


Figure 4.6-2. Cross section indicating borehole and contact locations.

experiments, using both fractured and unfractured segments of the injection borehole. Locations of the test and observation intervals are selected using gas injection to optimize the results of the tests. Then, water containing a tracer is injected into the upper borehole, and the pressure in both the injection and observation borehole response is monitored. Any water flowing from the drift face at its intersection with the hydrogeologic contact will be collected. The water injected into the fractured and unfractured segments contains different tracers so that the two sources of water can be differentiated.

Fault Testing

The proposed fault testing configuration is illustrated in Figure 4.6-3. The portion of each borehole near and intersecting the fault will be cored. The portion of the boreholes adjacent to the fault will be logged, and corresponding samples analyzed in the same fashion as those for cross-contact testing.

Fault testing consists of three test series. The first test series is identical to the fracture location testing described for the cross-contact testing. The second test series uses gas withdrawal to investigate the relationship between gas permeabilities and water potential in the fault zone. Individual experiments will span the entire fault zone or a limited unfractured portion of the fault zone. The response of the borehole to gas injection will be compared with the response to water injection conducted in the third series of tests. In this last series, water will be injected into a zone straddling the entire fault, and pressure response will be measured in both boreholes.

Fracture and Matrix Permeability Testing

The instrumentation and measurement methods developed in the

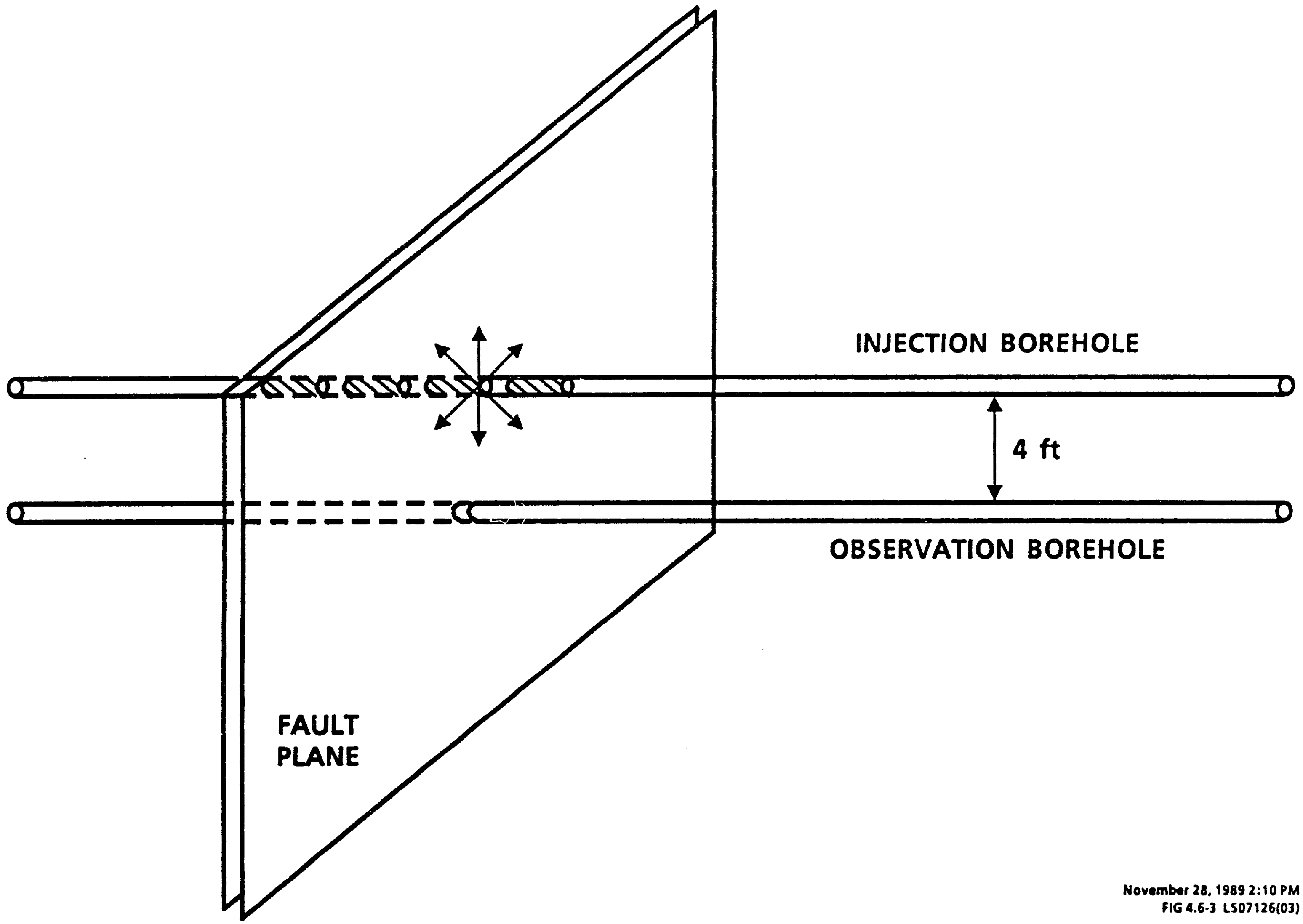


Figure 4.6-3. Borehole configuration for testing a fault.

cross-contact and fault tests will be applied to bulk permeability testing (Section 4.12). The bulk permeability test will evaluate the relative importance of matrix and fracture permeability as increasingly larger volumes of rock are tested.

Historical Perspective and Background

Individual measurements of permeability, porosity, and other hydraulic parameters can be made in a laboratory, using samples extracted from rock. However, in making these measurements, it is difficult to reproduce the in situ stress and hydrologic conditions, and the tests commonly reflect the bulk matrix properties of the rock rather than accounting for the combination of matrix and fracture properties. Further, laboratory measurements on small samples do not represent well the larger scale characteristics of rock units such as bedding planes, fault contacts, or anisotropy that may have a dominant effect on water movement.

Cross-hole tests, by contrast, are conducted in situ and evaluate the bulk properties of the rock between the two boreholes. Proper location of the test interval can isolate predetermined segments of the testing zone.

The prototype cross-hole tests planned for the GTUF are designed to be representative of specific tests that will be conducted in the ESF. While the test configurations are similar to those illustrated in Figure 4.6-1, the geologic setting of the tests have been selected to emulate that in which a particular cross-hole test will be conducted in the ESF.

Cross-Contact Test

It has been suggested that capillary barriers exist at contacts between welded and nonwelded units at Yucca Mountain.[6]

These barriers result from marked contrasts in the pore sizes of the layered hydrogeologic units.

A contrast in hydraulic properties between two hydrogeologic units can have a significant effect on the direction of water movement near the contact. Where a fine-grained layer overlies a coarser grained layer, capillary forces may prevent water from moving from the upper to the lower layer. If the contact is inclined, water may move laterally along the contact, perhaps encountering a vertical structure such as a fault that will provide an alternative flow pathway. If the permeability decreases significantly in the rock above to that below a contact, high-percolation rates may produce a perched water table on the low-permeability layer. The probable water flow pathways in the vicinity of the contact can be determined from information about the contrast in hydraulic properties across the contact.

Fault Testing

It is suggested that the intersection of a fault with a hydrogeologic contact may serve as either a perching zone or a preferential pathway for water movement, depending on the contrast in hydrologic properties between the fault and the surrounding rock.[6] A proposed ESF test will investigate the Ghost Dance fault at the intersection with the upper surface of the Calico Hills tuff. Prototype fault testing will be conducted in the G-Tunnel at the intersection of a fault with the contact between the welded Grouse Canyon Unit B and the underlying nonwelded Tunnel Bed 5 unit. This situation in the GTUF is representative of the proposed ESF fault testing locations.

Fracture and Permeability Testing
Conduct of Test

Initial work on this prototype test consisted of the development of equipment and software that will be used in the cross-contact testing, the fault testing, and the fracture and matrix permeability testing. This consisted of development of the packer assemblies and the gas injection system, development of computer software for data processing and analysis, design of a data logger and supporting software, and calibration of pressure transducers and thermocouple psychrometers that will be placed in the injection borehole.

Two parallel 50-m-long (150-ft-long) horizontal holes were drilled in the G-Tunnel Facility at a fault intersection location. Unfortunately, "Line of Site" in these holes was lost at approximately 20 m (60 ft). This loss limited the prototype testing value. The distance between the instrumentation package that would have been inserted into the hole (i.e., the hole separation) is critical to the ESF test. However, the holes could have been used to check instrumentation package deployment if the facility had remained open.

Future Activities

Instrumentation and packer system refinements based on laboratory and off-site test hole data will continue. Installation and calibration procedures for the borehole test and inspection assemblies will be developed and revised.

4.7 Tracer

General Test Description

Tracers can be added to the liquids or gases that are used in hydrologic testing to provide a means of distinguishing among many possible sources of these fluids. However, successful application of a tracer requires that it move with the fluid in a predictable fashion and that the tracer is not significantly retarded relative to the flow as the fluid moves through tuff or other earth materials. This prototype test will evaluate possible tracers to be used in the test program proposed for the ESF and will develop methods of characterizing possible interactions between these tracers and the tuffs at Yucca Mountain.

Purpose and Objectives

Hydrogeologic tests planned to be conducted in the ESF, which include cross-hole, bulk permeability, percolation, and intact-fracture tests, will involve the injection of gas or water into the tuff. These tests will require that tracers be used to distinguish between native fluids and fluids injected for various experimental purposes. Water will possibly be used during construction of the ESF for the drilling of blasting holes and for dust control. The evaluation of moisture conditions surrounding the shaft and drift openings and the assessment of data collected during the hydrologic testing require the means to distinguish between native water and water that might have been introduced by ESF construction activities. It is particularly important that any unexpected losses of fluids that might occur during construction or testing be identified in subsequent investigations.

The overall purpose of the prototype tracer test is to develop recommendations for tracers suitable for use in both the hydrogeologic testing and in construction fluids. These recommendations will be based on an assessment of the interaction of potential tracers with the tuffs that will be encountered during construction of the ESF. The specific objectives of the test are to

- select potential tracers for use in liquids and gases and to conduct a literature survey to evaluate the cost, environmental reactivity and stability, and toxicity of these tracers;
- develop methodologies and technical procedures for characterizing the adsorption of potential tracers on samples of tuff from Yucca Mountain; and
- develop methods for modeling the sorptive behavior of these tracers on tuff.

Support Required

All experimental work associated with this test will be conducted in laboratory facilities, and no field support will be required. Part of the work will be conducted at laboratories of the USGS, and part will be conducted by other laboratories under subcontract to the USGS.

Detailed Test Description

The test program will consist of two phases: a literature review to identify and evaluate potential tracers and laboratory measurements of the sorption behavior of tracers on tuff. The literature-based assessment will evaluate the suitability of tracers for gas and water and will identify published methods of tracer injection, sampling, and analysis. The suitability of tracers is to be based on criteria such as conservativity, cost, toxicity, environmental stability and reactivity, and detection limits. This evaluation will produce a preliminary list of tracers appropriate for use in the ESF testing. In addition, the literature review will evaluate environmental tracers that can be used to identify contamination of native fluids in tuff by fluids associated with construction activities. Environmental tracers are relatively nonreactive substances inherent in native fluids contained in tuff (or other earth materials). These tracers are present in various concentrations in fluids used for construction activities. For example, the concentration of fluorocarbons in atmospheric air used for ventilation might differ from that in the air present in the tuff. Similarly, blasting will introduce nitrates into the tuff and will result in nitrate concentrations in pore water that differ from native concentrations. These effects can be used to evaluate the effects of shaft construction on the tuff surrounding the shaft.

The laboratory phase of the test program will characterize the chemical, mineralogical, and physical properties of the tuff that influence sorption. The proposed test program is based on the use of an alternative model that considers the actual process of sorption. The surface ionization and complexation (SIC) model[7] requires characterization of the sites on tuff surfaces where sorption occurs.

The behavior of tracers in gases can be adequately based on the literature review conducted in the first phase of this test program. However, the sorption of tracers in water has been observed to be dependent on tracer concentration and on the physical and chemical properties of the sorptive medium. Thus, laboratory measurements will be made on samples of tuff representative of, or similar to, those that will be encountered in the ESF. The sorption data collected by this test will not be used directly to assess the expected behavior of proposed tracers in the tuff in the ESF. However, in order to ensure that the recommendations, methods, and procedures developed by this test program are applicable, it is necessary that the tuff samples used in this test be comparable to those that will be encountered at the ESF.

A complete characterization of the tuff samples used in this test will be performed. This will include determination of the mineralogy, chemical composition and chemical abundances, texture, specific surface, and sorption site density. These measurements will allow discrimination between the properties of the tuffs used in this test and those encountered in the ESF during construction.

Following characterization of the tuff samples, batch and column experiments will be conducted using selected tracers to determine the sorptive response of the tracer in contact with the tuff. The parameters to be evaluated will include the effects of ionic strength of major ions, the tracer concentration, the presence of competing ions, and the presence of complexing species, such as organic compounds, in the tracer solution. These measurements, in conjunction with the data characterizing the tuff, will provide the necessary parameters for use of the SIC model in describing sorption behavior.

Historical Perspective and Background

Traditional approaches to describing sorption behavior use a single-variable, lumped-parameter model. The use of a distribution coefficient, K_d, to characterize sorption limits the ability to extrapolate empirical sorption measurements to conditions outside laboratory parameters. The use of the proposed SIC model will significantly reduce the uncertainty associated with predictions of tracer response. Confidence regarding tracer behavior is essential to the proper conduct of the various hydrogeologic tests because no specific element is included in those tests to evaluate tracer response. Rather, the tests will assume that the selected tracer is a conservative, nonreactive tracer. This prototype test is focused on developing the methods and procedures for ensuring that tracer behavior is properly understood before hydrologic tests are conducted.

The SIC model has been successfully applied to describing ion adsorption on pure mineral species,[8] and a set of parameters for experiments that must be conducted to support use of the SIC model is established.[9] The design of the laboratory experiments that will be conducted in this prototype test is based on those parameters. However, the application of these tests to multimineral sorbates is untried, and some modification to the test design is expected during the conduct of the test.

The measurements made in support of the SIC model can also be used in support of other sorptive models, such as the distribution coefficient approach or the ion exchange model. Thus, the applicability of these models can be assessed with the data produced by this test, and their utility can be compared with the SIC model.

Evolution of Test Design

The gaseous tracer sulfur hexafluoride (SF_6) has been introduced in boreholes during drilling to determine the extent of gaseous contamination of the unsaturated zone atmosphere. Freon-11 (F-11) and freon-12 (F-12) have been used to determine gas diffusion coefficients in the unsaturated zone, and ^{14}C dating of unsaturated zone water is used to determine travel times of percolating water. Doubts are beginning to be raised concerning the conservativity of SF_6, F-11, and F-12. It also appears that isotopic exchange or fractionation of the various carbon isotopes of CO_2 can influence the concentration of $^{14}CO_2$ in the near-surface unsaturated zone. Therefore, additional batch experiments are being designed to determine the behavior of these gaseous tracers when in contact with Yucca-Mountain-type tuffs and borehole stemming material.

Conduct of Test

Work has proceeded on several phases of the tracer project during fiscal year 1989, including methods testing and development, characterization of tuffs, detailed dissolution and tracer tests, initial modeling efforts, and subcontract work on column tracer tests.

One researcher has completed a review of zero-point-of-charge literature with emphasis on natural materials. The laboratory work tested various methods of determining zero point of charge of various lithologic tuff units. The methods used included potentiometric titration, the salt addition method, the coagulation method, the back titration method, and electrophoretic mobility. The zero point of net charge of the three tuffs was measured. It was determined, for boron adsorption batch tests, that the filtering and centrifuging method was most efficacious for separating colloidal material from the supernatant. Testing indicates that aluminum and silica are not adsorbed by sample bottles, centrifuge tubes, or filtering apparatus. Results of part of this work are being prepared for a publication that will give details of this method for determining colloidal versus dissolved silica.

Detailed dissolution and adsorption tests have begun. Mineral dissolution and readsorption processes can occur in crushed-rock batch tests. Because silica has been shown to compete with boron for adsorption sites, it is important to determine if silica dissolution or readsorption is affecting boron adsorption. This project has performed the first four detailed dissolution tests of ground tuff and measured changes in silica and aluminum with time of exposure to solutions. For these tests, solutions used deionized water at natural pH (pH = 6.0 or 7.0, depending on the tuff sample) and deionized water adjusted to pH = 10.0. Three different samples of tuff and two water-to-rock ratios were tested. Boron adsorption on tuff samples that had been preconditioned (soaked in deionized water) for various periods was tested. Adsorption of boron, both with and without the addition of silica to solution, was measured. The data are being evaluated as analyses are obtained. A kinetic analysis of silica dissolution has been performed and confirms earlier work on similar material.

Beginning in early 1989, the New Mexico Institute of Mining and Technology (NMIMT), a subcontractor to the USGS, began performing unsaturated and saturated column tests using crushed tuffs and fracture minerals to study the possible adsorption of various aqueous tracers. Based on consultation with researchers at Los Alamos, minerals for synthetic fracture columns were selected. The three tuffs used in the NMIMT column tests, which were selected to represent various lithological units, and the fracture minerals were prepared and characterized. The surface area of both fracture minerals and ground portions of tuff units were measured by using nitrogen gas adsorption. Starting-column solution compositions that simulate J-13 well water and an "average" unsaturated tuff water were specified, and calibration of instruments was accomplished.

Future Activities

Detailed dissolution and boron adsorption tests will continue on several tuff unit specimens after exposure to various solutions (various pH values and various chemical compositions to mimic J-13 water and pore water) and various water-to-rock ratios. Comparison of boron adsorptions by ground tuff conditioned for various periods will continue. If no difference is noted, dissolution tests will be discontinued and detailed boron adsorption tests will proceed. These detailed adsorption tests will examine boron adsorption by various tuff units, in various solutions (various pH values and various chemical compositions to mimic J-13 water and pore water), and at variable boron concentrations and water-to-rock ratios.

To facilitate the boron adsorption experiments, ion chromatography equipment will be set up in a laboratory near the G-Tunnel. The appropriate column and suppressor have been ordered for boron analysis.

The sensitivity study of MINTEQA2 will be completed. As results are available from boron adsorption tests, MINTEQA2 will be used to model the adsorption. The kinetic analysis of silica dissolution will proceed using data from the detailed tuff dissolution tests.

NMIMT will continue saturated and unsaturated column testing of possible aqueous tracer adsorption on crushed tuffs and fracture minerals with computer modeling of the data from such tests.

Several publications are planned. A review paper on zero point of charge and problems of measurement of natural materials will be completed. A summary paper on experimental variables affecting boron adsorption and the nature and range of these effects will be written. A publication detailing the method of determining colloidal versus dissolved silica will be completed. A presentation, "Applicability of Simple and Complex Models of Tracer Adsorption in Water-Rock Systems," was given at the annual meeting of the Association of Ground Water Scientists and Engineers (Houston, Texas, October 31-November 1, 1989).[10]

It is planned to complete the revision of the detailed technical procedure to include gas-phase tracers. Batch experiments will be designed and implemented to determine the behavior of SF_6, F-11, and F-12 and the carbon isotopes of CO_2 in the presence of Yucca-Mountain-type tuffs and borehole stemming materials.

4.8 Excavation Effects

General Test Description

Standard mining practices applied to welded tuffs can result in the formation of stress-induced fractures and, thus, enhance gas or liquid transport in the rock within a zone immediately surrounding a shaft or drift opening. The prototype excavation effects test is designed to evaluate the feasibility of, and develop procedures for, measuring permeability changes in the rock mass around a mined opening.

Field studies performed in the G-Tunnel demonstration drift will use instrumented boreholes to measure stress and subsequent permeability changes that occur in welded tuffs adjacent to the drift. The prototype excavation effects test is closely associated with the prototype controlled blasting and blast effects tests, because the drift and instrument alcoves used by both of these tests provide access to the area needed for conducting the prototype excavation effects test.

Purpose and Objectives

The purpose of the prototype excavation effects test is to develop the ability to measure stress changes and consequent permeability changes that occur in rock adjacent to a drift as it is being excavated. The results of the prototype excavation effects test will be used to ascertain whether the test design is practical, whether the instruments can survive combined blast effects, and whether modifications in borehole instrumentation and data-acquisition equipment will be required to ensure success in the ES excavations effects testing program.

Stress- and deformation-measuring instruments will be developed in this prototype test, while the permeability measuring instruments will be developed in the prototype cross-hole test. Stress-, deformation-, and permeability-measuring instruments will be evaluated as a system in the prototype excavation effects test.

The objectives of the prototype excavation effects test are to

- investigate the various types of stress- and deformation-measuring instruments that can be used to measure changes in the in situ stresses in fractured rock,
- develop a reliable installation and monitoring procedure for the various types of instruments used for this prototype test,
- develop a reliable method of determining in situ changes in permeability of fractured rock that are caused by excavation-induced in situ stresses and deformations around an excavated underground drift, and
- develop a coupled hydrologic-mechanical simulation model for the prototype excavation effects test for use in estimating permeability changes around other openings.

Success in prototype testing will indicate that excavation effects measurements can be scheduled and accomplished in the short time available for data collection in the ESF.

Support Required

Special equipment, supplies, and requirements for this test include the following:

- a Longyear-38, or equivalent capacity, drill rig sufficient for drilling and coring of (1) 9.5-cm-ID (3.79-in.)(inside diameter) by 15-m-(50-ft-) long holes, (2) 8.8-cm-ID (3.5-in.) by 10-m-(30-ft-) long holes, (3) 5.9- cm-ID (2.375-in.) by 11.5-m-(38-ft-) long holes, (4) 3.8- cm-ID (1.5-in.) by 0.7-m-(2-ft-) long holes at the end of the 5.9-cm (2.375-in.) hole, and (5) a core-barrel centering mandrel;

- close monitoring of tolerance on the inside diameter of finished boreholes (2), (3), and (4) above (important where a small clearance between the instruments and the borehole walls is required in order for the instruments to operate properly);
- an air compressor for drilling support;
- general lighting;
- a 110-V alternating current, uninterruptible power system for instrumentation and operation of the data-acquisition system; and
- provision of transportation of personnel and equipment between the test area and the surface as required.

Special testing requirements include dry-drilling and dry-coring methods that must be used to avoid contamination of the samples and the host rock.

Special staff requirements will include provision by the contractor of geologists or hydrologists and technicians to assist the USGS during drilling and testing. As directed by USGS investigators, the contractor's staff will assist in, or perform, the following field activities:

- analysis of bit cuttings and core;
- core logging and sample identification;
- core-hole surveys; and
- safety inspections to ensure safe working conditions.

Detailed Test Description

The prototype excavation effects test consists of developing the methodology needed to investigate and record changes in rock permeability and fractures that occur as a result of changes in in situ stresses and deformation of the rock during excavation in rock adjacent to a shaft or drift opening. Simultaneous measurements of stress, deformation, and permeability changes around an underground opening are required to accomplish the objectives of this test.

Two sets of boreholes, with three holes per set, will be used to make stress and permeability measurements. These boreholes will be drilled using air and will be arranged parallel to the axis of the controlled blasting drift at the G-Tunnel. Fracture deformation will be measured from two horizontal boreholes, one perpendicular to and the other diagonal to the controlled blasting room axis as illustrated in Figure 4.8-1. The two sets of boreholes used in the fracture deformation studies will be logged using a deviatometer (for measuring borehole alignment), television camera (fiber-optical), and neutron moisture, porosity (epithermal), and gamma-gamma logs. These logs are used to estimate the initial condition of boreholes in the vicinity of the controlled blasting room before prototype testing.

Two MPBXs are placed in two boreholes to measure fractured rock displacement, while 12 to 15 stress-measuring stations (stress deformation gauges) are placed in three boreholes to measure changes in stress. In the permeability-measuring phase of the study, the test will use two packer string assemblies for air injection alternately in three boreholes to measure permeability changes. The packer string assemblies are being developed in the prototype cross hole test (Section 4.6).

The sequence of major events for the prototype excavation effects test is to

- set up a dust-collection system to collect borehole dust and cuttings;

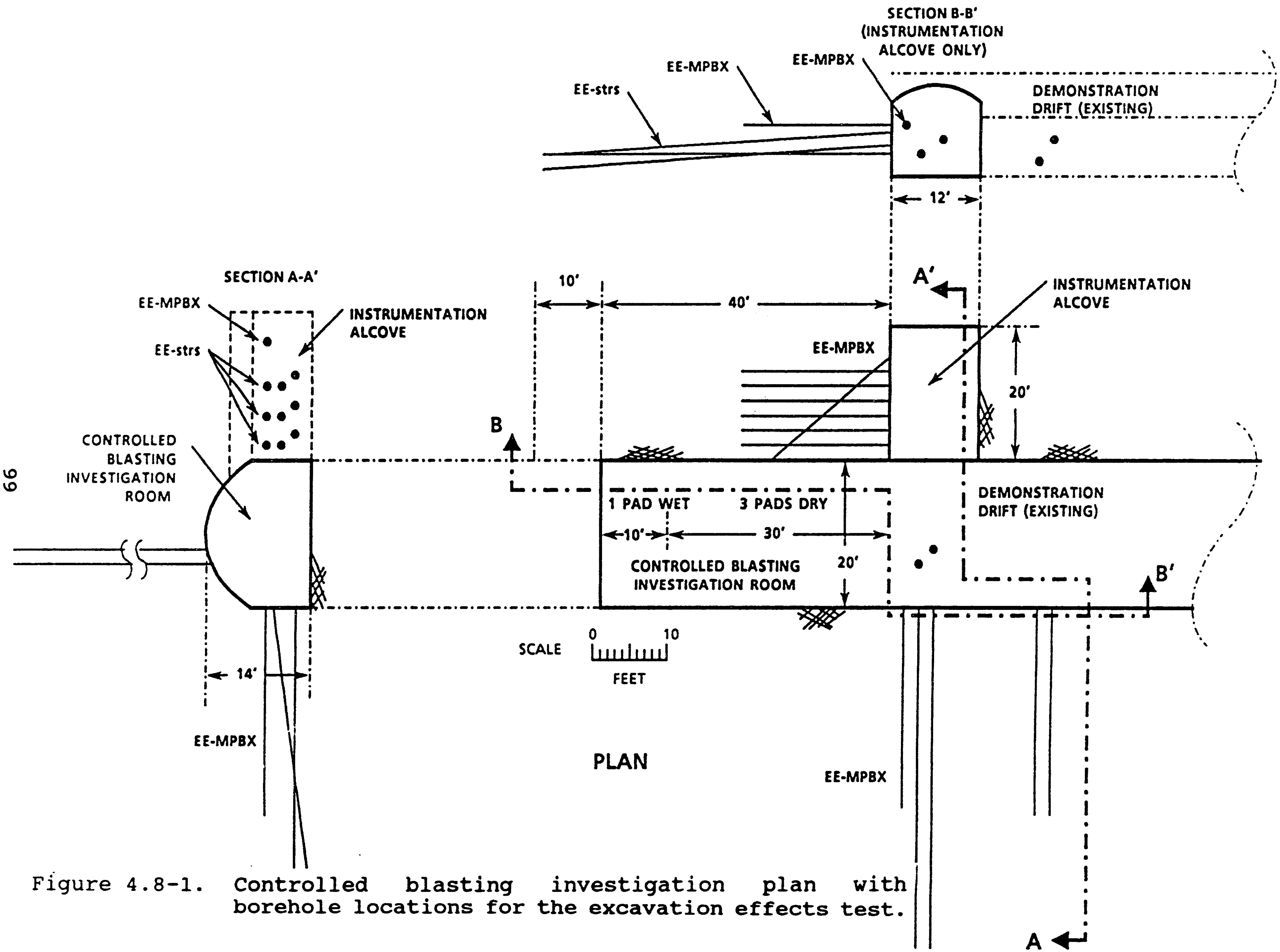


Figure 4.8-1. Controlled blasting investigation plan with borehole locations for the excavation effects test.

FIG/4.8-1 LS07126(03)

- survey fore and aft spat (reference) points to provide correct alignment;
- survey as-built holes to support drilling operations;
- drill boreholes (air method);
- log boreholes using television camera and neutron moisture meters;
- install between 12 and 15 stress-measuring stations (stress deformation gauges) in three boreholes;
- install two MPBXs in two boreholes and install MPBX instrumentation leads to data acquisition equipment;
- install hole caps for MPBXs;
- install two air-packer injection string assemblies alternately in three boreholes;
- install instrumentation leads to air-injection packer string assemblies and data-acquisition equipment;
- collect data during drift mining operations; and
- perform final analysis and prepare report.

Before instrumentation is placed in boreholes, stress-measuring instrumentation and deformation-measuring equipment will be tested and calibrated in the laboratory.

Historical Perspective and Background

The new prototype methods to be developed and tested in the prototype excavation effects test are derived from current technology, standard mining practices, and other available techniques. Other sources of methodology are derived from both published and unpublished field-testing data in the G-Tunnel.

Hydraulic pressure cells made by the US Bureau of Mines (USBM) have been selected to measure rock stress changes. Other stress-measuring instruments were considered, such as the CSIRO gauge and the vibrating-wire stress meter. Both of these types are limited in the number of sensors that can be installed in each borehole and are poor performers in fractured rock, which is the case in this test.

The selection of a borehole extensometer to measure borehole deformation was based on a study made by Atomic Energy of Canada, Limited, in their underground research laboratory.[11] Several types were installed and compared, and one type, manufactured by ROCTEST, Inc., showed the best performance and stability in an excavation environment similar to that in which this prototype test will be conducted.

Permeability-measuring instruments are currently being built and tested under the prototype cross-hole test.

Evolution of Test Design

Technology available from the mining industries has contributed greatly to the evolution of the current proposed test design. The air-injection packer string assembly used in the permeability-measuring studies of the prototype excavation effects test has been developed, and preliminary field and laboratory testing of the equipment has been conducted.

Conduct of Test

Other prototype testing programs related to the prototype excavation effects test are

- geologic mapping (Section 4.1);
- laboratory analysis of intact fractures (Section 4.10);
- controlled blasting and blast characterization tests (Section 4.16) for rock mechanics and related explosives property data, the instrument alcove, and the required drift area;
- thermal stress test (Section 4.17);

- in situ stress test for measuring the original in situ stress in the vicinity of the drift (Section 4.18);
- mineralogy and petrology (Section 4.2);
- testing of blast effects on instrumentation (Section 4.5); and
- cross hole test (Section 4.6) for the air-injection packer string assembly and related equipment development for the prototype excavation effects test.

The original in situ stress test is required for the boundary conditions in the modeling stage of this prototype test and for the interpretation of the measurements of stress changes.

The air-injection packer string assemblies that are to be used during the permeability measuring phase of the prototype excavation effects test have been developed and tested in the prototype cross hole test, which has been in progress since May 1988. These studies have involved the drilling, coring, sampling, and analyzing of cored sections; blind-hole survey methodology; development, assembly, and calibration of test instrumentation; and deployment and debugging of the packer assembly.

The prototype controlled blasting and blast characterization test is designed to study and determine rock characteristics governing the magnitude of explosive-generated shock. Rock mechanics, geometry parameters, development and excavation methodology, and development and testing of instrumentation are also studied in this prototype test. Each of these test activities provides data relevant to defining the drift area in which the prototype excavation effects test activities will be conducted. The prototype controlled blasting test and the blast characterization test began in January 1989 when related tests were consolidated. A criteria letter for the prototype controlled blasting and blast effects tests was put into final form in February 1989 and submitted with revisions. The scientific investigation plan and the quality assurance level assignment were submitted to the Project Office in April 1989.

The geomechanical rock properties will be obtained from the prototype mineralogy and petrology and thermal stress tests. These properties will be required during the modeling stage of this study.

Fracture maps made for prototype geologic mapping are needed to identify the fracture zones within the test area because fractures greatly affect rock behavior.

The unsaturated flow mechanism in fractured rock will be obtained from the prototype laboratory analysis of intact fractures. This information will also be used during the modeling stage of this test.

The effect of blast vibration on the performance of measuring instruments in this test will be studied in the prototype testing of blast effects on instrumentation. This study is important in that the excavation method will be drill and blast.

Future Activities

The prototype excavation effects test program is currently on standby. The final project criteria letter was put into final form in January 1989, and an open work order was issued in April 1989. The prototype excavation effects test program will take place when preparations, equipment, and contractor services are available.

4.9 Optimal Rubble Size

General Test Description

Rock samples are required for site characterization activities in the ESF at Yucca Mountain. Rock samples are traditionally obtained by borehole drilling and coring using water-based drilling fluids. These drilling fluids infiltrate geologic formations and can alter the hydrologic or geochemical properties of rocks. Because maintaining the integrity of the potential repository units is of primary importance throughout the design and development of the ESF and throughout the site characterization testing within the ESF, blast rubble derived from shaft construction is being considered as an alternative to coring as a source for samples. The pieces of rubble selected for sampling must be sufficiently large to ensure that the contained water is representative of natural conditions but small enough to provide a large quantity of samples. Before rubble can be used, however, it is necessary to determine the optimal size of a rubble block that can be successfully cored for samples. It also must be determined whether or not samples are contaminated by chemicals from blasting or affected by heat generated during blasting or by exposure to the atmosphere.

The G-Tunnel prototype test modeled the conditions that are expected in the ESF. The prototype test duplicated, as closely as possible, future construction activities in the ESF in order to anticipate and solve potential problems. The main difference between the prototype test and testing in the ESF is that mining in the prototype test was done in a horizontal, rather than vertical, orientation.

Pore water extracted from cores obtained from intact rock (nonrubble cores) will be analyzed and compared to pore water extracted from cores cut from rubble samples in order to examine the effects of blast materials and heat. The effect on pore water chemistry of samples exposed to the atmosphere and to drilling fluids will be examined.

Purpose and Objectives

The prototype test is a developmental effort that must be accomplished before construction of the ESF. If rubble samples are shown to be consistently contaminated or structurally damaged, another sampling method must be explored. This test has four purposes: to establish the technical feasibility of collection, transportation, and processing of rubble samples; to identify and assess problem areas that could compromise the accuracy of ESF study data; to determine the approximate amount of time needed for bulk sampling and to assess its associated costs; and to determine the optimal size of blast rubble from which 6.1-cm (2.4-in.) core samples can be obtained while maintaining the structural and chemical integrity of the samples.

There are two specific objectives of the test: (1) to develop procedures to collect, log, seal, label, transport, and store blast rubble samples to prevent evaporation and to maintain structural and chemical integrity of samples while minimizing construction downtime and cost; and (2) to determine the optimal size of blast rubble needed to avoid contamination by either gas or liquid blast chemicals and their byproducts.

Information and procedures obtained from this study will be used in the collection of samples from ESF rubble for the matrix properties tests, the chloride-36 tracer tests used to determine the ratio of chloride-36 to total chloride from pore water samples collected from rubble, and hydrochemistry tests in which pore water obtained from samples is analyzed for chemical and isotopic constituents. Results of the prototype optimal rubble size test will help minimize wasted efforts in coring blasted rock in the

Exploratory Shaft Facility (ESF), will determine if some core orientations produce more water than others, and will reduce the number of rock cores to be drilled for testing. Data from this test will not be used in site characterization.

Support Required

The activities in the prototype optimal rubble size test are closely related to the prototype tests for pore water extraction from tuff by compression. The preblasting, dry-cored samples will be collected in the working face before the first controlled blasting round is detonated, and rubble samples will be collected from welded and nonwelded rocks after each round of the blasting test. The development of dry coring of rubble techniques is necessary to provide samples for analysis.

All work will be performed under the direction of the principal investigator (PI), who has overall responsibility for the experimental effort. With the exception of the following activities and personnel, all test requirements will be conducted by US Geological Survey (USGS) staff. Drilling, blasting, sample identification, wrapping, transport, site storage of samples, and mucking in the G-Tunnel will be performed by Reynolds Electrical and Engineering Company, Inc. (REECo), who will provide a drilling superintendent, mining specialist, geologist, surveying party chief, and support personnel. Fenix and Scisson of Nevada (FSN) will provide a geologist. The rubble coring of 54 samples is being conducted by Holmes and Narver, Inc. (H&N) in Mercury, Nevada, and by the US Bureau of Reclamation (USBR) in Denver. Prototype tests for pore water extraction from tuff by compression are being conducted by the US Geological Survey (USGS) and the USBR. Excess sample pieces will be stored in the Yucca Mountain Project (YMP) Sample Management Facility; all other samples will be stored by the USBR in Denver.

Detailed Test Description

The prototype test will determine the optimal sample size and the suitability of blast rubble samples for use in other tests that will characterize the properties of the repository rock. Samples of welded and nonwelded tuff will be collected by two methods: rock core samples will be obtained by dry coring in intact rock, and two general sizes of rubble samples will be collected following blasting. Rubble of about 15.2 cm (6 in.) and 30.5 cm (12 in.) in diameter will be collected and dry cored to determine which size is more amenable to coring and to producing chemically and isotopically unaltered pore water.

Pore water will be extracted by either triaxial compression, the preferred method, or by centrifugation if the samples will not withstand compression. The pore water will then be analyzed for specific conductance, pH, cation content, ratio of stable oxygen to stable hydrogen isotopes, tritium content, and anion content. The results of the analytical tests on pore water extracted by the two methods will be compared statistically to determine any differences that may result from the two collection methods.

Sample work will be conducted in the G-Tunnel and will consist of the collection, preparation, preservation, and transportation of a number of rubble and nonrubble rock samples. Laboratory work, primarily conducted in the USGS and USBR facilities in Denver and in the H&N material testing laboratory in Mercury, Nevada, includes instrument and equipment preparation and calibration, dry coring of rubble (Section 4.14), and the extraction and chemical analysis of pore water.

The prototype test also includes activities related to experiment design, development of a technical procedure of rubble sampling and handling, and the evaluation and analysis of laboratory and field data.

Historical Perspective and Background

In the past, representative samples of a unit were collected by vertical and horizontal drilling to obtain sample rock cores. In the case of the ESF, however, the number of holes drilled into the rocks will be minimized to keep the repository units intact. Rubble resulting from shaft construction can be obtained, however, and could be used to characterize the repository units. This prototype test examines the potential problems of, and develops the procedures necessary, for using rubble as source material for tests.

Conduct of Test and Results

A blast round pattern has been designed for the optimal rubble size test in welded and nonwelded tuff in the area located at the end of the demonstration drift and in the CFE2 drift in the G-Tunnel. The blast round pattern to be used in the excavation to produce rubble samples is outlined by the prototype controlled blasting test (Section 4.16). Rubble pieces have been collected that include nonwelded and welded core and nonwelded and welded rubble samples.

Future Activities

The prototype test field activities for this test have been completed and laboratory analyses of the samples is in progress. Sample collection and analysis procedures are being finalized.

4.10 Intact Fracture

General Test Description

The hydrologic characteristics of welded and nonwelded tuffs at Yucca Mountain will be investigated in a series of tests performed in the ESF. Fracture flow characteristics will be studied in the unsaturated zone that is the potential repository site. Intact fracture samples will be collected and studied in laboratory tests. Few tests have been performed on intact fractures from unsaturated tuff; sampling methods for collecting intact fracture core samples and analytical procedures for determining the hydrologic properties of the fracture core samples must be developed. The prototype test will be performed to develop these methods and procedures.

Intact fracture core samples will be collected in welded and nonwelded tuffs at the G-Tunnel, where geological conditions closely resemble those at the ESF. Both axial and radial fracture samples will be collected. Sampling methods will be developed that minimize the effects on the hydrologic properties of fractures. The fracture core samples will be used to develop procedures for measuring hydraulic transport parameters and the geometric properties of fluid-phase distributions and fracture apertures. The primary laboratory tests include fluid displacement, stress, permeability, tracer injection and dispersivity, and flow channelization tests. The feasibility of using rock-bolt-overcore and clamp-core fracture sampling methods for the ESF will be evaluated.

Purpose and Objectives

The purpose of these investigations is twofold: (1) to develop methods and procedures for collection of core samples containing intact fractures while causing minimal disturbance to the fracture sample and (2) to develop methods and procedures for conducting laboratory tests on intact fractures so that these results and procedures will be available for the ESF hydrologic test program. The objectives of the sampling methods portion of the tests are to develop formal procedures for radial and axial intact fracture sampling, to identify appropriate equipment for radial and axial intact fracture sampling, and to collect samples for the laboratory analyses portion of the test.

The specific objectives of the laboratory analyses are to

- determine technical procedures for preparing fracture samples for testing;
- identify and test specific instruments that will measure the desired variables;
- design and implement a local data acquisition system that will record data as it is generated during the various tests;
- determine the feasibility of conducting laboratory tracer injection and dispersivity tests on intact fracture cores; and
- determine the feasibility of conducting fracture flow channelization and tortuosity tests on intact fracture cores and to define fracture flow geometry.

Support Required

The fracture orientation data will be obtained from USGS data sources and geologic mapping. Sampling technique development work was proposed for the laboratory and the Colorado School of Mines (CSM) experimental mine at Idaho Springs, Colorado, before sampling in the G-Tunnel. Subsequent laboratory testing of the core collected will be conducted in the USGS Denver laboratory.

Detailed Test Description

The sampling portion of the intact fracture test will include the following steps: mapping fractures; drilling pilot or access holes; placing anchor devices; coring and/or overcoring and retrieving fracture samples; and weighing, measuring, and packaging samples. The preliminary development of the sampling technique will be conducted in the laboratory, first with concrete and then with a large boulder of tuff. Following the laboratory trials, further sampling development is proposed for the CSM experimental mine before actual prototype sampling is attempted in the G-Tunnel.

Fracture sampling locations will be based on the results of fracture mapping in the Grouse Canyon member of the Belted Range tuff and in the Tunnel Bed, level 5, which is one of a series of units underlying Grouse Canyon informally referred to as Tunnel Beds 1, 2, 3, 4, and 5. A proposed location will be eliminated if it is determined that more than one predominant fracture crosses its sampling area. Radial and axial fractures will be collected by air coring in both welded and nonwelded tuff. Sampling will be conducted using operations and methods that minimize disturbance to the fracture plane. Radial fracture samples will be collected by a rock-bolt-overcore sampling method, and radial fracture samples will be collected by a clamp-core sampling method. Samples will be sealed and shipped to the laboratory. The samples used for testing will be those in which a fracture is assessed to be minimally disturbed. Development of disturbance assessment techniques and criteria is an additional aspect of this test.

The laboratory analyses portion of the intact fracture test will include the following major tasks: sample preparation, core fracture mapping and sample description, fluid displacement tests (stress-permeability tests), tracer injection and dispersivity tests, fracture flow channelization tests, computer modeling, and data analysis. As part of sample preparation, samples will be subjected to load cycling (a minimum of three loading and unloading intervals) to minimize hysteretic effects. Sample cores will then be fitted with sensors, including pressure-transducer tensiometers, linear variable differential transformers, electrical resistivity electrodes, and possibly thermocouple psychrometers.

Sample cores will be subjected to single- and two-phase permeability tests that are conducted while the fracture samples are under applied stress. These loads will be applied to simulate in situ stress conditions and will be maintained until steady-state conditions are reached. This may require several weeks or more. Chemical tracers will be injected into fracture samples and the dispersivity results compared with results from samples without fractures. The flow channelization testing, which includes Moire projection techniques, will provide data on fracture plane geometry that includes aperture width, surface roughness, flow path tortuosity, asperity height and distribution, and contact area determination. Two techniques will be used to obtain casts of the fracture plane: resin impregnation and injection of a low-melting-point alloy. Moire projection techniques will be used to determine the three-dimensional contours of the fracture plane surfaces and will produce still photographs and videotapes.

A computer model of fluid flow will continue to be developed, and the model-generated results will be compared to data obtained from the intact fracture tests. The comparison between model results and empirical data may provide a better understanding of the transport mechanisms that operate on a microscale. The applicability of transport modeling in a fracture-dominated flow system will also be evaluated. The results of the laboratory tests can then be used to calibrate models for subsequent larger-scale hydrologic tests.

Data analysis will consist of analyzing laboratory test results to determine characteristic relationships and responses.

Computer modeling, initially used to design the laboratory tests, will also be used at various stages of testing to optimize test results. Modifications to the computer models will be made as needed to increase efficiency and accuracy.

Historical Perspective and Background

Characterization of the hydrology at Yucca Mountain will require that fluid flow in fractured tuff be investigated. Samples of fractures will need to be collected and analyzed in the laboratory. Because there have been few studies of this type in the past, procedures and techniques must be developed for fracture sampling and analysis. The intact fracture test is proposed for this purpose.

Evolution of Test Design

The Grouse Canyon and Tunnel Bed level 5 tuffs accessible in the G-Tunnel were selected for sampling because they are petrologically similar in their major element compositions and physical and mineralogical properties to Topopah Spring and Calico Hills at the potential site for the repository at Yucca Mountain. Hysteretic effects in fracture samples have been shown in previous work to be more pronounced in samples that are larger than 24 cm (9.65 in.) in diameter. These samples will be collected and subjected to a minimum of three loading cycles before analysis of fluid flow properties. The clamp-core sampling method is included as a result of a suggestion made by Lawrence Livermore National Laboratory (LLNL).

Conduct of Test

Tests were conducted in the laboratory on a well-cured concrete beam and formed grout blocks, both with artificial fractures. The Brazilian method of loading was used to induce a fracture in the beam. The high, unconfined compressive strength of the beam (much greater than the compressive strength of rock materials present at Yucca Mountain) caused drilling difficulties, and the beam was therefore abandoned as a material for prototype work.

Grout blocks containing artificial fractures that were fabricated using waxed paper or plastic sheeting were also used to assess the proposed methods. The grout blocks proved to be better samples to investigate the basic concepts of the two sampling methods proposed for axial and radial fracture orientations.

Design and fabrication of equipment needed for sampling and analysis has begun and in some cases has been completed. Variables such as hardware, degree of compression and torque, number of anchors or straps, tightening tool configuration, and a wedge tool for separating cores from the rock mass at the bottom of boreholes were assessed in the laboratory before the G-Tunnel work was started.

G-Tunnel testing was divided into axial and radial fracture sampling attempts to obtain the optimum use of drilling crews when available. Some axial fracture sampling attempts were completed in both the Grouse Canyon member and Tunnel Bed, level 5, with some degree of success in March 1989. Radial fracture sampling was started in July 1989.

Laboratory work to date includes near completion of a vacuum saturation table, vacuum oven apparatus (flexible for other test applications), and preliminary imbibition studies on smaller-scale rock cores to test electrical resistivity instrumentation. Several instruments for measuring capacitance and resistivity (conductance) at various frequencies have been used and evaluated (on a loan basis before purchase).

Methods development for using Moire projection was started again in June 1989. The amount of progress made in the future will depend a great deal on the purchase of capital equipment necessary to do the work. No progress will be reported regarding stress-permeability studies until capital equipment for the confining vessel(s) apparatus is purchased.

Future Activities

Unconfined laboratory tests are planned, to be conducted with samples collected from the G-Tunnel in order to test instrument applicability and configuration. Equipment modification and procedure development will continue.

4.11 Percolation

General Test Description

This prototype test will determine the appropriate design and configuration for the test block and will examine the effectiveness of various instruments intended to monitor water and tracer movement through fractured, welded tuff. The tests will be conducted in a laboratory setting using small and large blocks of welded tuffs from Yucca Mountain.

Purpose and Objectives

Determination of the rates and volume of groundwater flow from the land surface to the saturated zone beneath Yucca Mountain is a central issue in site characterization. A quantitative description of the water flow must include the infiltration rates of precipitation and the subsequent downward percolation of the water. Direct measurement provides the most reliable method of determining these rates. The instruments employed in the percolation test must be capable of the following: (1) measuring water content and potential in the matrix; (2) distinguishing conducting (wet) fractures; (3) monitoring the arrival of the wetting front or tracer pulse in the fractures; (4) and quantifying imbibition into the matrix through fracture walls.

Before initiating these tests at Yucca Mountain as part of site characterization, it is necessary to evaluate the effectiveness of the proposed instrumentation and measurement methods. This evaluation will ensure successful conduct of these tests in a field setting. The specific objectives of this prototype test are to

- determine the final operational design of the infiltrometer components (sprinkler system sand bed instrumentation, flow tank apparatus) and ancillary equipment (i.e., experiment control system, automated data acquisition system);

- verify that the instrumentation techniques used to determine matrix hydrologic properties of soils are also applicable to in situ monitoring of the welded tuff matrix;
- develop the methodology and technical procedures for locating fractures and making air permeability measurements in small-diameter boreholes;
- determine the feasibility of detecting flow in fractures by using commercially available unsaturated zone instrumentation (i.e., tensiometers, conductivity probes);
- determine in a generic manner the optimal drill hole network and instrumentation pattern necessary for characterizing water and tracer movement through fractured, welded tuff;
- modify and advance the existing technology in the area of time domain reflectometry (TDR) in order to differentiate between fracture and matrix flow, as well as to measure bulk-rock moisture content in welded tuff; and
- estimate the time required to perform various phases of the ESF percolation test, based on the results of the laboratory experiments and on computer modeling.

Support Required

This test will be conducted entirely in a laboratory setting. Field support will consist of the collection and transport to the laboratory of several large blocks of rock that are characteristic of the tuffs at Yucca Mountain.

Detailed Test Description

Prototype laboratory investigations will be conducted in two stages. The first stage will consist of individually testing each component or instrumentation technique of the overall system in small blocks of welded tuff containing, at most, a few identifiable fractures. This will enable the investigators to identify problems that otherwise might be more difficult to isolate if all components of the system were tested simultaneously. After the performance of each of the system components has been evaluated individually, instruments that have been judged to perform successfully will be incorporated into a larger, 1-m^3 (30-ft^3) block along with the infiltrometer, lower porous plate, and vacuum pump. The purpose of the larger block test is to evaluate all of the instruments simultaneously under conditions similar to those anticipated in the ESF percolation test.

The energy status of water held within the welded tuff matrix will be determined with tensiometer and transducer systems and thermocouple psychrometers. Prototype testing will involve the construction of the tensiometer and transducer systems and the calibration and testing of these instruments as well as the thermocouple psychrometers.

Tensiometer-transducer systems will be used to measure matric potential during wetting and subsequent steady-state conditions. The difficulties associated with tensiometers are that air bridging can sometimes be introduced into the system, and tensiometers can dry out completely at low saturations. Saturated tensiometer systems must be placed in boreholes within their measurement range and may have to be resaturated periodically. In recognition of these potential difficulties, a monitoring program will be developed for tensiometers that will include real-time data displays with storage and retrieval options. This will enable problems to be identified as they occur. Tensiometers will be arranged such that measurements in the vicinity of the fracture and in the center of the matrix block can be recorded simultaneously. In this way, moisture exchange between the matrix and adjacent fractures can be estimated during the transient wetting and drying phases. The tensiometer-transducer system can also confirm that steady-state conditions predicted by inflow and outflow measurements have been attained.

In addition to tensiometers, borehole-fracture intersections will also contain a conductivity probe that can be used to provide an independent check on the arrival of the infiltration wetting front. The conductivity probe will consist of a platinum wire located downhole adjacent to the tensiometer tip. The conductivity probe will be wired to an uphole conductivity meter. Potassium bromide added to the infiltrating water will cause a response to be recorded on the data acquisition system as this water enters the borehole-fracture intersection.

Screen-caged, single-junction Peltier thermocouple psychrometers will be used to monitor the ambient water potential and changes in water potential during the initial wetting phase of the percolation test. Under isothermal conditions, psychrometers are very accurate but require careful calibration. As part of prototype testing, calibration curves relating water potential to voltage output will be generated for individual psychrometers for a range of salt solutions and for various temperatures.

It has been observed that temperature gradients are often associated with the leading edge of a wetting front during infiltration. These temperature gradients can introduce errors into estimates of water potential produced by psychrometers by disrupting the thermal stability between the sensing junction of the psychrometer and the evaporating sample surface or between the sensing and reference junctions. These phenomena will be studied and corrected (if possible) during the prototype percolation test.

TDR will be used to measure bulk-rock water content in all phases of the experiment. During wetting, TDR will be used to monitor the wetting front in the matrix (and possibly fractures). Thereafter, TDR will be used to measure moisture redistribution during drying.

All instruments will be emplaced horizontally within the test block with the exception of the TDR probes. Horizontal instrumentation will minimize disturbance of the percolation surface and will eliminate the problem of preferential flow channeling that can occur along vertical boreholes.

The design of a sprinkling infiltrometer is one of the principal goals of prototype testing. This device consists of a flow tank apparatus, low-volume metering pump, spray nozzle, and accompanying valves and instrumentation. The low-volume metering pump controls the flow of water and tracer through the spray nozzle suspended immediately above a sand bed. Flow will be monitored by use of a series of pressure transducers and a data-acquisition system, and the flow will be servocontrolled by a microcomputer. The system will be contained in a frame covered with plastic sheeting to minimize evaporation. The thickness of the sand within the frame will be approximately 10 cm (4 in.). Capillary forces within the sand will tend to distribute water evenly from the spray nozzle so that the moisture content and matric potential for a relatively homogeneous sandbed will be relatively constant at a given height above the rock surface. A sealant material may be used to cement the bottom of the frame to the rock surface, which will minimize leakage of water around the edges of the sand bed. The sand bed will be instrumented with tensiometers equipped with pressure transducers to monitor matric potential. At higher flow rates (i.e., small matric suctions) the hydraulic conductivity of sand can be smaller than that of individual fractures transecting the upper surface of the block. Thus, the sand can act locally as an impeding layer. In this case, the matric potential within the rock mass might be less than the matric potential measured with the sand. Measurements of matric potential within the rock itself are therefore necessary to accurately characterize the energy status of water held within the block.

The block will rest on a ceramic (or metal) porous plate supported by a stainless steel frame. A suction less than the air-entry suction of the plate (nominally 500.0 kPa [0.072 psi]) can be applied to the lower plate surface with a vacuum pump. The applied suction would draw the percolating fluid out of the plate to where it could be collected, measured, and analyzed. A thin sand layer, approximately 1.3 cm thick (1/2-in.), placed between the block and the porous plate will ensure that good hydraulic contact is maintained between the rock and the plate and will reduce pressure buildup in the vicinity of the fractures due to plate impedance.

Approximate fracture locations within the test block will be determined by projecting fracture traces from the sides of the block into the area where a drill hole would intersect. The drilling will then be advanced until it is within 2.5 cm (1 in.) of the expected location of the fracture. At this point, a mechanical packer assembly will be inserted into the borehole to a depth that is approximately 0.65 cm (1/4 in.) from the bottom, and air will be injected through the mandrel of the packer. A constant air pressure will be maintained in the test interval, and the flow rate will be allowed to vary. In intervals devoid of fractures, the flow rate will eventually decay to a very low value dictated by the matrix permeability. Drilling and air-injection testing will be advanced in 0.65-cm (1/4-in.) increments until a significantly higher steady-state flow rate indicates that the fracture has been intersected. The equivalent pneumatic aperture can then be computed for the fracture, and these results used to calibrate a preliminary numerical model of the subsequent percolation test. A downhole video camera will be used to verify the location of the fracture and to determine if more than one fracture exists within the test zone.

Cross-hole pneumatic testing will also be used to determine directional permeabilities within the block. In this method, a steady-state test is conducted at several flow rates, and stabilized pressures are measured at the injection well and observation well for each flow rate. The directional permeabilities are calculated by fitting the observed results to type curves determined from analytical solutions. The cross-hole testing apparatus will be constructed with five major components: (1) a nitrogen gas source, (2) flow regulating and monitoring manifolds, (3) gas injection lines, (4) a minimum of two straddle packer systems, and (5) a data monitoring and recording system.

Fractures or fracture zones that have been intersected by a borehole and identified by one of the previously mentioned methods will be instrumented with tensiometers. These tensiometers will be used to measure the change in matric potential that occurs when a fracture moves from a no-flow to flow condition. Because of their small diameter, each borehole will probably contain only one tensiometer system. The remainder of the borehole will be sealed with packers, thereby ensuring that fractures do not communicate via the borehole. The stainless-steel body tube, on which the porous cup is mounted, will be threaded through the center of the packers. Additional boreholes would need to be drilled in order to instrument all of the fractures intersected by the borehole (Figure 4.11-1).

Historical Perspective and Background

The percolation tests in the ESF have been conceived to provide experimental data against which the validity of numerical

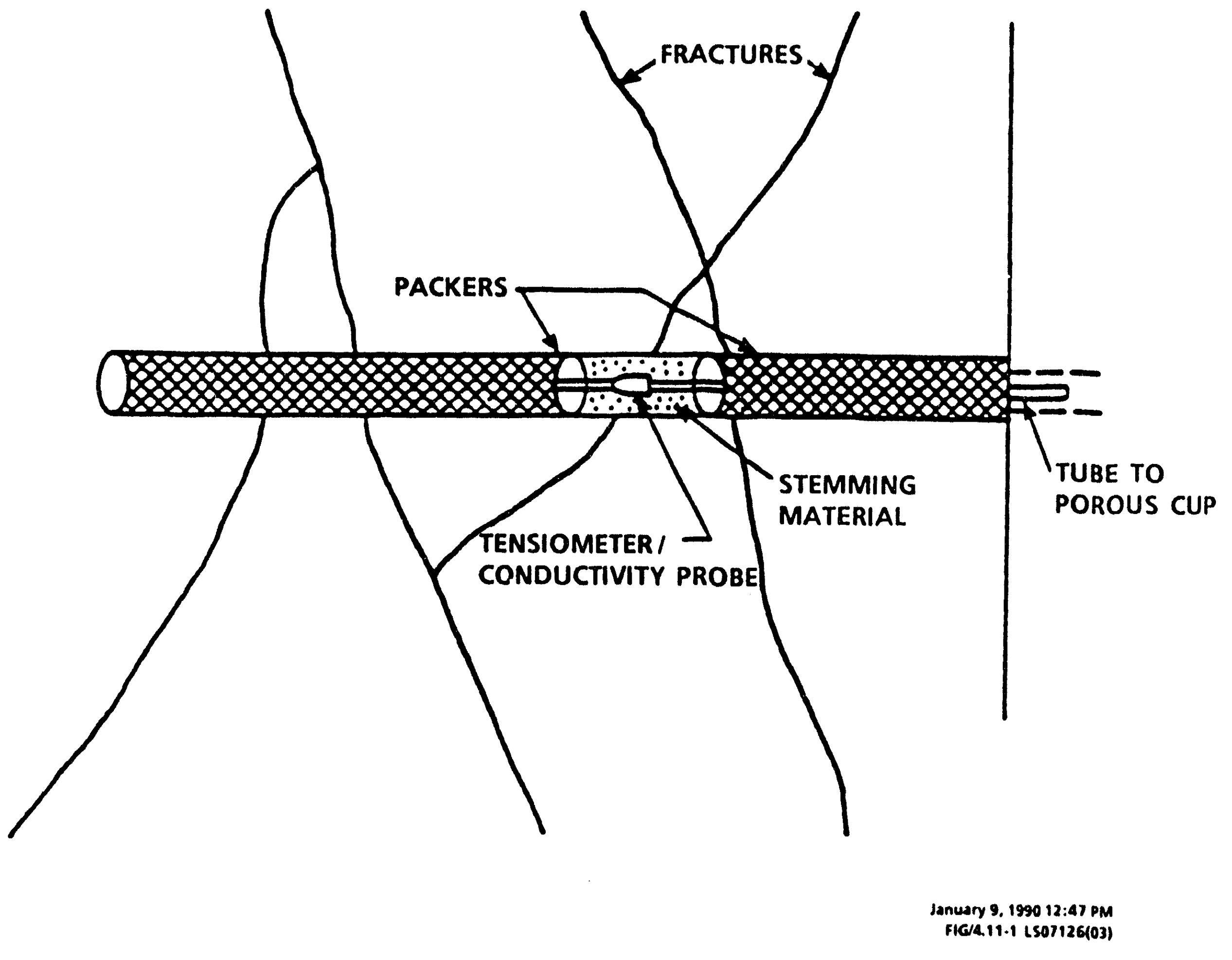


Figure 4.11-1. Borehole-fracture intersection instrumented with tensiometer/conductivity probe and isolated with packers.

and conceptual models for simple fracture networks can be tested. The prototype percolation tests have been designed to develop the necessary experimental and theoretical tools for the exploratory shaft testing program.

As originally described in the scientific investigation plan,[12] this prototype test required two phases of testing: laboratory and G-Tunnel. More recently, scoping calculations and continued planning have resulted in the elimination of G-Tunnel testing from the test plan. More emphasis will be placed on laboratory analyses, which will be conducted in the Denver Federal Center Building 20. At the USGS's fractured-rock hydrology laboratory large block samples of fractured, welded tuff have been transported from Yucca Mountain to the laboratory. These blocks will be used for the integrated prototype test of the instruments, infiltrometer, and data acquisition systems.

Evolution of Test Design

The prototype percolation test has evolved from an in situ sand bed infiltrometer test in the GTUF to a laboratory test on large block samples using a low-volume sprinkling infiltrometer. A sand bed infiltrometer does not provide adequate means of introducing and maintaining low infiltration rates in a rock that has the extremely low hydraulic conductivities of a densely welded tuff. The experiment will be performed with steady-state conditions at varying saturation levels in rock matrix and fractures. Ideally, infiltration rates will be decreased (from saturated hydraulic conductivity) incrementally over a range at which various fracture flow and matrix interactions can be observed. This will provide a means to measure enough water content and potential values to determine moisture retention curve relationships.

Computer modeling using VS2D (an integrated finite difference, variably saturated flow computer code) has been performed. The results show that the likelihood of obtaining steady-state moisture conditions in the rock mass will be highly dependent on fracture spacing and, of course, on boundary conditions. The prototype percolation test has been designed to control and vary the boundary conditions of the test block (in the laboratory and field). Block samples with simple fracture networks have been selected. Preliminary air injection tests will provide information on fracture permeabilities and apertures. The experimental design requires the ability to differentiate the fracture flow component from that of the matrix. Techniques of instrumentation of fractures to measure qualitatively water content and water potential are being developed.

Conduct of Test

The prototype work conducted during the year involved developing instrument and data acquisition techniques, testing and calibrating instruments in small block samples, preparing computer models, and acquiring large blocks of tuff samples to work with in the laboratory. These activities, which were done in preparation for the prototype laboratory test, are essentially completed. Prototype testing could begin once all remaining test equipment has been delivered, constructed, and calibrated.

Future Activities

Future activities include the actual prototype testing in the large infiltration block. This will be conducted in the unsaturated-zone, fractured-rock hydrology laboratory at the USGS office in Denver, Colorado.

The first step in the prototype percolation test will be to saturate the block to the maximum extent possible by ponding water directly on the surface of the block. Outflow collected from the bottom of the block will be de-aired and recirculated. Water should move through the fracture network and be imbibed from the fractures into the matrix. Small amounts of air are expected to be trapped and compressed within each of the fracture-bounded matrix blocks as the wetting front advances from the saturated fractures toward the centers of the blocks. Based on preliminary computer modeling, it is believed that this small amount of compressed air will not significantly alter the results of the test.

Steady-state conditions are considered achieved when the rate of inflow into the block equals the rate of outflow (within a certain tolerance). The saturated bulk-rock conductivity and the associated percolation rate are determined in this first phase of the test.

The sand bed and flow tank apparatus will then be installed on the upper surface of the test block, and the ceramic (or metal) porous plate will be attached to the base of the block. Water will be applied to the sand bed surface by using a sprinkling infiltrometer with a spray nozzle. At high percolation rates, water movement at the base of the sand bed will have a strong horizontal component because the water will tend to pond above the intact matrix blocks and drain into the intervening fractures. Sand, with a high saturated conductivity, will keep these lateral pressure gradients small. This will cause the matric potential at the base of the sand and within the upper part of the block to be relatively uniform. Saturated conductivity of the sand should be larger than measured bulk-rock conductivity.

When the sand bed and porous plate are in place, water will be infiltrated into the sand bed at rates less than the saturated conductivity of the rock mass. The block, and particularly the fractures, will have drained somewhat as the sand bed and porous plate were being installed. However, steady-state conditions can be re-established fairly rapidly at the new percolation rate because the matrix will have drained only slightly. Because the matrix remains at near-saturation conditions over the range of matric potentials in which fracture flow is thought to be important, very little water needs to be drained from or added to the matrix to maintain pressure-potential equilibrium between the fractures and the matrix. Therefore, the system should equilibrate quite rapidly to altered boundary conditions once the initial saturation phase has been completed. By measuring the average matric potential and average hydraulic gradients at steady-state for successively lower applied-percolation rates, the composite conductivity-matric potential relationship of the block can be established. Because it becomes increasingly difficult to re-establish steady flow (or for that matter to measure fluxes) when flow is primarily through the matrix, the percolation test will focus on that portion of the composite curve above and just below the so-called critical point. This is the matric potential at which the fracture and matrix contributions to the total flux are equal, and below this potential, the fracture contribution to the total flux becomes less significant.

After steady-flow conditions have been established at a given percolation rate, a conservative tracer, such as potassium bromide, will be added to the in-flowing water. The effective porosity (or more precisely, effective water content) of the block at that flow rate can be determined by dividing the Darcy flux by the length of the block and multiplying the result by the time required to observe an effluent concentration that is half the input concentration. Effective moisture content—that is, the water-filled pore volume available to solute moving through the rock—is believed to be a function of the flow rate, becoming smaller with increased fluid fluxes. Effective moisture content is essential to the calculation of groundwater travel time.

4.12 Bulk Permeability

General Test Description

Prototype testing of the bulk permeability test is necessary to determine the appropriate design of the experimental apparatus and to ascertain the feasibility of conducting air permeability tests at a variety of scales within fractured, welded tuff. Prototype testing will consist of (1) designing and testing the straddle-packer manifold system; (2) calibrating and testing the instrumentation package; (3) drilling, permeability testing, and tracer testing four boreholes located in a thick unit of welded tuff and arranged in a frustum geometry; and (4) evaluating the resultant field data. Permeability testing will consist of single-hole nitrogen-injection tests, cross hole nitrogen-injection tests, and frustum air-injection tests.

Although the prototype bulk permeability test and prototype cross-hole test are both involved in taking air permeability measurements, the objectives of these tests, and therefore the designs, are different. The cross hole test will be checking equipment, test procedures, test design, and theoretical concepts for the cross-hole test method that will be used in the radial boreholes test and excavation effects test. In the bulk permeability test, the cross hole testing method will also be used; however, the basic equipment, test procedures, and test design will be modified to accommodate the objectives of the bulk permeability test. Areas of concern that will be addressed in the bulk permeability test, but not in the cross-hole test, include (1) the effectiveness of variable scale testing, (2) the procedure for conducting in situ gaseous tracer testing, (3) the variation in aperture distribution with interval size, (4) and the evaluation of modeling approaches.[13]

Purpose and Objectives

The purposes of the prototype bulk permeability test are to prove the theoretical concept, test the equipment and instrumentation design, and determine the feasibility of analyzing data for the frustum test; to determine that a cross-hole flow test can be conducted in a reasonable time frame, if at all, on a large scale; to determine the initial feasibility, appropriate concentration levels, injection pressures, and testing procedures for in situ gas-tracer testing; and to evaluate the methods of analyzing data. The results of the prototype bulk permeability test will be used to ascertain whether or not the test design is practical and what modifications in instrumentation and data-acquisition equipment are required to ensure success in the ESF bulk permeability testing program.

Support Required

The test bed construction will require coring four boreholes of specified depth and orientation after the completion of an area geologic field map. Operational equipment for conducting the tests will include a straddle-packer system, flow-controller manifold, pressure-injection manifold, and data-acquisition system. Measurement equipment will include thermistors, pressure transducers, mass flow controllers, and psychrometers. The tests will require a nitrogen gas supply at the test location.

Detailed Test Description

Borehole Configuration

Four boreholes are required to conduct the permeability testing. Each borehole will have an inside diameter of 98 mm (3.87 in.)(HQ) and will be 32 m (106 ft) long. Boreholes will be arranged in a frustum, or conical volume, geometry to maximize the number of permeability tests that can be conducted at various scales and orientations with a minimum number of boreholes (Figure 4.12-1). The center borehole will be drilled horizontally, and the three surrounding boreholes will be drilled outward from near the center borehole at an angle of approximately 25° to the center borehole. The radial distance between the center borehole and the three surrounding boreholes at the collar will be 1.5 m (5 ft).

Matrix Properties and Fracture Location Testing

Drill cores will be collected from the center borehole and used to define lithology, determine fracture characteristics, and provide a sample of the matrix for physical and hydraulic properties testing in the laboratory.[14] Core logs will include lithologic descriptions (mineralogy, welding, alteration), fracture locations, fracture type (open, closed, natural, drilling induced), fill material type (if present), fracture trace (regular or irregular, continuous or discontinuous), and fracture-wall description (rugose, smooth, polished). The rock-matrix physical properties testing will include pore-size distribution, welding, grain density, bulk density, and porosity. Hydraulic properties testing will include moisture content (gravimetric and volumetric), water potential, matric potential, and moisture retention. These data are required in order to analyze permeability test results.

All four of the boreholes will be cleaned and logged using a neutron moisture meter and a video camera. Neutron logs will be used to determine the ambient volumetric moisture content of the surrounding rock before fluid injection. Video logs will be used to view changes in lithology, locate open and closed fractures, estimate in situ fracture apertures, and determine fracture orientations. Video logs will also be used to identify packer seats during permeability testing if borehole sealing becomes a problem.

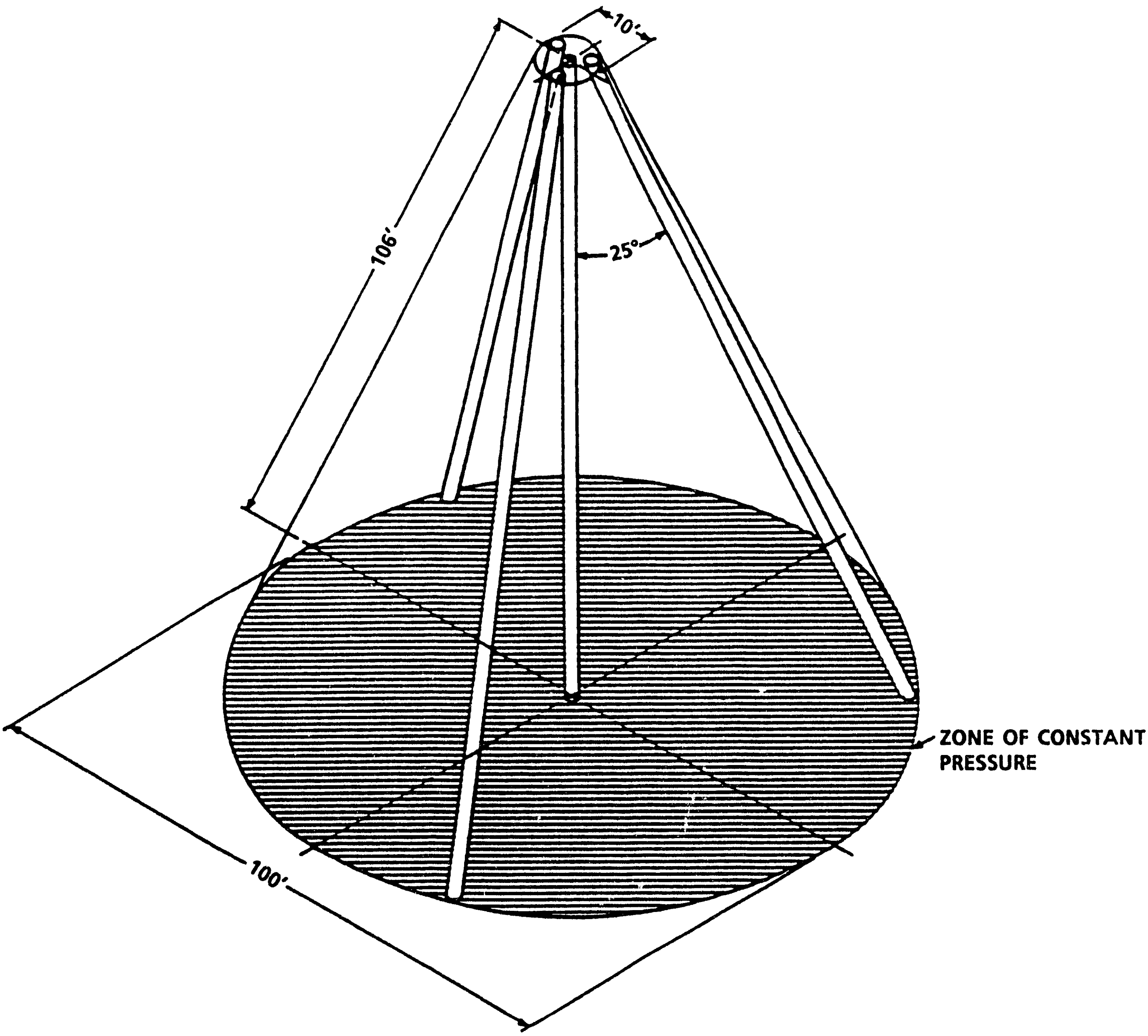


Figure 4.12-1. Frustum borehole configuration.

A steady-state pneumatic test will be conducted at regularly spaced intervals throughout the length of all four boreholes in order to locate fractures and permeable zones for cross-hole testing and to apply an appropriate modification of Snow's method of determining the spacing and aperture distributions of open fractures. This testing will consist of injecting gas into a 0.3-m (1-ft) test interval at a constant pressure and observing the flow response. If an open fracture exists in the test zone, flow response will stabilize at a high flow rate. If an open fracture is not present, flow rate will drop off significantly while injection pressure remains high. Nitrogen gas will be used for the injection fluid. An on-line mass flow meter will be used to monitor mass flow rate, and a pressure transducer will be used to monitor injection pressure. These sensors will be connected to a data logger to provide continuous monitoring during testing. The manifold and straddle-packer system developed for cross-hole testing will also be used for this test.

Cross-hole Testing

Cross-hole testing will be used to determine the three-dimensional hydraulic conductivity tensor of the rock mass. The test procedure consists of injecting nitrogen into an isolated test interval within the injection borehole and monitoring in the nearby observation boreholes the formation's response to the change in fluid pressure (see Figure 4.12-1). The steady-state test is conducted at several flow rates, and stabilized pressures are measured in the injection borehole and observation borehole for each flow rate. A minimum of six observation intervals, arranged in an appropriately three-dimensional pattern, are required to define the hydraulic conductivity tensor. Directional permeabilities are calculated by fitting observed results to type curves determined from analytical solutions.

Cross-hole tests will be conducted in two stages to maximize the variety of scales at which testing can occur, and thus provide the most data possible for determining the scale at which the rock mass behaves as an equivalent porous medium. The first stage will consist of drilling the three peripheral boreholes that diverge from near the center borehole at an angle of approximately 25°. Cross-hole testing will be conducted as a series of tests wherein each borehole is used as the injection borehole, with the other two boreholes being used as observation boreholes. The second stage will consist of drilling the center borehole to cut the distance between the peripheral boreholes in half. Cross-hole testing will then be conducted at the reduced scale in the same manner as the first stage. This prototype testing of the cross hole method is required because rock mass parameters such as fracture length, interconnectiveness, and conductivity are unknown. Therefore, it must be determined whether or not the cross-hole testing method is capable of achieving measurable pressure changes between widely spaced boreholes.

The test equipment required to conduct cross-hole pneumatic tests consists of a gas source, a flow regulating manifold, a gas-injection line, a straddle-packer system, and a data-acquisition system. The fluid source will be compressed nitrogen gas, in cylinders, because it is portable, clean, readily available, inexpensive, nonbuoyant, nonflammable, and readily absorbed at low pressures. The nitrogen will flow from the cylinders through a flexible rubber hose to the flow regulating manifold. The manifold will consist of the required filters, valves, regulators, pressure gauges, and flow meters. Five mass flow meters will be placed parallel to a regulator located upstream from each meter to control flow volume, and a valve will be placed downstream of each flow meter to shut off flow. Upon leaving the flow manifold, the nitrogen will enter the fluid injection line, which will extend from the collar of the drill hole through the straddle-packer system to the test interval.

The straddle-packer system will consist of four inflatable packers placed in series and separated by spacer rods or well screens. During each test, one packer system will be located in the injection borehole and one in the adjacent observation borehole. The straddle-packer system located in the injection borehole will contain two guard zones bordering the test interval. These zones will be used to monitor fluid leakage from the test interval past the packers confining the test zone. In the observation borehole, the three zones between the packers of the straddle-packer system will be constructed so that individual packers can be removed from the system, thus making the string shorter. A shorter string might be required if the desired test interval lies close to the collar or bottom of the drill hole. The straddle-packer and manifold system will be prototype-tested during the prototype cross-hole pneumatic and hydraulic test (Section 4.6) and modified as required before the prototype bulk permeability test.

Three types of sensors will be located in the test, observation, and guard zones for monitoring in situ air pressure, air temperature, and relative humidity. The instruments are strain-gauge pressure transducers for measuring absolute pressures, resistance temperature detectors (RTD) for measuring temperature, and thermocouple psychrometers for measuring relative humidity. Piezoresistive strain-gauge pressure transducers are being used because they are small, rugged, sensitive, and relatively inexpensive. Resistance temperature detectors are being used because they are relatively sensitive, stable, and rugged. Screen-cage, single-junction Peltier thermocouple psychrometers are being used because under isothermal conditions they are very accurate in the 95% to 100% relative humidity (vapor pressure deficit) range. Before field testing, calibration curves relating water potential to microvoltage output will be generated for individual psychrometers for a range of salt solutions at various temperatures. Calibration curves of millivolts versus pressure will also be generated for pressure transducers. Electrical leads from sensors will be routed from test zones through packers (using gas-tight connectors) to the collar of the drill hole and will be connected to a data logger for continuous monitoring during testing.

Tracer Testing

During cross-hole testing, the permeability and storativity of the porous system will be determined. In addition, an evaluation of the bulk effective air-filled porosity is possible as storativity is directly proportional to the porosity of the system and the viscosity and compressibility of the gas. Tracers will be injected into the airstream during the cross-hole tests. The breakthrough curves from these gaseous tracer tests will be used to provide an independent evaluation of the effective porosity, as well as to quantify the pneumatic dispersion coefficients of the fracture system. The air-filled effective porosity will, in turn, be used to calculate the effective coefficient of diffusion of gases through the rock and, thus, evaluate diffusive transport.

The procedure for pneumatic tracer tests will be thoroughly evaluated during prototype bulk permeability experiments, and the utility of a gaseous tracer for calculating mass transport phenomena will be investigated. The introduction of a conservative tracer of constant concentration (C_o) at time (t_o) in the packed-off testing intervals will result in time-varying concentrations (C_t) of the tracer being monitored in the observation intervals. A plot of the ratio of observed concentration to initial concentration (C_t/C_o) versus time will render a breakthrough curve for that tracer. The tracer will be introduced (in known volume and concentration) through a flexible tube inserted into the packer system. Metering valves, mixing chambers, and pressure regulators will be utilized for this purpose. Gas composition samples will be collected intermittently from the observation intervals by using a syringe inserted into the gas tubing installed through the packer system.

An alternative method for collecting gas composition samples involves pumping the gas into a flow-through gas container. However, it is speculated that any prolonged gas pumping in the observation interval will change the pressure response and flow (transport) phenomena of the fracture system. Therefore, gas-composition sampling by syringe is preferred over collection in a flow-through cylinder, as the syringe method allows the sample to be injected directly into the gas chromatograph mass spectrometer for analysis.

Candidate tracers being considered are sulfur hexafluoride (SF_6), freon, and methane (CH_4). The final tracer, or combination of tracers, to be used during the bulk permeability test will be selected during prototype testing, with the selection based on availability, controllability, and detection limits.

Frustum Testing

The frustum test is a method for measuring bulk permeability at a scale large enough to represent the rock mass as a continuous, porous medium. The test procedure is equivalent to conducting a large-scale, single-hole injection and withdrawal test whereby air is injected into and withdrawn from boreholes under steady-state flow conditions. By monitoring pressure recovery, pneumatic permeability values and storativity can be determined for a rock mass.

Before testing, the first 9.3 m (30 ft) of each borehole will be packed off at the end of the borehole closest to the collar to minimize the permeable boundary effects of the relaxed zone. The remaining length of each borehole will be fitted with instruments and left open as the test interval. Instrumentation in test zones will consist of pressure transducers, resistance temperature detectors, and thermocouple psychrometers to monitor in situ air pressure, air temperature, and relative humidity during testing. Air will be used as the injection fluid, instead of nitrogen, because of the large volume required to simultaneously supply all four boreholes during injection and withdrawal. A compressor will be used to supply air during the injection test and a vacuum pump to remove air during the withdrawal test. A manifold system will be designed and constructed with the appropriate filters, gauges, mass flow meters, and valves to uniformly control flow from the compressor or pump to the four test zones. The downhole instrumentation will be connected to a data logger to provide continuous monitoring during testing.

Pneumatic testing will be conducted in two stages. The first stage will consist of withdrawing air simultaneously from the four test zones. After steady-state flow conditions are established, the flow will be shut off and equilibration monitored. The second stage will consist of injecting air into the borehole system. Again, after steady-state flow conditions are established, the flow will be shut off and the pressure system decay monitored. In both stages, the tests are simulating a large-diameter, single-hole injection test in which a zone of constant pressure is formed from the center out to the radius of the circle created by the ring of outer boreholes.

Prototype frustum testing test is designed to verify theoretical concepts, methodology, and instrumentation and equipment design. The theoretical concept of using four boreholes to simulate one large-diameter borehole, or test chamber, will be evaluated by monitoring the pressure response in each of the four boreholes during testing to determine if it is possible to obtain an equivalent steady-state flow response in the collective borehole system. The methodology of using the air injection-withdrawal and manifold system will be established, and technical procedures written. The accuracy, range, ruggedness, and reliability of the instrumentation will be tested, and the effectiveness of the interpretive methods evaluated.

Historical Perspective and Background

The prototype methods to be developed and tested in the prototype bulk permeability test are derived from current well-bore testing techniques used in the petroleum industry and in civil engineering. The single-hole, nitrogen-injection tests will provide an accurate means of determining fracture aperture and will make it possible to construct permeability-versus-potential curves. Cross-hole tests will provide an accurate means of determining directions of principle permeability; the frustum test will estimate bulk permeability.

A borehole approach is currently being proposed, instead of a chamber approach based on the results of scoping calculations. Because a practical limit of air injection into a test chamber is approximately 34.5 kPa (5 psi), the radius of influence is less than that obtainable from a borehole with injection pressures of over 172 kPa (25 psi). Therefore, more rock can be tested in the borehole approach, and a more accurate determination of bulk permeability can be made.

Evolution of Test Design

Technology currently available from the petroleum and civil engineering industries has contributed greatly to the evolution of the current proposed test design. The packer system has been designed to accommodate the test's need for a 0.3-m (1-ft) injection interval. Also, a downhole shutoff valve has been added to the packer system design to provide a means of testing the system for leaks in situ before testing. The associated packer-injection manifold and flow-controller manifold have also been designed. The required instrumentation and components for the data-acquisition system have been ordered. Construction of the packer system and associated manifolds is under way.

Conduct of Test

The startup of prototype bulk permeability test field work is contingent upon the progress of the following prototype testing programs:

- the prototype drill hole instrumentation test studies (for the development of borehole instruments and related data-acquisition equipment to be used in the prototype bulk permeability test);
- the prototype cross-hole test (for air-injection packer string assembly and related equipment development for the prototype bulk permeability test); and
- the prototype wet- versus dry-drilling test (for the study and determination of the most feasible method of drilling test boreholes in the prototype bulk permeability test).

Drill hole instrumentation studies concerned with the development and operating specifications of the instrumentation to be used in the prototype bulk permeability test were initiated in July 1988. These studies have involved the development of drill hole instrumentation methodology, design and fabrication of data-acquisition racks, design and fabrication of a data-acquisition system, neutron logging, and equipment alignment and calibration methods.

The air-injection packer string assemblies that are to be modified for use during the prototype bulk permeability test have been developed and tested in the prototype cross-hole test, which has been in progress since May 1988. These studies have involved the coring, sampling, and analysis of cored sections; the development of blind-hole survey methodology; the development, assembly, and calibration of test instrumentation; and deployment of the calibrated instrumented packer system.

The prototype wet- versus dry-drilling test used to determine the most feasible drilling methods in welded tuffs, specifically the determination of drilling methods that are least likely to adversely affect the rock materials in which the prototype bulk permeability test studies will be conducted, were initiated in July 1988. Data collected during this test primarily indicate that dry coring using air as the drilling fluid is both feasible and desirable for test bed borehole construction.

Future Activities

The prototype bulk permeability test field work, once initiated, will continue for approximately two years. The currently proposed location of testing will be the Edgar Mine in Idaho Springs, Colorado. These field activities will consist of single-hole, nitrogen-injection testing; cross-hole testing; frustum testing; and gaseous tracer testing.

4.13 Perched Water

General Test Description

This prototype test will develop methods for characterizing perched water zones should they be encountered during construction of the ESF. No major zones of perched water have been identified during any drilling or logging activities at Yucca Mountain. However, hydrogeologic properties of the tuff units are such that perched water zones could exist and might be encountered in the ES. This test will investigate and develop methods of measuring seepage rates of perched water into a shaft or drift, of measuring hydraulic heads within a perched water zone, of collecting representative water samples, and of conducting aquifer tests of saturated rocks within a perched water zone.

Purpose and Objectives

The characteristics of any zones of perched water that might be encountered in the ESF must be thoroughly evaluated because of the direct impact of these zones on performance assessment calculations. If methods for testing and characterizing perched water zones are not adequately developed, the suitability of Yucca Mountain as a potential repository site could be severely compromised. Perched water, if present, must be sampled to characterize its chemistry and to date the water, if possible. This information will assist in determining the source of the water. Some perched water zones might be artificially created by the loss of water from earlier drilling operations or from unexpected loss of water during construction of the ESF. Alternatively, water used in various experiments in the ESF could contribute to the formation of perched water zones. Although all ESF construction operations and experiments are being carefully designed to avoid such an event, it must be considered a possibility. Knowledge of the extent and hydrologic characteristics of any perched water zone encountered in the ESF is essential to understanding the occurrence and flow of ground water at the Yucca Mountain site.

The sampling and measuring equipment proposed for evaluating perched water zones in the ESF is standard equipment, but it might need to be adapted for specific application to the ESF. More important, scientists need to become more experienced in using various sampling and measuring techniques so that they can correctly choose which techniques to use and so that they can develop formal procedures for their use in the ESF.

Specific objectives of this prototype test are to develop

- methods for air drilling of boreholes to be used for sampling and testing zones of perched water;
- methods for installing monitoring instrumentation;
- methods for testing, sampling, and obtaining flow measurements of perched water zones; and
- detailed engineering and testing plans.

Support Required

Boreholes for testing instrumentation and procedures will be drilled in the G-Tunnel at selected locations where perched water is known to exist. Preliminary development of equipment and calibration of instrumentation will be conducted in the laboratory.

Detailed Test Description

This prototype test will consist of a series of activities to develop and test equipment and instrumentation for collecting information used to characterize any zones of perched water that might be encountered during the construction of the ESF. The major components needed for characterization are flow and hydraulic head measurements, water samples, and hydrologic conductivity tests. The activities will be conducted in three phases: preparatory work and laboratory testing, field testing, and evaluation of results in order to prepare formal sampling and testing procedures.

Proposed field tests constitute the bulk of activity under this prototype test. Methods must be developed for accurate measurement of flows or seeps from perched water bodies into shafts or drifts. Such flow might be concentrated in small channels, such as fractures, where measurements are relatively easy or might emerge from the matrix of the rock, in which case some means of concentrating the flow will be necessary in order to perform measurements.

Samples of perched water must be collected both from free-flowing seeps, as previously described, and from boreholes drilled into the zone of perched water. Various orientations of boreholes will be evaluated to establish optimal orientations with respect to observed fracture patterns. Both pumps and suction devices will be evaluated as possible means of borehole sampling. Pore water will be extracted in the laboratory from some core samples by using uniaxial or triaxial compression (Section 4.15). The chemical composition of this water will be compared with that of water collected from boreholes or drift faces. The comparison will provide some insight into the usefulness of pore water extraction methods in determining in situ water chemistry.

Locations for evaluating borehole test methods will be selected to permit testing of both discrete fractures and larger zones consisting of matrix and fracture porosity. The test evaluation will consider both single-hole and cross-hole methods of conducting pumping tests that determine hydrologic characteristics. Methods for long-term monitoring of hydraulic head changes will be tested, and the data will be compared with changes in flow into the drift.

Subsequent to field testing, all collected data will be analyzed to establish their usefulness. From this analysis, the preferred methods for characterization will be selected and formal procedures developed to guide testing in the ESF.

Historical Perspective and Background

The proposed methods for perched water testing were chosen on the basis of prior experience with perched water testing in tunnels in Rainier Mesa at the NTS. The monitoring and sampling equipment being used is standard equipment used for hydrologic testing and is commercially available. Two types of packer and instrumentation systems are being tested and evaluated. One of the systems will be chosen for use in the ESF in the event that perched water is encountered.

Evolution of Test Design

Minor modifications were made to the proposed test design before field implementation. Thermocouple psychrometers were eliminated from the instrument package. Tensiometers will be installed in drift walls where water seeps are observed. These tensiometers will provide data on how perched-water zones change over time in response to changing hydrologic conditions in the unsaturated zone.

Conduct of Test

A criteria letter for the proposed field testing was approved, and field work was started in April 1989. Field work began in the G-Tunnel on May 10, 1989. Several boreholes were cored at welded and nonwelded tuff locations. Borehole stability problems prevented instrument package installation and redrilling was required. Sample collection procedures and instrument package installation, calibration, and monitoring was completed.

Future Activities

Reliability testing on the instrumentation packages and a long-term sampling program was in progress when the G-Tunnel facility closed. Finalization of procedures and fabrication of instrument assemblies and packers based on prototype test results continues.

4.14 Dry Coring of Rubble

General Test Description

During site characterization at the ESF, investigators will need rock samples to determine pore water chemistry. It must be demonstrated that the techniques for obtaining the rock samples do not affect the results of the water analyses. Consequently, the prototype dry coring of rubble test is being developed to determine if dry coring (air coring), when used to collect rock core samples, affects the results of subsequent geochemical tests. Because blast rubble will be available for sampling in the ESF during construction, it is desirable to perform this test with rubble from welded and nonwelded tuff to approximate the sampling conditions at the ESF and to determine if rubble is an appropriate sampling medium.

This prototype test will be performed on blast rubble obtained at the G-Tunnel at the NTS, where welded and nonwelded tuffs similar to those at Yucca Mountain are available for sampling. Dry coring will be performed on rubble, and the pore water will be extracted and analyzed.

Purpose and Objectives

The purpose of the dry coring of rubble prototype test is to develop a coring technique that will have little or no effect on the pore water chemistry of the sample rock. During the test, problem areas will be identified and assessed. The approximate time required and the cost of dry coring of rubble will be determined also. The primary objective is to obtain, modify, or develop a coring machine that will produce smooth, unbroken cores of the appropriate sample size that are not heated excessively during coring. Excessive heating could reduce the amount of pore water obtained and could alter water chemistry. Another objective is to demonstrate that Principal Investigators (PIs) can successfully obtain some cores that are oriented either perpendicular or parallel to the rock fabric and some cores that are oriented parallel to the direction of fluid flow.

Support Required

The chemistry analyses will be performed in USGS laboratories and Rocky Mountain Analytical Laboratories, except for the tritium analysis, which will be performed at the University of Miami. The materials required for obtaining the samples will be provided primarily by the USGS, the USBR, and H&N. Contractor-supplied coring machines will be used for dry coring.

Detailed Test Description

The prototype dry coring of rubble test uses blast rubble from the G-Tunnel on the NTS and, for comparison, cores obtained from unblasted rock at the G-Tunnel. Both welded and nonwelded tuffs are sampled in both cases. Samples for geochemical analysis are obtained by both dry coring and by chipping the rock with a chisel to determine the effect, if any, of drilling on the analytical results. Pore water can be extracted from the samples by triaxial compression or, if this is not possible, by centrifugation. Pore water is analyzed for specific conductivity, pH, cations, oxygen and hydrogen stable isotope ratios, tritium, and anions. Gas samples are also extracted and analyzed for carbon dioxide, methane, sulfur hexafluoride, nitrogen, and volatile organics.

The results of the geochemical analyses will be evaluated with computer statistical and graphics programs to determine any differences between blast rubble and samples from other sources, such as drill cores, and between cored and chipped samples. The chemical results will not be used for site characterization at Yucca Mountain. The data will be used to develop a sampling technique for pore water characterization studies at Yucca Mountain.

Historical Perspective and Background

Because wet-coring methods might introduce fluids that can alter the hydrological characteristics of the rock at Yucca Mountain, prototype tests are being developed to assess the feasibility of using dry coring for site characterization studies. After construction of the ESF has begun, blast rubble will be available for sampling. This rubble may provide a means for collecting water samples that cannot be obtained from some drill cores. However, it must be determined that chemical or physical effects of the blasting do not alter the basic properties being studied. Obtaining smooth rock cores from the rubble is desirable, because the preferred water extraction technique, triaxial compression, requires smooth, unbroken, unfractured samples. It must be demonstrated that dry coring of the rubble is feasible and that the coring technique does not alter the basic properties of the pore water chemistry. Consequently, the dry coring of rubble test is being developed to make these determinations before ESF construction begins, thus avoiding delays or unnecessary efforts during actual site characterization if the dry-coring technique does not prove feasible for blast rubble.

Evolution of Test Design

The original plan was to obtain a sawed cube, .3-m (1-ft) square, from the G-Tunnel; this plan was changed to a .3-m-(1-ft-) diameter core. The large sample obtained in both the welded and nonwelded tuff locations will be tested in the laboratory and compared hydrochemically with blasted samples.

Conduct of Test

Preparatory administrative actions for the dry coring of rubble test were begun in January 1989. In April 1989, large cores were recovered from the welded and nonwelded tuff units in the G-Tunnel. Nonwelded rubble was collected, and coring was begun by both H&N and USGS to test the effects of the advancement rate, method of cooling, and revolutions per minute for the coring device on pore water chemistry.

Future Activities

Future activities will consist of continuation of the sampling and analysis as planned. Any changes to the planned conduct of the test as a result of practical considerations or analysis results will be incorporated as needed.

4.15 Pore Water Extraction

General Test Description

The pore water extraction experiments are part of the broader category of characterization tests that are performed in order to determine the properties of the repository rock and the fluids it contains. Specifically, this test involves compression of tuffs by equipment designed to put high pressure on the rock and to collect interstitial fluids that are squeezed from the rock. These fluids are then analyzed to determine the chemistry of the natural pore waters. Determination of pore water composition is a site characterization activity that is fundamental in assessing waste package performance and in addressing questions pertaining to the behavior of radionuclides in the unsaturated zone. Compression of the rocks will be accomplished by uniaxial and triaxial compression equipment.

Prototype testing will be designed and conducted at the USGS Denver Federal Center and the G-Tunnel and involves field, laboratory, and analysis activities. Field work includes the collection, preservation, and, if feasible, the dry coring of rubble samples. The suitability of rubble samples for dry coring is being evaluated in other prototype tests (Sections 4.9, Prototype Optimal Rubble Size test, and 4.14, Prototype Rubble Coring test). As part of the laboratory work, the equipment that will be used to compress the tuff samples is set up and calibrated. The actual testing, which includes the compression of the tuffs and the extraction and chemical analyses of the water will be done in the laboratory. Dry coring of rubble samples will be performed in the laboratory if coring in the field proves to be infeasible.

Purpose and Objectives of Test

The primary purposes of this prototype test are to establish the technical feasibility of, and develop operating procedures for, pore water extraction by triaxial and uniaxial compression of cored rubble samples; to identify and assess problem areas that could compromise the accuracy of test data; and to determine the time required for and the cost associated with the conduct of the compression tests. The prototype tests will duplicate as closely as possible planned ESF activities in order to anticipate and solve potential problems. As a result of the prototype pore water extraction tests, equipment and procedures will be developed that will perform as planned within the restrictive time constraints expected in the ES testing program.

Extraction of pore water by using triaxial or uniaxial compression is being developed and evaluated. If pore water chemistry is found to be significantly affected by the compression process or if the water extracted is of insufficient volume to allow analysis, then another method for determining pore water chemistry must be developed before ESF construction is begun. The prototype extraction tests described here will help to ensure that usable moisture samples can be obtained during site characterization activities at the ESF and that a reliable determination of the chemical composition of pore waters is possible. The study should help enhance the ability to core satisfactory blast rubble samples and will reduce the number of rock cores sampled to a manageable number.

The objectives of this prototype test correspond to the major subtasks involved: the compression and water extraction experiments, core sampling and coring techniques, and analysis. Generally stated, the objectives are

- to develop technical procedures for pore water extraction by triaxial compression of cores;
- to extract water from welded and nonwelded tuffs of various saturations and in different core orientations;

- to determine if high confining pressures will prevent the brittle failure of welded tuff samples under compression;
- to determine the magnitude of changes in tuff mineralogy and pore water chemistry as a result of the extraction process (this determination will be accomplished by comparing pore structure to mineralogy at increments of compressive stress);
- to determine whether a particular orientation of the rock under compression is more favorable than others for water extraction; and
- to determine the relative effects of compression on welded versus nonwelded tuffs.

Support Required

The extraction process requires samples that can be cored and that are suitable for the compression tests. Previously, rock samples used for pore water extraction tests have been obtained from vertical drill holes. However, concerns that the drilling process may change the saturation and composition of pore waters have shifted emphasis toward blast rubble as the best potential source for unaltered rock samples. In the ESF, blast rubble will be available for sampling. Activities in the prototype optimal rubble size test (Section 4.9) and rubble coring test (Section 4.14) are closely related to the sampling activities planned under this pore water extraction test. These studies are required to determine whether the centers of large fragments of rubble are sufficiently unaltered by the blast process to permit representative samples to be obtained and whether this unaltered zone can be air-cored to provide a sample that is acceptable for use in the compression and extraction test.

The prototype controlled blasting test (Section 4.16) and blast effects test (Section 4.5) will provide the rubble necessary for the sampling activities of the prototype pore water extraction test. Rubble collection and block sampling in the G-Tunnel will be done by REECo. The USBR and the US Bureau of Mines (USBM) will core the rubble to make the samples for the extraction tests. Procedures and equipment developed in the prototype air-coring test will be used for the rubble-coring operations. Triaxial press work is to be performed by the USBR, USGS, and possibly by H&N at the NTS.

Detailed Test Description

In a triaxial cell, fluid pressure is applied to compress and confine the sides of the sample while the largest stress is applied to the ends of the sample to compress it longitudinally. Because the sample is being actively compressed on all sides, the test is said to be triaxial. The sample is enclosed in a urethane sleeve to isolate the rock from the fluid that is used to apply the confining pressure. The uniaxial test (Figure 4.15-1) differs in that compression is applied only to the ends of the sample and is not actively applied to the sides. The geometry of the cell itself encloses the sample and prohibits the expansion of the sample perpendicular to the axis. Triaxial compression is effective on samples that deform in a ductile way, such as nonwelded tuffs. Welded tuffs tend to break at high compressive stress and may rupture the sleeve that seals them from the fluids used to apply confining pressure. Therefore, the uniaxial method is considered better suited for use on welded tuffs and is being developed and refined as part of this prototype test.

Historical Perspective and Background

Besides the compression method, two other methods can be used to extract pore water from core samples: high-speed centrifugation and vacuum distillation. The centrifugation method uses the large forces developed in a high-speed centrifuge to force water out of a sample.

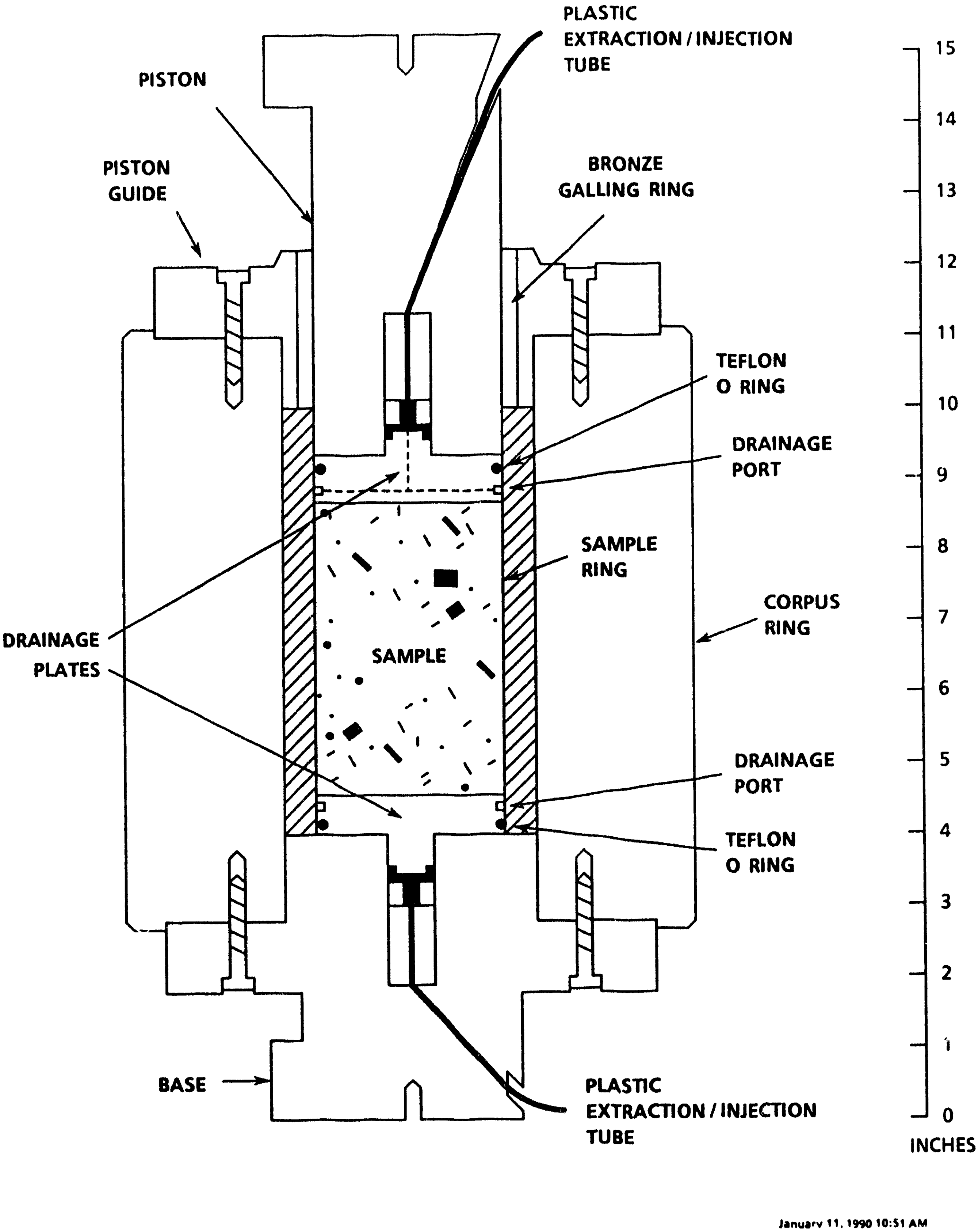


Figure 4.15-1. Uniaxial compression cell with sample.

As an alternative to simply forcing the pore fluids out by acceleration, fluid recovery may be enhanced by introducing an immiscible fluid into the rock pores to displace the pore fluids. The distillation method involves heating the sample under a vacuum and condensing the vaporized water in a low-temperature trap.

Triaxial compression is preferred over the vacuum distillation method because the distillation process produces deionized water, which is of very limited use in characterizing in situ pore waters. The compression method is favored over the centrifugation techniques for the following reasons:

- The effects of forces acting on the sample during compression in a testing cell are better understood than the effects that occur during centrifugation.
- Gas can be recovered from pores of the sample by using the compression method but not by centrifugation. Data on the composition of the gas are useful in pore fluid characterization.
- Whereas compression does not introduce fluids into the sample, trace water present in an immiscible fluid used in centrifugation could affect the chemical composition of the pore water.

Evolution of Test Design

A method for extracting matrix water from nonwelded tuff was developed and refined during a series of triaxial compression tests on cores from UE-25 UZ 4 and UE-25 UZ 5. Emphasis was placed on using the shortest possible test duration at the lowest differential compressive stress consistent with collecting adequate volumes of fluid. Short test durations have the advantage of reducing the time available for reaction between the pore fluids and the mineral surfaces that are freshly exposed during compaction. Using low differential stress levels reduces the potential for extracting waters bound up in zeolites and smectites.

The ability to extract water from a sample was found to be affected by the initial water content of the sample and the duration of compression. Efficient extraction from core samples containing more than 15% water generally can be achieved over a period of about 2.5 hours at low to moderate pressures. Successful extraction was not generally demonstrated for samples containing less than 13% water. The investigators determined that the compressive stresses must be applied in a gradual manner to avoid developing excessive fluid pressures in the rock and the potential for brittle failure.

The experiments showed that the composition of extracted water was affected by the stress levels applied to the sample. Preliminary interpretations based on limited chemical data indicate a few distinct trends in the composition of extracted pore water relative to the magnitude of the differential stress that was applied to the sample. These trends are shown in Figure 4.15-2. As axial pressure increased, the concentration of silica and sodium in the expelled fluids increased, calcium concentrations declined, and at moderate to high pressures chloride concentrations increased. Based on these findings, it is essential that the prototype tests determine the range of compressive stresses that will produce adequate volumes of recovered fluid but will not affect pore water chemistry.

An encouraging finding of the early work is that adding of nitrogen gas at the top of the sample chamber during maximum compression substantially enhanced fluid recovery because the gas displaces pore water. This finding will be explored during prototype testing. The experiments described above were performed on nonwelded tuffs using axial compression techniques.

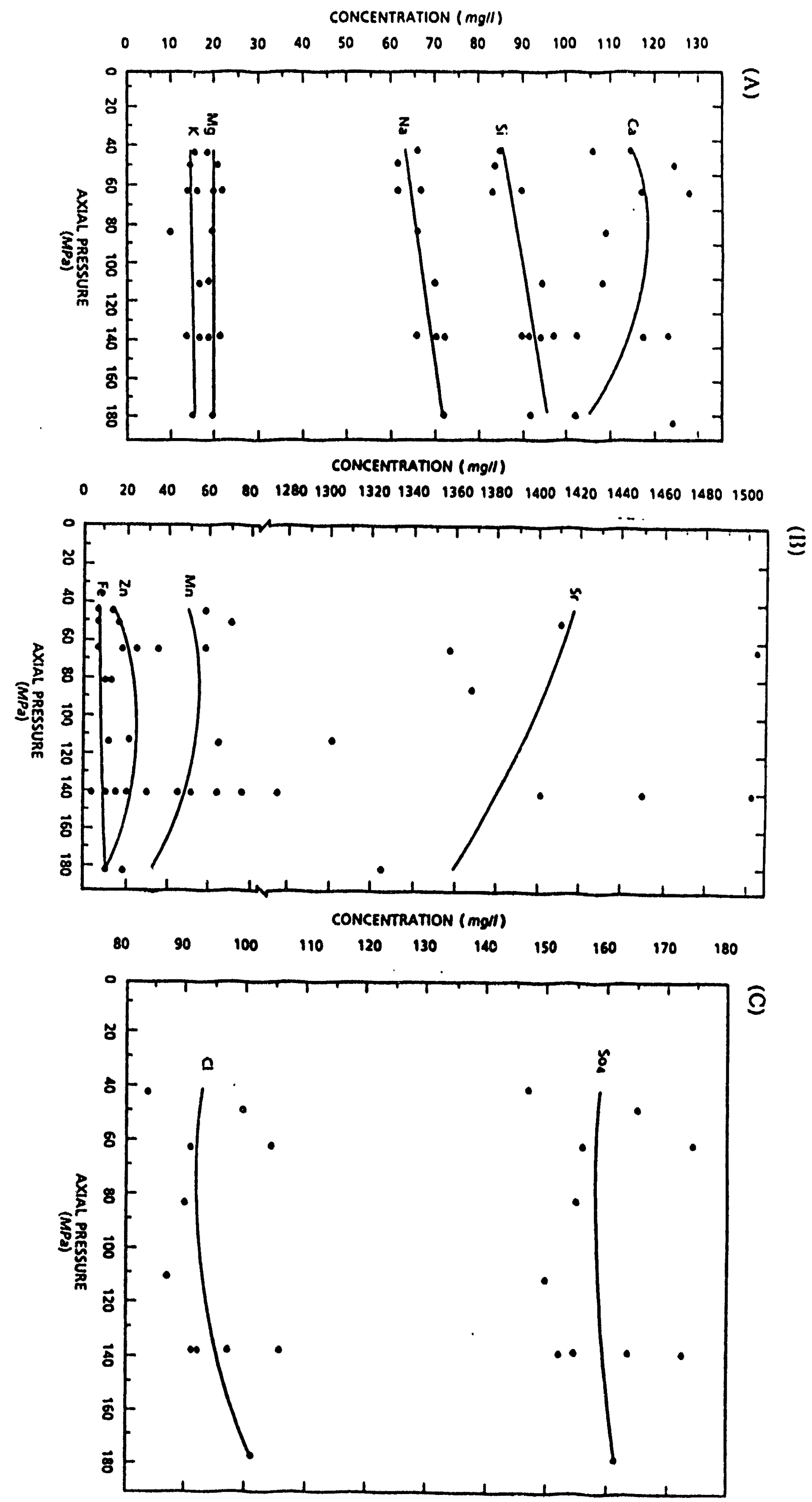


Figure 4.15-2. Trends in chemical composition of extracted pore water versus axial pressure applied during compression for nonwelded tuff samples.

Trial extraction experiments revealed that most samples exhibited macroscopically ductile behavior and that pore water was expelled quickly from the tuff at low to moderate pressures. This expulsion was probably the result of initially rapid pore collapse that forced water from the interstices of the tuff. Extracting pore water from welded tuff is more difficult because the rock is more brittle and tends to break under high compression. When the rock breaks, the pressure seal enclosing the sample (in a triaxial rig) ruptures. To overcome this problem, a uniaxial compression system similar to one used to extract water from concrete is being fabricated. Because there are no seals that can be compromised, a uniaxial rig should be acceptable to extract pore water from samples that are likely to break or crumble during compression. The findings from these earlier tests are the basis for the design of the prototype pore water extraction tests.

Conduct of Test

Activities so far have focused on developing the core rubble equipment to produce acceptable samples for the extraction experiments and on the development of equipment, software, and procedures to perform the tests. A coring frame and box have been completed by the USBR. The load cell and load frame have been calibrated, and materials have been collected to test the load frame. PIs are developing test procedures and preparing software to control the load frames.

Recent work on extraction of pore water has concentrated on three aspects of the research: (1) improvement of the uniaxial test procedure by using nitrogen injection, (2) completion and shakedown testing of the uniaxial cell, and (3) extraction of pore water from welded and nonwelded tuffs by uniaxial methods.

Experiments with the triaxial method included adding a nitrogen injection system to the method. The investigators found that when the triaxial test is at the maximum axial stress, after water expulsion ceases and the core stops compacting, additional pore water can be extracted by injecting nitrogen gas into the pore space and forcing out pore water. In this method, nitrogen pressure ranging from 1.4-4.1 MPa (200-600 psi) is applied from a nitrogen tank. The amount of time required for water to be expelled by nitrogen injection depends on the final saturation state of the core and the core permeability. Cores that already have produced water by compression alone often yield water as a result of nitrogen injection within a few minutes after injection begins; cores that have not produced water by compression may require more than 1 hour of injection before any water is recovered. The permeability of the core matrix controls the speed at which the nitrogen gas penetrates the pore spaces; cores with a low-permeability matrix require a long period of nitrogen injection for this technique to be effective. Practical criteria for stopping nitrogen injection are (1) when enough water has been collected for analysis or (2) when nitrogen injection has continued for at least 2 hours.

Table 4.15-1 summarizes the mechanical data collected from 17 pore water extraction tests using triaxial compression. The data are divided into two sets according to the degree of welding. The initial water saturation of nine of the cores used for triaxial testing was artificially increased to provide a wider range of saturations than was available from native-state cores. The initial moisture contents of these cores were increased from 5-12% to 13-32% by weight. This increase corresponds to increases in initial saturation from 20-39% to 42-56%.

In nonwelded cores, triaxial compression resulted in porosity reductions of 32 to 55% with an average reduction of 43% based on initial porosity values. Total axial strains for nonwelded tuffs ranged from 8 to 37% with an average value of 23%. These values for total axial strain agree closely with data acquired by previous triaxial testing.

TABLE 4.15-1

MECHANICAL DATA FOR TRIAXIAL COMPRESSION

Sample	Initial Moisture Content (%)	Extracted Pore Water Volume (ml)	Maximum Axial Stress (MPa)	Total Test Duration (min)
Nonwelded				
UE-25 UZ5-330	12.4	0	117	87
UE-25 UZ5-223	25.7*	42	138	90
UE-25 UZ5-334	21.0	18	152	146
UE-25 UZ4-190	24.1*	47	152	149
USW UZ13-354	17.2*	30	152	300
UE-25 UZ4-182	32.3*	60	97	310
UE-25 UZ4-242	12.6*	18	165	365
UE-25 UZ4-241	16.5*	23.5	117	343
UE-25 UZ4-240	17.5*	16.5	76	364
UE-25 UZ4-238	14.3	28	117	240
UE-25 UZ4-237	16.3*	21	152	399
UE-25 UZ5-334B	9.6	0	152	133
UE-25 UZ5-246	11.8	11	179	507
UE-25 UZ5-269	11.0	6	179	288
UE-25 UZ5-235	6.8	0	193	292
Moderately Welded				
USW/UZN46-8	3.1	0	34	9
USW/UZN46-33	7.6	6	193	237

* Initial moisture content was artificially increased.

Figure 4.15-3 illustrates the results of pore water extraction from nonwelded tuff using triaxial compression. This figure compares the volume of water extracted by compression alone (before nitrogen injection) in this study with data collected during previous testing using the same technique. A simple regression analysis is included for each of the data sets to aid in a comparison of the data. The two data sets closely agree; in both cases, the minimum water content percentage at which the investigators were able to extract pore water was about 13%.

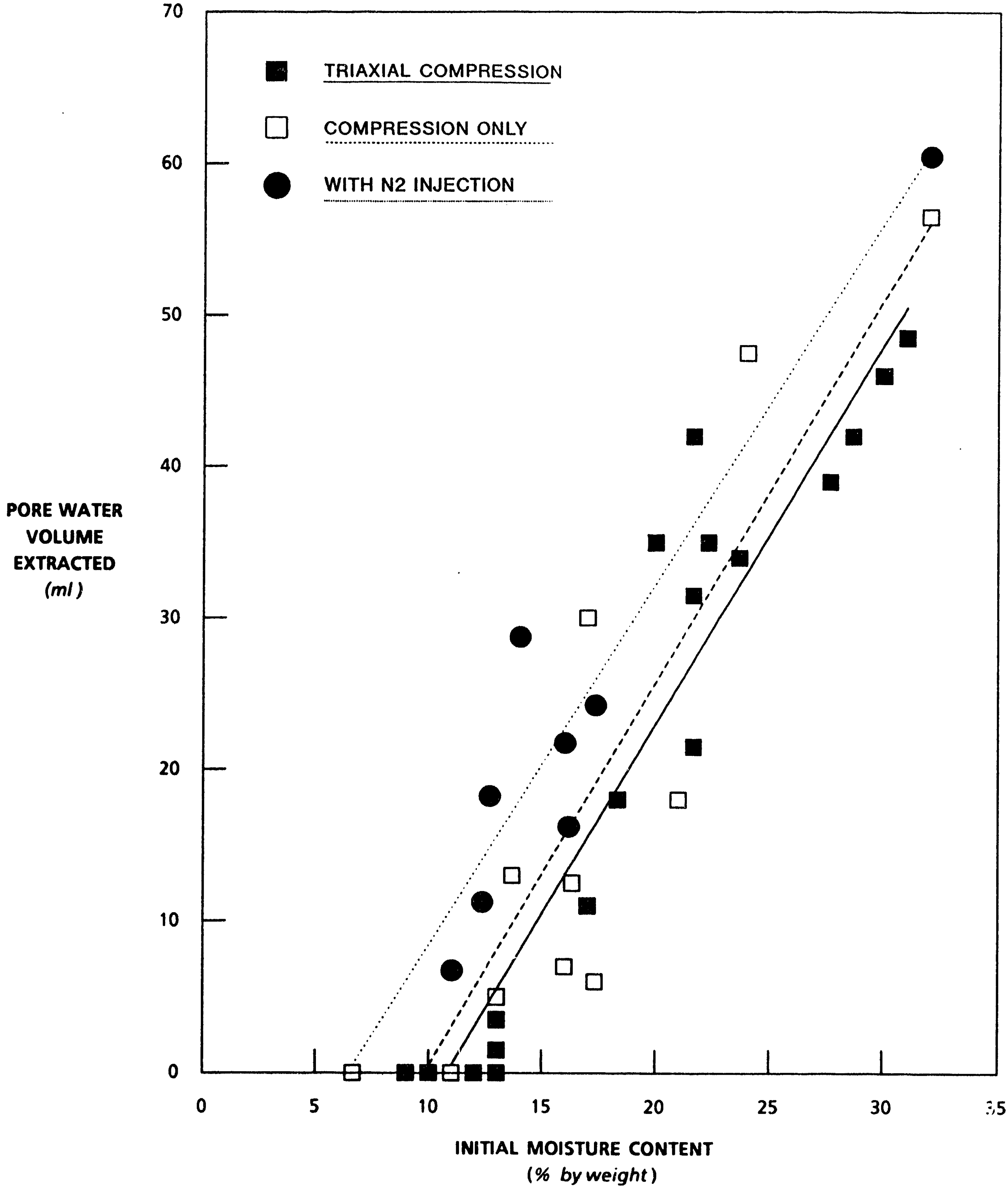


Figure 4.15-3. Pore water volume extracted versus initial moisture content for triaxial compression of nonwelded tuff samples best fit lines are based on regression analysis.

Figure 4.15-3 also shows data acquired during this study, which include additional pore water recovered by nitrogen injection. The same general trend is present; however, it is clear that injection of nitrogen gas while the core is held at its maximum compression significantly increases the volume of pore water recovered compared with compression alone. The two curves (compression only and nitrogen injection) show that 6- to 9-ml additional pore water are expelled by nitrogen injection. The actual minimum core water content required for pore water extraction was decreased from 13% to 11% by using nitrogen injection; the curve on Figure 4.15-3 suggests that the minimum water content required for successful pore water extraction may be as low as 7%, but no tests were conducted on cores in the 7 to 11% water content range.

The temperature of the core during compression was measured with a thermocouple in contact with the core during 12 of the 17 triaxial tests. No temperature changes were noted during any of the tests.

Only two triaxial compression tests were done on welded tuff because the uniaxial compression cell became available at that time and scoping calculations indicated that the triaxial compression cell would not be able to apply enough stress to produce water from densely welded cores. Subsequent testing of these welded cores by uniaxial compression showed that the 193-MPa axial stress (cell capacity) that was used in triaxial compression was much too small to cause pore water expulsion from welded tuff cores with low moisture contents.

The uniaxial cell system for pore water extraction was designed and fabricated specifically for this study. The primary objectives were to (1) design a system that did not have the inherent problems of the triaxial system, such as membrane leakage, (2) make a system that is simpler to operate, and (3) make a system that would operate efficiently over a broad range of stresses so that welded as well as nonwelded tuffs could be compressed.

The uniaxial cell is assembled as shown in Figure 4.15-1. Axial stress was applied to the core by a load frame with a capacity of 2.7 MN. Pore gas and water are collected as the core compacts under the load. Loading continues in increments of 69 MPa until the final stress level of 552 MPa is reached. At the maximum axial stress, after water expulsion ceases and the core stops compacting, additional pore water is extracted by injecting nitrogen in the same manner as for triaxial compression.

Uniaxial compression is an effective means of reducing core porosity. Porosity reductions of 32 to 74% with an average reduction of 56% (based on initial porosity values) were measured from nonwelded tuff tests. Welded tuff porosity reductions ranged from 14 to 33%, with an average reduction of 26%. Total axial strains for nonwelded tests ranged from 31 to 49%, with an average of 39%; welded test strains varied from 6 to 11%, with an average of 8%.

Table 4.15-2 summarizes selected mechanical data collected from 21 pore water extraction tests using uniaxial compression.

TABLE 4.15-2

MECHANICAL DATA FOR UNIAXIAL COMPRESSION

Sample	Initial Moisture Content (%)	Extracted Pore Water Volume (ml)	Maximum Axial Stress (MPa)	Total Test Duration (min)
Nonwelded				
UE-25 UZ5-217	9.5	0	221	106
UE-25 UZ4-115	12.5	15	427	244
UE-25 UZ4-338	9.5	0	434	309
UE-25 UZ5-230	7.6	6	434	321
UE-25 UZ5-327	9.4	5	434	305
UE-25 UZ5-345	12.0	7	552	357
GT-EX-DH3-2	30.8	39	552	325
GT-EX-DH3-3	30.8	61.5	552	455
UE-25 UZ5-347	18.8	16.5	552	415

TABLE 4.15-2 (cont.)

Duration Sample	Initial Moisture Content (%)	Extracted Pore Water Volume (ml)	Maximum Axial Stress (MPa)	Total Test (min)
Densely Welded				
GT-LD-AC2-5	8.4	5	552	175
USW UZ13-62	1.5	0	552	204
GTG-LD-WB-3-1	3.5	0	552	204
GT-LD-AC2-17	6.5	trace	552	241
GT-LD-AC2-26	6.6	1.5	552	328
GT-LD-AC2-25	6.7	2.5	552	473
GT-LD-AC2-41	6.5	1.2	552	446
GT-LD-AC2-42	6.5	1.2	552	480
GT-LD-AC2-18	6.6	0.8	552	491
GT-LD-AC2-55	7.7	6.2	552	1,305
GT-LD-AC2-62	6.6	5.8	552	1,341
GT-LD-AC2-63	6.6	3.2	552	485

The data are divided into two sets according to the degree of welding.

As a core compacts and looses porosity during a uniaxial compression test, its water saturation increases. Besides producing more water, cores with higher initial moisture contents reach 100% saturation and begin producing water sooner than cores with lower moisture contents. The nonwelded data in Figure 4.15-4 show this relationship; the welded data do not exhibit any clear relationship between initial water saturation and volume of water extracted. This may be because welded tuffs compress much less than nonwelded tuffs and the volume of water extracted from welded tuffs is more sensitive to the total axial strain than to initial water saturation. Figure 4.15-5 shows this relationship between the volume of water extracted and total axial strain for the welded tuff tests. The investigators found no relationship between the volume of water extracted and total axial strain for the nonwelded tuff tests.

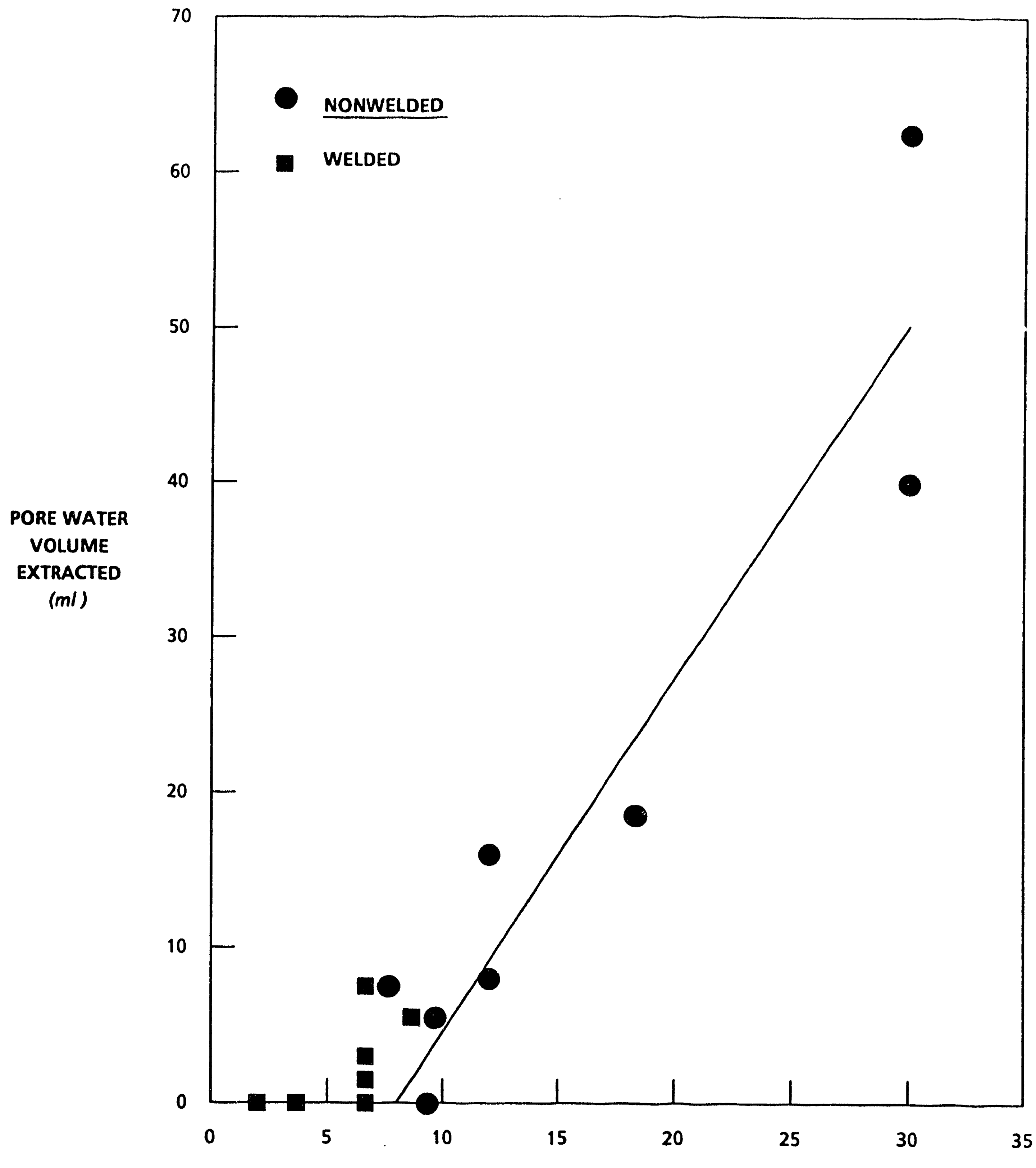


Figure 4.15-4. Pore water volume extracted versus initial moisture content for uniaxial compression.

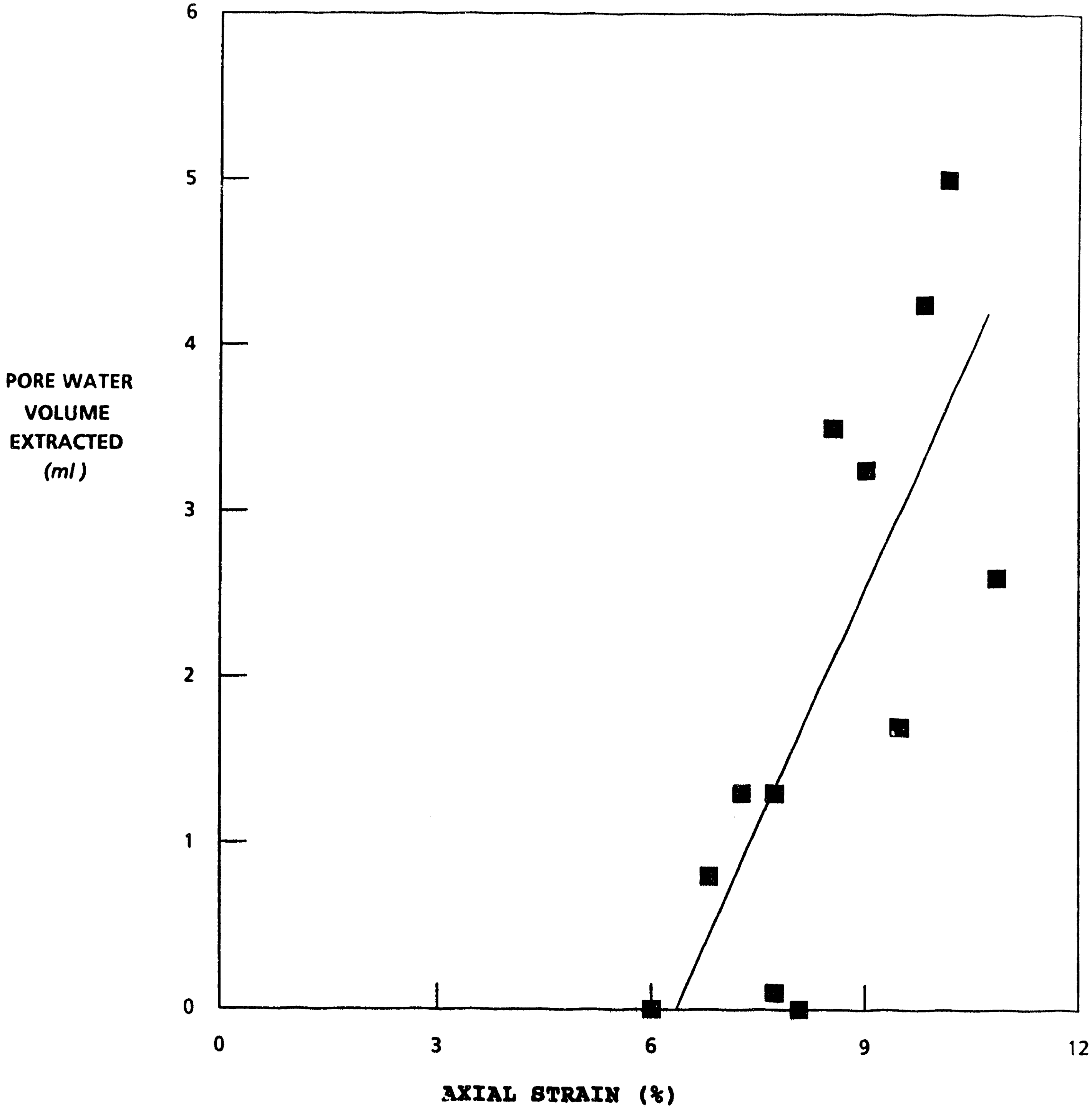


Figure 4.15-5. Pore water volume extracted versus total axial strain for uniaxial compression of welded tuff best fit line is based on regression analysis.

Almost no water was recovered by compression alone in any of the welded tuff tests; nearly all collected water was produced by displacement of pore water by nitrogen gas. The volume of water extracted was dependent on the duration of nitrogen injection; longer periods of nitrogen injection resulted in higher water recoveries. The temperature of the core during compression was measured during 5 of the 21 uniaxial tests. No temperature changes were noted during any of the tests.

Figure 4.15-6 is a plot of preliminary data initial moisture content versus pore water volume extracted for all the compression tests conducted on nonwelded tuffs. Examination of the available data appears to indicate some general trends. The regression lines in the figure are very similar for both triaxial and uniaxial compression. Both extraction methods indicate that the minimum moisture content required may be 7 to 8% for pore water extraction from nonwelded tuffs. The reason for the similarity between the methods may be simply that both are testing the same type of tuff. However, close examination of the data on Figure 4.15-6 reveals that uniaxial compression is successful in extracting pore water at lower initial moisture content than is triaxial compression. The minimum initial moisture content required for nonwelded tuffs tested by uniaxial compression was 7.6%; the minimum saturation was 18%. For triaxial compression, the minimum moisture content was 11.0%; minimum saturation was 24%. These general trends are important because, at ambient conditions, the nonwelded tuffs at Yucca Mountain have low initial moisture content and saturation. A review of Table 4.15-2 shows that the minimum moisture content required for pore water extraction from welded tuff by uniaxial compression is 6.5% (minimum saturation about 70%).

Besides permitting the extraction of water from tuffs with lower initial moisture contents, uniaxial compression has the following mechanical advantages over triaxial compression:

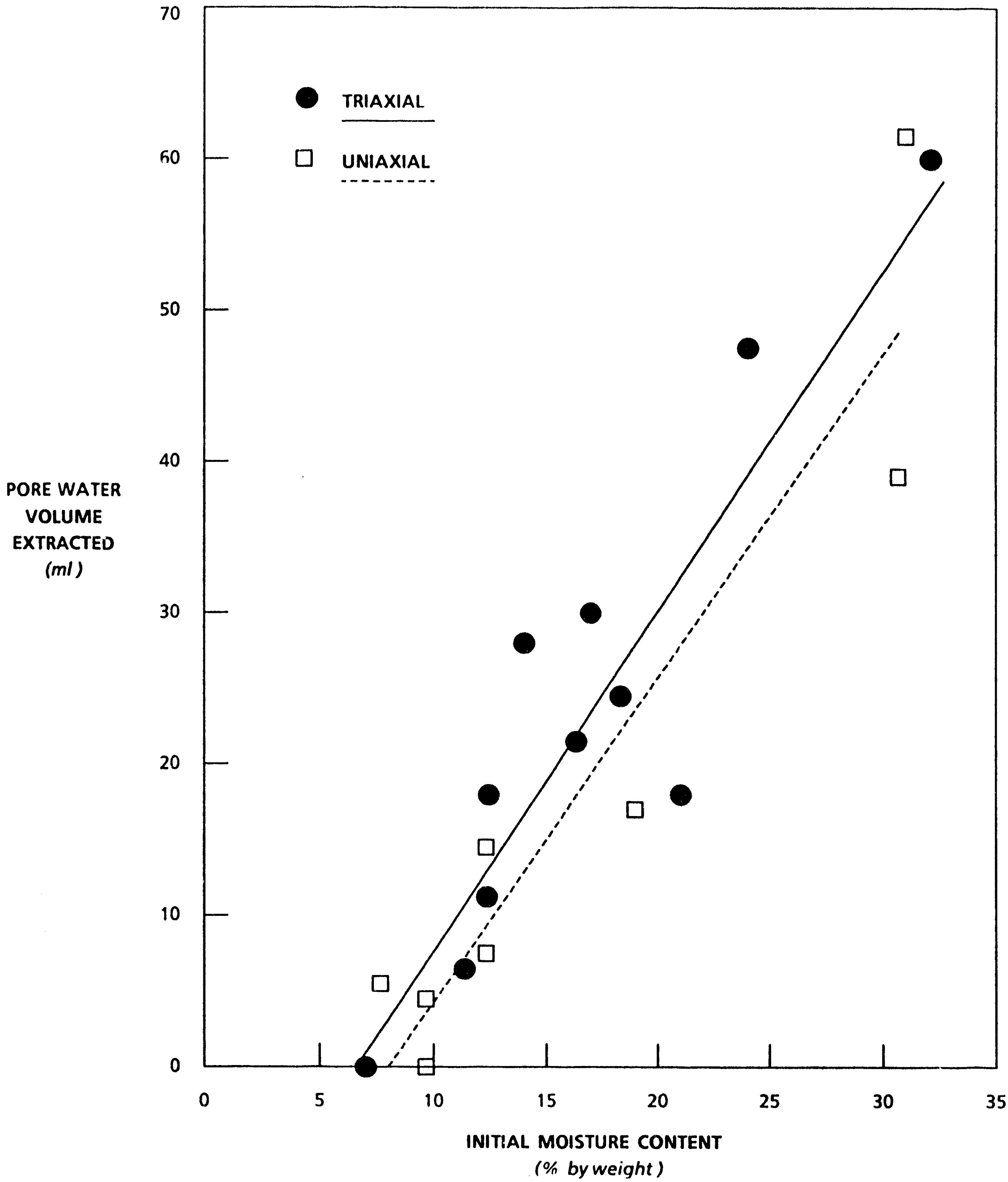


Figure 4.15-6. Pore water volume extracted versus initial moisture content for all tests using nonwelded tuff. Best fit lines are based on regression analysis.

- Higher stress—uniaxial compression can apply more than 2.5 times the axial stress to a core than can triaxial compression. Higher axial stress increases pore-space reduction and water expulsion.
- Smaller system volume—the uniaxial compression cell has a drainage system volume of less than 1 ml; the triaxial cell drainage system volume is about 8 ml. A smaller system volume allows more rapid recognition than water expulsion is occurring and minimizes the loss of water that results when the water adheres to the inside of the water drainage pathway.
- Variable core length—the uniaxial cell can easily accommodate a core of any length; triaxial cell cores must be of a specific, closely constrained length.
- Lower contamination risk—because steel applies the confining force in the uniaxial cell, there is no risk of contamination by leakage of the confining fluid as there is with the triaxial cell.

The volume of expelled water is directly proportional to the volume of pore space eliminated by sample compression. Initial water saturation and total axial strain may be used as parameters to roughly estimate the success of future pore water extraction tests using uniaxial compression. For nonwelded tuffs, an initial water saturation of at least 20% is needed to extract pore water; in terms of initial moisture content, 8% is the approximate lower limit (assuming porosities in the 40 to 55% range). According to the above estimate, most of the nonwelded tuffs from Yucca Mountain should produce water under uniaxial compression.

For welded tuffs, initial saturation plus total axial strain are needed as parameters to estimate the success of pore water extraction using uniaxial compression. Although the minimum water saturation and minimum axial strain values are not well defined, they can be used as rough guidelines. For welded tuffs, an initial water saturation of about 80% and a total axial strain of at least

7% are necessary for successful water extraction. Welded tuffs with lower initial water saturations (about 70%) will yield water if their total axial strains are higher (about 11%). The average water saturation of 50 welded tuff samples from Yucca Mountain was 65%. Depending on the amount of axial strain, tuffs possessing the average moisture content may yield water by uniaxial compression; however, long-duration (>3 hr) tests using nitrogen injection will be required.

Future Activities

Future work on pore water extraction by compression involves the study of changes in the chemistry of the extracted water in relation to applied stress. Additional study of the mineralogy and pore structure of the tuffs, coupled with knowledge of changes in pore water chemistry, will help confirm that the compression techniques produce uncontaminated, unaltered pore water.

4.16 Controlled Blasting

General Test Description

Site characterization work in the ESF at Yucca Mountain could require excavating of approximately 3,050 m (10,000 ft) of investigation drifts and about 670 m (2,200 ft) of shafts.[15] The drifts and shafts will be advanced by controlled- or smooth-blast methods, which generally produce stabler openings than conventional blasting; reduce blast damage, overbreak, and excess muck; and improve tunnel ventilation.

The prototype controlled-blasting investigation involves designing blast rounds, monitoring blasting methods, and evaluating blast damage. The instrumentation alcove and the controlled blasting room are located in the G-Tunnel. These excavations are required to provide a controlled-blasting environment for prototype ESF tests. The controlled-blasting investigation room and the alcove excavations will be monitored and evaluated during the controlled blasting test.

Purpose and Objectives

The prototype controlled-blasting investigation room attempts to replicate ESF mining conditions by using controlled-blasting methods to excavate repository-sized openings in welded tuff. This test is essential to three other prototype tests as it provides the proper environment for prototype ESF tests that are affected by, or are related to, mining operations.

The prototype tests that depend on a controlled blasting environment are

- prototype blast effects/blasts characterization (Section 4.5),

- prototype excavation effects (Section 4.8), and
- prototype optimal rubble (section 4.9).

The simulated ESF mining conditions will be monitored along with blast damage to develop initial practical procedures for quality control of ESF blasting operations. The initial procedures and blast designs will be refined in the ESF to accommodate ESF conditions. The ultimate goal is practical quality control procedures for repository excavations.

The objectives of this investigation are to

- support other prototype investigations by providing a smooth-blasted excavation, by producing excavation blast pulses in the G-Tunnel similar to the pulses expected during ESF drift mining, and by yielding mining rubble samples required for laboratory testing;
- develop techniques to evaluate, both directly and indirectly, blast damage in the host rock; and
- develop methods to relate geophysical measurements of blast damage to o[illegible] indirect blast-damage indicators for possible use [illegible]lity control.

Support Required

Underground construction support is the primary activity required to conduct this investigation. REECo miners and G-Tunnel support will be the major cost. H&N will survey control points for photogrammetry. SNL will monitor blast vibrations. Pan Am will photograph the excavation for photogrammetric surveys. The remaining work will be conducted by the USGS and USBR.

Detailed Test Description

The prototype controlled-blasting investigation is located in the G-Tunnel. The test program uses prototype excavations to develop procedures and initial blast round parameters for controlled blasting. Close-range photogrammetry, surveying, powder measurements, vibration monitoring, and geophysical measurements are the methods employed by this test to evaluate blasting operations and to develop quality control procedures. The controlled-blasting test excavation room will be about 12.2 m (40 ft) long, 6.1 m (20 ft) wide, and 4.3 m (14 ft) high (Figure 4.16-1). The controlled blasting investigation room cross-sectional dimensions approximate the planned size of ESF access drifts.

The blast characterization, blast effects, and excavation effects prototype tests require excavating the instrumentation alcove before the controlled-blasting investigation room. The alcove provides access to drill instrumentation holes and to install blast monitoring instruments in rock adjacent to the controlled-blasting investigation room. The instrumentation-alcove excavation will be about 9.1 m (30 ft) long, 6.1 m (20 ft) wide, and 4.3 m (14 ft) high.

The controlled-blasting investigation includes the following activities:

- Design of initial blast rounds approximating expected ESF drift-mining operations;
- Drilling of the cut relief hole and other charged blast holes;
- Measurement of hole depths, spacings, and alignments;
- Priming, loading, and detonation of the round;
- Measurement of the muck pile shape, location, and rubble size with stereophotography before mucking and hauling;
- Documentation of the condition of the wall and roof with stereophotographs and recording of visual observations in a daily log;

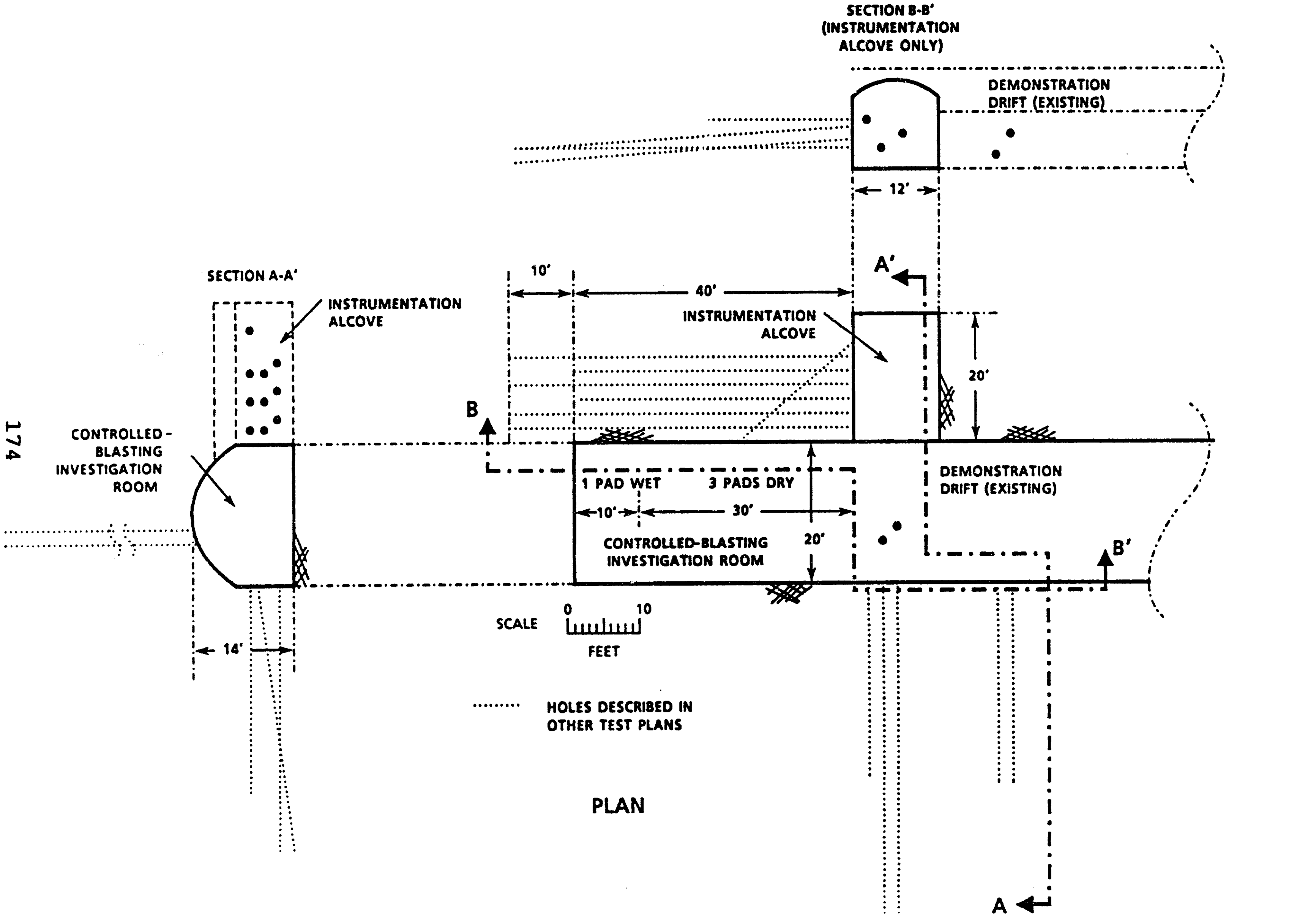


Figure 4.16-1. Controlled-blasting investigation room and instrumentation alcove—plan and section.

- Photogrammetry will be used to provide surface fracture density, ratio of half casts to perimeter holds, and surface profiles.
- Measurement of blast damage in the host rock through geophysical surveys and coring.
- Development of methods to relate peak particle velocities and indirect indicators to geophysical and coring measurements for quality control procedures.
- Adjustment of subsequent round designs. To reduce blasting vibrations that might damage or destroy test instruments and to minimize blast gas contamination of rubble samples needed for laboratory testing, the controlled blasting investigation will attempt to find the lowest practical charge density capable of consistently pulling the round.

Historical Perspective and Background

The G-Tunnel welded-tuff mining excavations (WBS 1.2.4.2.1.2) were conducted over a six-month period, from November 1985 through May 1986. The work was conducted by Parsons, Brinckerhoff, Quade & Douglas, Inc., for SNL.

The prototype controlled-blasting investigation grew out of the need to provide the proper testing environment for the tests mentioned previously. In addition to supporting these other tests is the need to develop practical quality control procedures and initial controlled blast-round designs for ESF controlled-blasting operations. This test focuses on monitoring mining activity and resultant blast damage. The excavations will be coordinated with the dependent prototype tests. The approach to meet project needs for blasting procedures is to use the excavations required for prototype testing to develop procedures and initial blast round designs as the excavations develop.

Evolution of Test Design

The controlled-blasting investigation refers to the welded tuff excavations located at the end of the demonstration drift in the G-Tunnel. Other prototype tests have included the controlled-blasting criteria as part of their test design and will generate records of how the blasting was done. These tests will report controlled-blasting data in an effort to broaden the knowledge base for controlled blasting in welded tuffs near Yucca Mountain. Blast round designs have been prepared for the prototype optimal rubble test, Fran Ridge (prototype geologic mapping), and prototype G-Tunnel mining.

Conduct of Test

Various delays in the prototype test program have prevented field work in all areas requiring controlled blasting except the nonwelded tuff excavation required to support the prototype optimal rubble test. The nonwelded excavation was conducted in April 1989 and provided the first opportunity to test both photogrammetry surveys of blast hole alignments and vibration monitoring done with surface mounted accelerometers.

Testing activities have been limited to document preparation, monitoring of one excavation of nonwelded tuff, blast hole pattern designs, and blast hole layout guide fabrication. Monitoring the nonwelded excavation-generated changes in field procedures for control point surveys as well as changes to the forms used to track the drilling and loading details during the blasting operations. These new procedures and forms will be used in monitoring the next excavation.

Future Activities

Future smooth-blast excavations will be

- the controlled-blasting room,
- the instrumentation alcove,
- the Fran Ridge test-pit deepening,
- the prototype G-Tunnel mining
  (demo II drift [thermal stress test])
  (stubb drift [engineered barrier test]),
- the prototype test shaft, and
- the ESF excavations.

These excavations will be monitored and documented as part of the controlled-blasting test or as part of the prototype test they support. The degree to which this happens will depend on project support and the need for controlled-blasting information. The reason for this work is to make use of required excavations to learn in the prototype phase as much as possible about how to evaluate, control, and conduct controlled-blasting excavations.

4.17 Thermal Stress

General Description

Heat generated by emplaced nuclear waste will induce high horizontal stresses around the emplacement drifts. This condition represents a significant departure from the stress state at ambient temperatures, which is dominated by vertical stresses. The changing stress conditions may cause rock blocks to shift and new fractures to form, possibly jeopardizing the stability of the emplacement drifts. The thermal stress experiment will be conducted in the ESF to validate the numerical models that simulate thermomechanical behavior of rock masses; to demonstrate the mechanism of response of the host rock to excavation-induced stresses compounded by high heat loads; to develop criteria for assessing the stability of the repository drifts; and to contribute information for the design of repository ground-support systems. These goals are shared by another experiment planned for the ESF, the heated-room experiment. A fundamental difference between the two is that the thermal stress experiment is a short-duration test intended to provide results that can be used to support the license application; the heated-room experiment is a larger, more ambitious endeavor that will require several years to complete.

The prototype test described here is being performed to develop and test the instruments, equipment, and procedures that may be used for thermal stress testing in the ESF. This test effort includes work done in the laboratory, in offices, and in the field.

The laboratory work, which is being conducted at SNL and at the NTS, has focused initially on selection and testing of instruments and equipment and development and testing of the data-acquisition system. Later work includes instrument calibration, equipment preparation, and thermal-mechanical testing of rock samples. Analyses being performed by SNL personnel and their contractors started with scoping calculations for experiment design and eventually will include models of the field test as designed and as built. This prototype test is the subject of benchmark calculations for certification of several numerical codes used to predict thermomechanical rock mass behavior. Field activities that will be performed in the GTUF in an environment somewhat analogous to the environment that will be encountered in the ESF will consist of (1) site preparation, (2) installation of the data-acquisition system, (3) operational equipment, and instrumentation, (4) testing and verification of components, (5) the actual conduct of the test, and (6) post-test measurements and decommissioning.

Purpose and Objectives

The purpose of this prototype test is to develop and refine the constituent techniques, procedures, and equipment, as well as the overall approach to the thermal stress tests. Successful completion of the prototype test will imply that in the short time that will be available for data collection in the ESF, meaningful measurements can be obtained from the response of the rock mass around an excavated opening to heat-induced loads.

The specific objectives of the prototype thermal-stress test are to

- develop and refine the approach to field testing for determining the response of a rock mass to severe heat loads during a limited period of time;
- develop and test instruments and equipment for use in the high-temperature, high-stress environment; and
- provide preliminary information with which to assess the applicability and accuracy of various thermomechanical models of a jointed rock mass.

Support Required

SNL will be responsible for the majority of the field activities for the thermal stress test. Responsibility for checkout and installation of some of the displacement instruments will be assigned to an as yet unnamed contractor to SNL. REECo staff, under the general direction of the field coordinator, will provide support in drilling holes, assembling and constructing bulkheads to restrict access, and providing electrical power for instruments and equipment. Pressurized air and water must also be supplied to the test area. A geologist from FSN will map the test area and log cores. H&N will survey the test area and the drill holes.

Detailed Test Description

The prototype thermal-stress test will consist of heating the roof of a drift in fractured welded tuff along an 5.5-m (18-ft) length to a depth of approximately .9 m (10 ft) while measuring temperatures, displacements, and stress changes. The rock will be heated until the opening fails or for 180 days, whichever occurs first. After 180 days of heating, maximum temperatures and horizontal stresses along a vertical line through the crown of the drift cross section are expected to be on the order of 300° C and 60 MPa (8700 psi), respectively. Although the maximum stress is similar to that expected above a waste emplacement drift in a repository, the temperatures are much higher, and the stress gradients are much steeper than those expected in a repository because of the compressed time period allowed for heating.

The configuration of instruments and equipment is shown in Figures 4.17-1 and 4.17-2. Most of the drill holes for heaters and instruments are oriented radially from a centerline on the floor of the 4-m-high (13-ft-high) drift. The heat will be imparted by 16

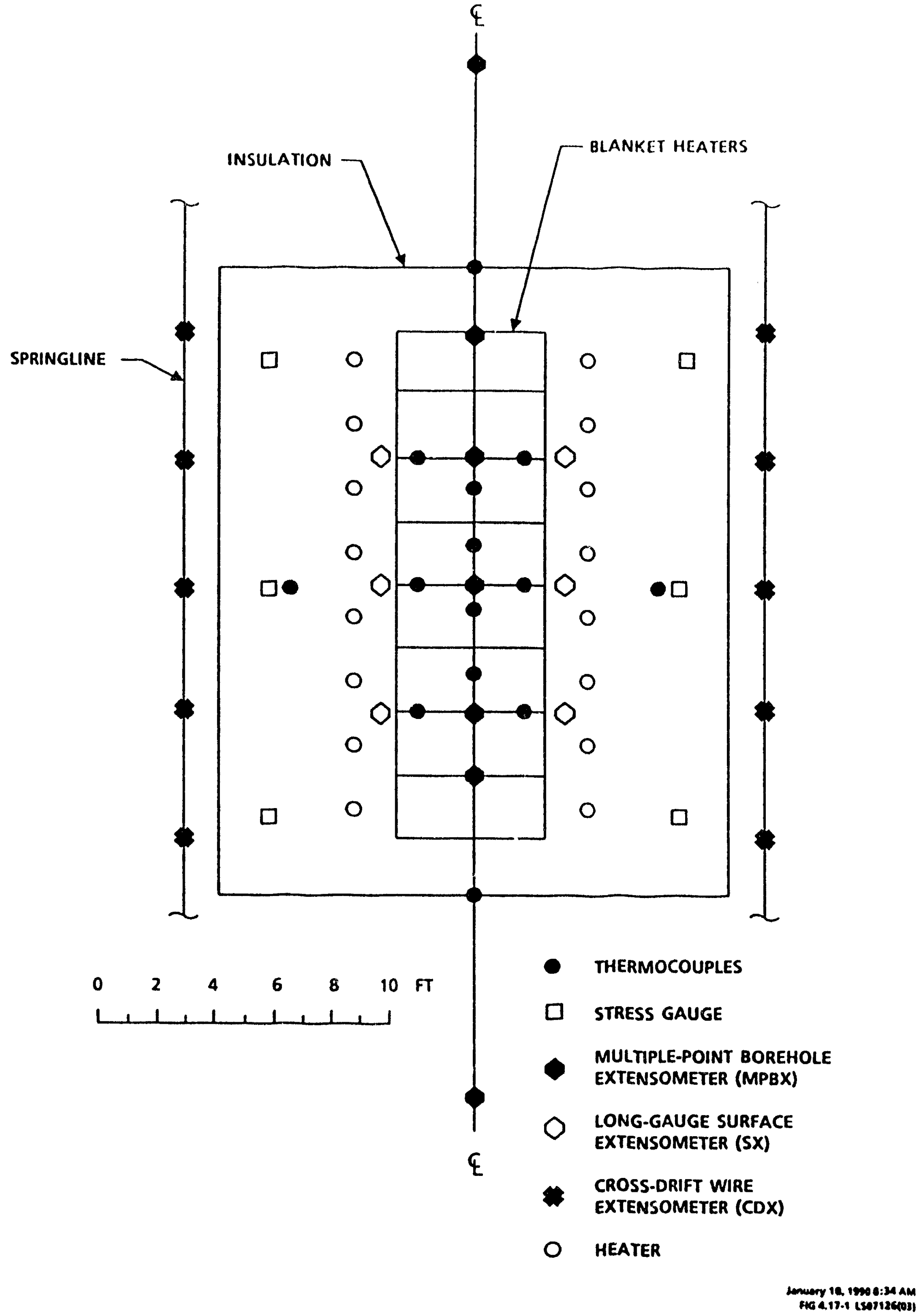


Figure 4.17-1. Plan view: Thermal Stress prototype test.

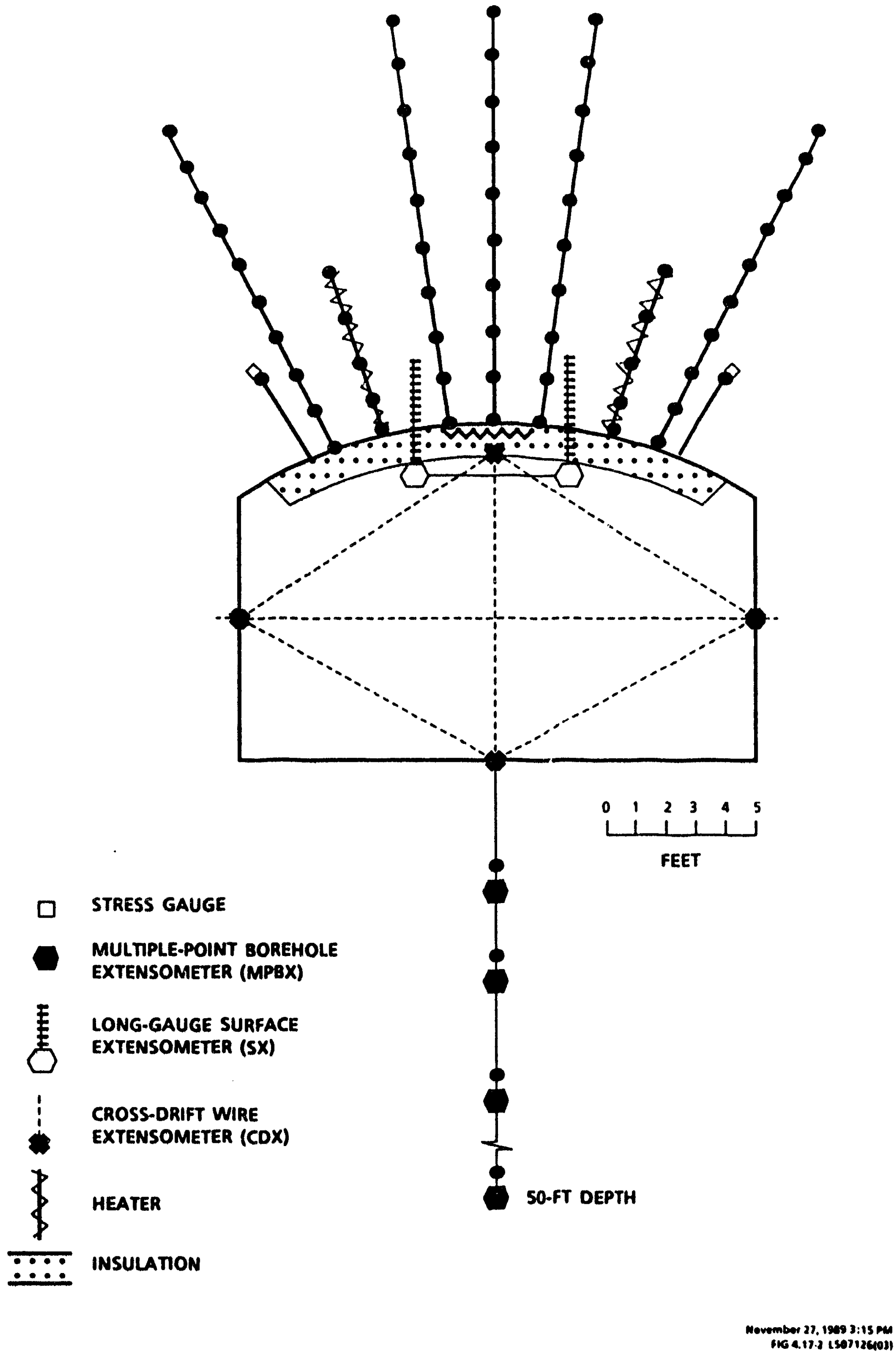


Figure 4.17-2. Cross section: Thermal Stress prototype test.

small-diameter, cylindrical heaters arranged in two rows and by blanket heaters placed against the roof between the rows. Instrumentation includes thermocouples, thermal flux gauges, long-gauge surface extensometers with tiltmeters, cross-drift wire extensometers, multiple-point borehole extensometers (MPBX), and borehole stress cells. The thermocouples will be distributed liberally throughout the test area, and the flux gauges will be installed in the insulation. Siting of the stress and displacement gauges with respect to the heated area is restricted by their thermal tolerances. Addition of seismic transducers for monitoring acoustic emissions and creating cross-hole seismic images is under consideration, and instrumentation of rock bolts and the insulation support structure is also being investigated. The entire heated surface will be covered with a 0.3-m-thick (1-ft-thick) layer of insulation. All control and monitoring will be done remotely.

Following is a sequence of major field events for the test:

1. Drill boreholes.
2. Install instruments and heaters.
3. Wire instruments to the data-acquisition system, check instruments, and perform in situ calibrations.
4. Assemble the support structure.
5. Install insulation.
6. Construct the bulkhead.
7. Begin data acquisition for system checkout and to obtain background data.
8. Start heaters.
9. Continue data acquisition and reduction for 180 days or until the data show signs of severe instabilities, whichever occurs first.
10. Turn off the heaters.
11. Lower the support structure if this is permitted by the integrity of the rock and add supplemental ground supports if necessary.

12. Remove the bulkhead, disassemble the test, and perform post-test calibrations.
13. Begin long-term periodic monitoring of drift convergence by using nonobstructive techniques (e.g., tape extensometer).

Historical Perspective and Background

The thermal stress experiment is intended to provide information regarding the thermomechanical response of a rock mass to high heat loads. In the ESF experiment, the results will be used to support the license application for a potential repository; hence, a time constraint is imposed. The duration of heating was selected to provide timely results and to allow for sequential repetition of the test if a need for repetition is indicated by the range in ground conditions encountered or by the test results.

The scale of the test was selected to encompass a sufficient volume of rock to be representative of a jointed mass of welded tuff. Although it would be desirable to demonstrate the performance of a drift in the high-temperature, high-stress environment of a repository, time constraints and the level of complexity dictated a decision to heat only a portion of the cross section of a drift. (The rock fully surrounding a drift will be heated in another ESF experiment, the heated-room experiment, which will require heating over a period of several years.) The roof was chosen for heating rather than a rib or the floor so that drift stability could be studied in the locale that has the greatest potential for failure.

The level of heating selected depended on the stresses that were expected to be induced rather than the temperatures. Numerical models of the potential repository predict horizontal stresses in the crown of an emplacement drift in the order of 60 MPa (using a vertical emplacement orientation). Heater power and configuration were chosen so that a numerical model of the experiment would also predict maximum horizontal stresses of about 60 MPa. To achieve this theoretical stress level in the experiment, temperatures will be much higher than those predicted to occur in the repository. Linear-elastic models of the experiment show that a large tensile area would form in the roof of the test area, whereas models of the roof of a repository emplacement drift show that the area would remain in compression. For this reason, the thermal stress test will create conditions that are much more severe in terms of stability than those expected in the repository. Failure of the opening in the experiment will provide the opportunity to study the modes of failure of jointed welded tuff and to establish criteria for opening stability or usability; its failure does not necessarily imply that the repository openings will not be stable.

Evolution of Test Design

Although the need for a thermal overdrive experiment in the roof of a drift has been a part of test plans for the ESF for a number of years, the present concept for instrumentation of the thermal stress test differs from the original. The test name is actually better suited to the original concept, which focused on measuring stresses in the rock by using a flat jack cancellation pressure technique, than to the current one, which emphasizes displacement measurements.

The original measurement concept called for cutting a slot in the center of the heated area, inserting a 1-m (3.3-ft) by 1-m (3.3-ft) square, high-pressure flat jack in the slot and determining stress by measuring the flat jack pressure required to return a set of reference pins to their original positions. This concept was abandoned after scoping calculations showed that it was not possible to induce a constant or linearly varying stress state across the face of the flat jack. The stress gradients across this region would be steep and highly nonlinear, meaning that it would be virtually impossible to translate the cancellation pressure registered from the flat jack to a stress state.

History has shown that it is difficult to measure stress changes in rock, particularly at high temperatures. Also, stresses are often derived indirectly from strain or displacement measurements based on the modulus of deformation of the rock mass, which in itself is extremely difficult to determine. For these reasons, it was decided to concentrate on measuring displacements rather than stresses. Displacements can be measured directly, and the measuring techniques have a long history of success, at least in ambient-temperature environments. Displacements will be measured between posts embedded in the heated area, across the drift, and to depths of 137 m (45 ft). The latter measurements will be made at a significant standoff from the heaters because of the temperature limits of the instrumentation. Stress change measurements will still be attempted in boreholes sufficiently remote from the heaters to provide a reasonable chance for instrument survival. Research is ongoing to identify or develop an appropriate gauge to measure stress changes in a high-temperature environment.

Although the basic philosophy of the test and the approach to instrumenting it have been settled, many details are still evolving and will continue to do so until the test actually is conducted.

Future Activities

Test installation has not yet begun. A drift is currently being excavated to house the test. Once the thermal stress drift has been mined, drilling and other preparatory activities at the site will commence. In the meantime, instrument and equipment selection, development, and testing will continue. Major preparations yet to be completed are selecting instruments to measure stress changes, finalizing and installing the Data Acquisition System, and preparing an operating procedure governing safety.

4.18 In Situ Stress

General Test Description

Tuffs at Yucca Mountain are under pressures (stresses) that are caused by the weight of the overlying rock (lithostatic load) and by tectonic stresses superimposed on the lithostatic load. These total stresses on the in-place rock are referred to as in situ stresses. As part of the activities to assess the geomechanical properties of rock at Yucca Mountain, tests are planned to characterize in situ stresses. Data on in situ stresses are necessary input in thermal stress models and other models that are used to assess the stability of underground openings and to determine failure criteria for rock excavations. Knowledge of in situ stress is therefore of fundamental importance in repository design considerations. The prototype in situ stress test described here is being performed at the G-Tunnel, where the stress state and rock conditions that are likely to be encountered might be similar to those in the ESF. It will refine equipment and procedures needed to determine in situ stresses in brittle, fractured, welded tuff.

Field work at the G-Tunnel consists of stress and deformation measurements and the description and documentation of the number, spacing, condition (filled or not), and orientation of fractures in recovered core and in borehole walls. Laboratory work includes instrument preparation and calibration, equipment preparation and testing, and tests on selected cores to investigate anisotropies in the rock in order to relate variations in field measurements to these anisotropies. Analyses, performed in the office, consist of data reduction and interpretation.

Purpose and Objectives

The purposes of the tests planned under the prototype in situ stress test are to test field procedures and instrumentation and to compare alternative methods to determine in situ stresses under conditions very similar to those expected in the ESF.

The specific objectives of the tests are the following:

- Determine, using the USBM borehole deformation gauge, principal stress directions of the in situ stress at three stations (boreholes) in the G-Tunnel and determine the adequacy of this type of gauge for use in the ESF;
- Compare the results of anelastic strain recovery (ASR) and overcore stress test (OST) techniques in order to determine the method that will be the most reliable for use in the ESF (ASR testing was not done in fiscal year 1989);
- Evaluate dry and wet drilling for overcore stress-relief measurements;
- Field test and verify the use of video systems for the inspection of boreholes and evaluate the suitability of these systems for ESF tests; and
- Train the personnel who will conduct testing in the ESF.

Support Required

Contractors will provide support in areas of drilling/coring, sample storage, and sample transport. Specifically, contractors will

- provide mining personnel and equipment to core and remove large core samples;
- provide boxes for storing the samples in a cool, dry place until the samples are transported; and
- provide transportation for the samples from inside the G-Tunnel and load the samples onto USGS vehicles outside the G-Tunnel.

Detailed Test Description

OSTs relieve the stresses from a rock core and then measure the change in size and shape of the core as the rock recovers following removal of stress. Rock expands different amounts in different directions, depending on the orientation and magnitude of the stress field in the area from which the sample has been taken, and on the mechanical properties of the sample. The OST techniques are described briefly below.

OST testing will be conducted in two phases. The first phase involves borehole dilatometer measurements in which a borehole dilatometer is used to determine the in situ rock mass modulus of deformability by measuring the volumetric change of a dilatable membrane in contact with the borehole wall. (These measurements are used in conjunction with core analysis and borehole video camera logs to determine stress measurement locations.)

The second phase uses a deformation gauge in overcored boreholes and consists of several steps. First, a small-diameter hole is drilled and a three-component deformation gauge mounted in it. A large-diameter, thin-walled hollow drill bit is then used to core around (overcore) the small hole. Overcoring relieves stresses on the inner hole, and the deformation gauge registers changes in the size and shape of the wall of the inner hole as the rock recovers following removal of stress. After overcoring, the deformation gauge is removed from the hole, and the core is freed from the bottom of the hole and retrieved. The oriented core is then tested to determine the modulus of deformation of the rock. The modulus of deformation and strain measurements are used to calculate stress distributions normal to the axis of the borehole. To determine the orientation and magnitude of the three-dimensional stress tensor, it is necessary to have stress-relief data from at least three orthogonal (nonparallel) overcore holes. Overcore stress relief holes and dilatometer core holes will be drilled parallel to one another.

Historical Perspective and Background

To obtain information on the present three-dimensional state of stress in fractured, welded tuff in the G-Tunnel, the stress relief technique has been selected as the primary method. This passive method of obtaining data on the in situ stress state in shallow boreholes <50 m (<164 ft) has witnessed steady progress in development and application, is firmly based in theory, is supported by extensive literature spanning more than two decades, and has met with general acceptance in the rock-mechanics community. Its chief alternative is the active method of hydraulic fracturing.

Various techniques are available for monitoring stress changes in response to environmental influences (e.g., Gloetzel cells, flat jack pressure cells, rigid-inclusion stress meters), but they are not standard techniques for measuring the pre-existing in situ state of stress.

The three principal candidate instruments for use in the ESF are the USBM deformation gauge, the Australian hollow-inclusion cell, and the doorstopper method. The USBM and doorstopper methods both require three noncoplanar boreholes for a complete determination of the stress state; the hollow-inclusion cell method requires only one borehole. The USBM and hollow-inclusion cell methods of measurement require that the length of the recovered core be at least twice its diameter to allow for complete stress relief and for measurement of its elastic properties. The CSIRO and doorstopper instruments must be cemented to the borehole wall, introducing potential difficulties in getting satisfactory bonding. The bonding material could also conceivably interfere with subsequent chemical testing. Both methods also require the use of numerically or experimentally derived geometrical or strain-coupling constants for data interpretation.

Notwithstanding the advantages of the doorstopper and CSIRO methods, the USBM method was selected as the primary method for prototype testing, principally because of its inherent simplicity and relative stability. The USBM gauge is wedged and oriented in the pilot hole, and because of its circuit design (full Wheatstone bridge), it is more sensitive to heat-induced expansion in the pilot hole, which cannot be flushed with cooling fluid during overcoring.[16] The selection of the USBM or CSIRO method (displacement or strain measurement) is based on the prevailing site and rock conditions in the ESF. The USBM gauge will be the primary instrument, but the CSIRO cell can be used as a secondary instrument if stresses are sufficiently high, and if the thermal response of the cell is sufficiently low to allow accurate measurements.

Biaxial Elastic Modulus Tests

The biaxial elastic modulus test is required to interpret strain-relief data from the USBM gauge or CSIRO cell. Most of the rock is expected to be reasonably isotropic. If the rock is isotropic, or nearly so, this technique of modulus determination is adequate for data interpretation using standard methods. Its chief advantage is that modulus measurements can be made in the field immediately after overcoring and performed at pressures in the biaxial device that approximate the stress level in the rock prior to overcoring. If biaxial testing reveals significant anisotropy, the alternative of laboratory triaxial core testing on oriented samples cored from test overcores will be used to determine required anisotropic elastic parameters.[17]

The additional laboratory alternative of polyaxial testing techniques[18] will be used to fully characterize the elastic properties of rock that is highly anisotropic. By testing cubes obtained from the annular portion of the oriented overcores, values of Young's modulus and Poisson's ratio may be obtained in three orthogonal directions. These property measurements can then be used in a data-analysis procedure[19] that assumes the rock to be orthotropic; that is, the rock is assumed to have three mutually perpendicular planes of elastic symmetry, with the overcore perpendicular to one of these planes. Extreme anisotropy is sometimes caused by a fracture contained in an overcore annulus that otherwise remains intact; results from such a sample will be discarded as not representative of in situ stress conditions, in that the overcore sample is not representative of relatively homogeneous material where stress relief can be applied.

Rock Fabric Analysis

Microscopic rock fabric analysis will supply detailed three-dimensional information on fracturing and mineral grains; this information will be used to evaluate variations observed in elastic rock parameters, which is necessary for interpreting overcoring data. Directional variation of intact rock modulus is caused primarily by microscopic fractures, which this analysis will identify.[20] The petrographic techniques to be used for rock fabric analysis have no reasonable alternatives.

Evolution of Test Design

All modifications to the design of this test are the result of testing activities as described in the conduct of test section.

Conduct of Test

Field testing in the G-Tunnel began in April 1989. Laboratory and office activities were continuous throughout the year.

Drill-Hole Completion Summary

Dilatometer/exploratory drill holes of NQ (63.5 mm [1.875 in.]) size were cored at three selected sites in the G-Tunnel. In the demonstration drift, drill hole IS-2 (Figure 4.18-1) was drilled approximately horizontal into the side wall, and drill hole IS-3 was drilled in the ceiling at an angle of approximately 60° up from the horizontal. These holes were drilled with air. Drill hole IS-4 (Figure 4.18-2) was drilled in the laser drift using water. All holes were approximately 15 m (50 ft) long. Drill hole IS-1 will be drilled in the CBI alcove after its completion. Parallel to, and approximately .6 to .9 m (2 to 3 ft) away, USBM overcore stress test holes were drilled. Overcore drilling on IS-3 was terminated at 7.6 m (25 ft) because of scheduling conflicts with other prototype tests, and because of a need to order and fabricate drill bits and support equipment.

Drilling Results

All of the drill holes were drilled in densely welded tuff. Because drilling was done with air (IS-2 and IS-3) and water (IS-4), a comparison of penetration rates and bit life is possible. Drilling of the NQ hole was faster per 1.5 m (5 ft) core run with water than with air, but not dramatically so. Bits tended to wear out faster with air drilling. Other factors, such as drill rig position and the necessity to take apart and reset the dust-collector's collar rubbers and hoses, increased the overall drilling time more than the increase as a result of bit performance.

The standard drilling scheme used for the overcore stress measurement drill hole was greatly modified during prototype testing. The first overcore hole was drilled parallel to (5° up from horizontal) and .9 m (3 ft) from drill hole IS-2. The normal technique is to core an EX 3.8 cm (1.5 in.) hole 1.5 to 1.8 m (5 to 6 ft) long, select a suitable instrument site (an unfractured zone of 25.4 cm (10 in.) or more) within the EX hole, emplace the instrument, and core over the instrumented zone with a narrow kerf masonry bit. This procedure is repeated at selected intervals out to a prescribed distance; in the prototype studies, this distance was approximately 14 to 15 m (45 to 50 ft). The rock between test zones is normally removed in .9 m (3 ft) coring runs using masonry bits. Problems encountered with this standard technique, their resultant effects, and solutions follow.

- EX coring bits and 15 cm (6 in.) overcore barrels, both with premium grade surface-set diamonds, penetrated well for the first couple of feet, averaging 2.54 cm (1 in.)/min or better; however, the diamonds "polished" after .6 to .9 m (2 to 3 ft) of drilling and the drilling rates rapidly dropped to .3048 m (1 ft) per h. The results of this problem were (1) little to no usable EX core, which is used to identify suitable instrumentation zones; (2) very slow drilling rates; and (3) using up overcore barrels, which also are needed to overcore the USBM instrument, in the process of removing rock between testing zones.
- The highly fractured nature of the rock mass, the presence of rubble zones, and the desired test spacing required the removal of up to 3.5 to 7 m (10 to 20 ft) of rock between test sites. Advancing the 15-cm-diam (6-in.-diam) hole was the most critical problem. This problem was overcome by using a small-tooth tricone "hole-opener" rock bit. This bit was able to drill .9 to 1.5 m (3 to 5 ft) of hole per hour, depending on the hardness of the rock and the frequency of fractures and rubble pockets. The EX pilot hole core bit was replaced with a solid-face, two-port, diamond-plug bit and a borehole camera was used to locate USBM instrument test zones.

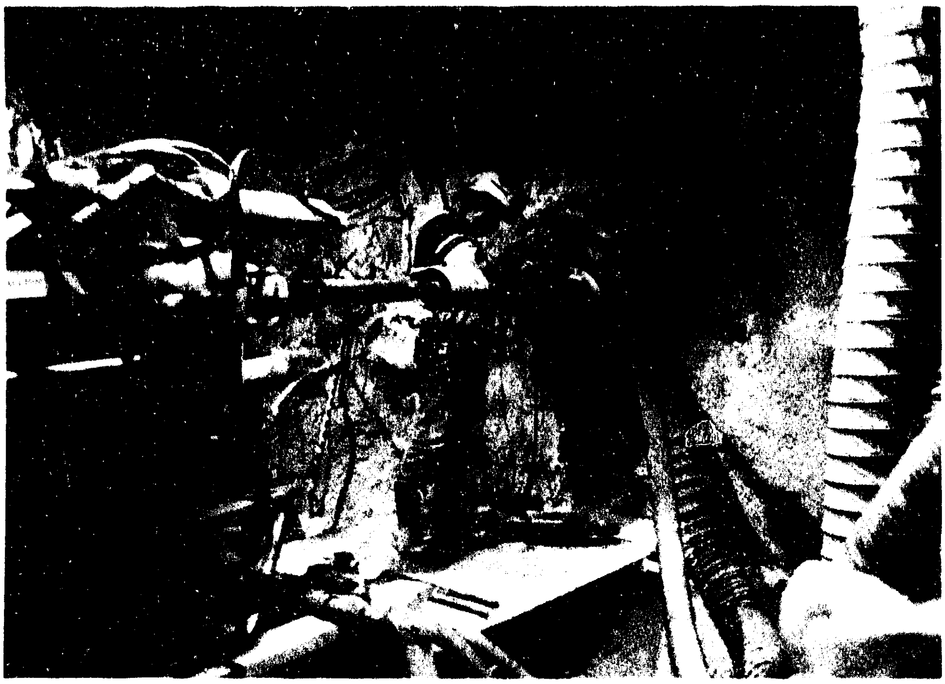


Figure 4.18-1. IS-2 overcore hole in Demonstration Drift (G-Tunnel) showing air-seal collar and dust suppression equipment.

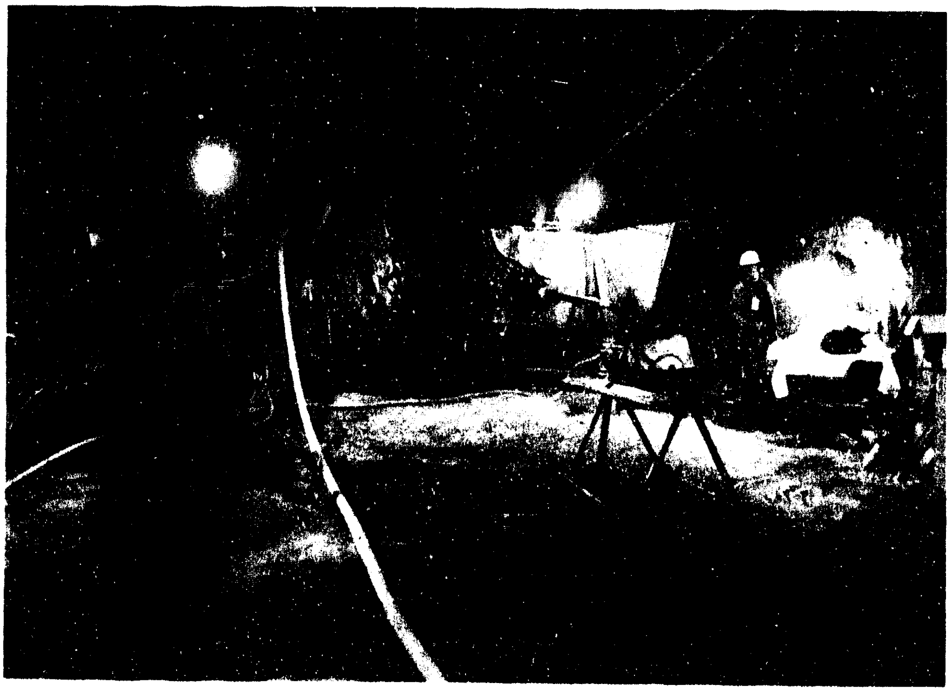


Figure 4.18-2. IS-4 Overcore hole in Laser Drift (G-Tunnel).

- The next problem to arise was that even with stabilizers along the drill string, the weight of the tricone bit was causing the hole to drop downward. Additionally, air is a very poor lubricating medium, so as the hole got deeper, more and more drag occurred between the rotating stabilizers and the wall, which resulted in more and more chatter in the drill string and slower drilling RPMs and penetration rate. The slower drilling RPM was a critical problem because during an experimental test using a new 15-cm- (6-in.-) narrow-kerf core barrel, it was found that the RPMs desired to achieve an overcore penetration rate of 30 to 59 seconds per 13 mm (0.5 in.) was difficult to nearly impossible because of chattering of the drill string. The driller suggested a double-rod technique that we were able to adapt to our needs and that proved very successful in the horizontal hole. This technique consisted of driving the 15 cm (6 in.) core barrel and the EX pilot bit with BQ-size rods that fit smoothly inside NQ drill rods centered in the drill hole with stabilizer sections designed to fit into a 15-cm-diam (6-in.-diam) hole. Because the NQ rod stabilizers do not rotate, the drill string chatter is eliminated and higher RPMs allow better bit performance and faster drilling. This drill string setup is shown in Figure 4.18-3. Additionally, the NQ drill string provided better support for the tricone hole-opener bit, thus eliminating the problem of the hole dropping. This double-rod technique was used to successfully finish drill hole IS-2. The double-rod technique is not adaptable to steeply inclined drill holes, such as IS-3, because there is no way to hold the NQ rods in the hole behind the dust collector while drilling with BQ rods.
- A tricone bit, with a pilot "stinger" (Figure 4.18-4)

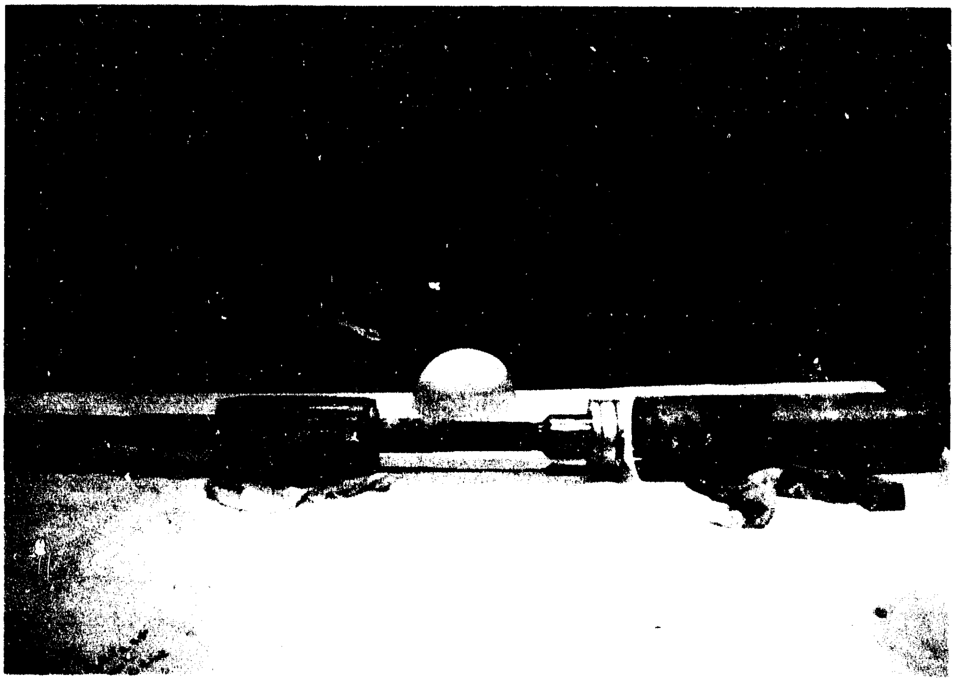


Figure 4.18-3. Drill-string assembly used for horizontal overcore holes. (The stabilizers fit over the BQ rods and do not rotate, eliminating or greatly reducing detrimental drill-string chatter.)

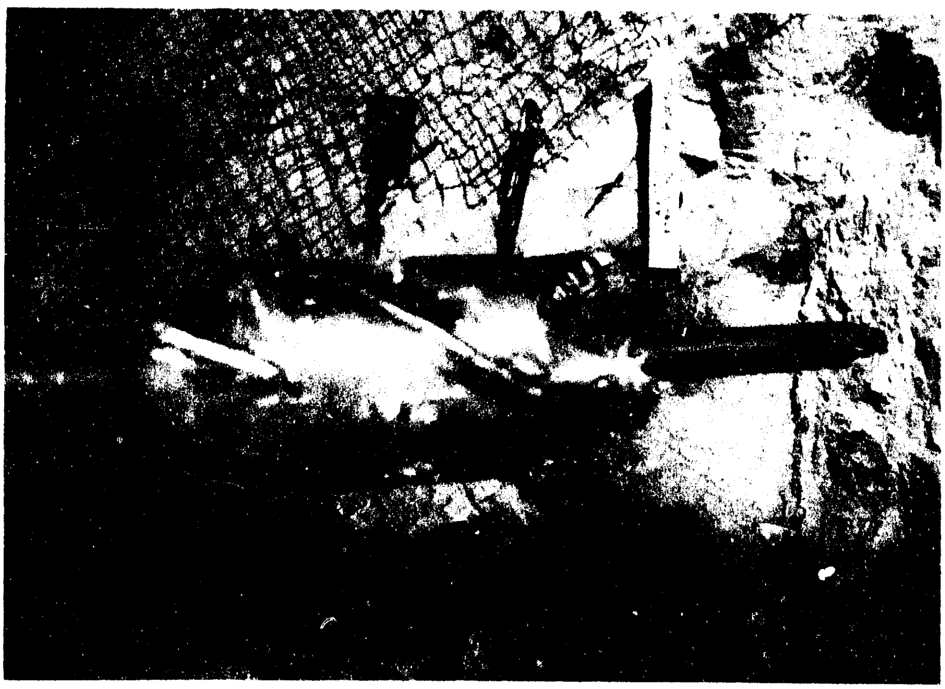


Figure 4.18-4. Six-inch tricone bit fitted with a pilot "stinger" that makes this bit follow the previously drilled EX pilot hole.

designed to follow a previously drilled EX pilot hole, was used in drilling overcore holes IS-3 and IS-4. A 15-m-long (50-ft-long) EX pilot hole was drilled using solid-face, 2-port plug bits (Figure 4.18-5). Using water in IS-4, the 15-m (50-ft) EX hole took approximately five hours to drill giving a penetration rate of 3 m (10 ft) per hour. Using the same type of bit with air, the diamonds polished, and the penetration rate was typically 0.9 m (3 ft) per hour. By having a 15-m (50-ft) EX hole and using the borehole camera, a quick decision could be made on which zones were suitable for USBM overcore testing. The tricone hole-opener bit with the pilot stinger worked very well. In advancing the hole to the desired depth, the stinger always keeps the 6-in. hole centered with respect to the EX pilot hole. Because the hole is advanced by just adding rods (core barrels do not have to be repeatedly removed from the hole to be emptied), drilling time was reduced. Drilling rate using this bit with water was approximately 3 m (10 ft) per hour. Drilling rate with air was 0.9 to 1.5 m (3 to 5 ft) per hour.

Air Versus Water Drilling

In situ stress measurements using air as the drilling medium are possible and can be done using modified drilling techniques. However, it should be expected that actual drilling rates with air will be approximately one-third as fast as with water, and that bit life (EX coring or plug, and tricone with stinger pilot) will also be about a third as long. The drilling of overcore hole IS-1 in the CBI alcove will provide additional information on drilling rates and bit life using the new drilling techniques. Impregnated 15 cm (6 in.) core barrels and EX core bits have yet to be evaluated when used with air.

Figure 4.18-5. EX two-port plug bit used for both air- and water-drilling of the pilot hole for the overcore test.

Borehole Video Camera Surveys

The use of a small-diameter video camera for surveying the EX pilot hole has become a necessity with the adoption of the new drilling scheme and the fact that EX core recovery in the densely welded tuffs is very poor.

Newly invented fracture orientation and aperture measurement gauges, to be used with the borehole camera, are currently being tested and modified.

Prototype Dilatometer Testing

Calibration experiments on the Probex-I (NX) Dilatometer (Figure 4.18-6) purchased from Roctest, Inc., began in February 1989. To aid in the assessment of the performance of this borehole instrument, an aluminum test cylinder was obtained that

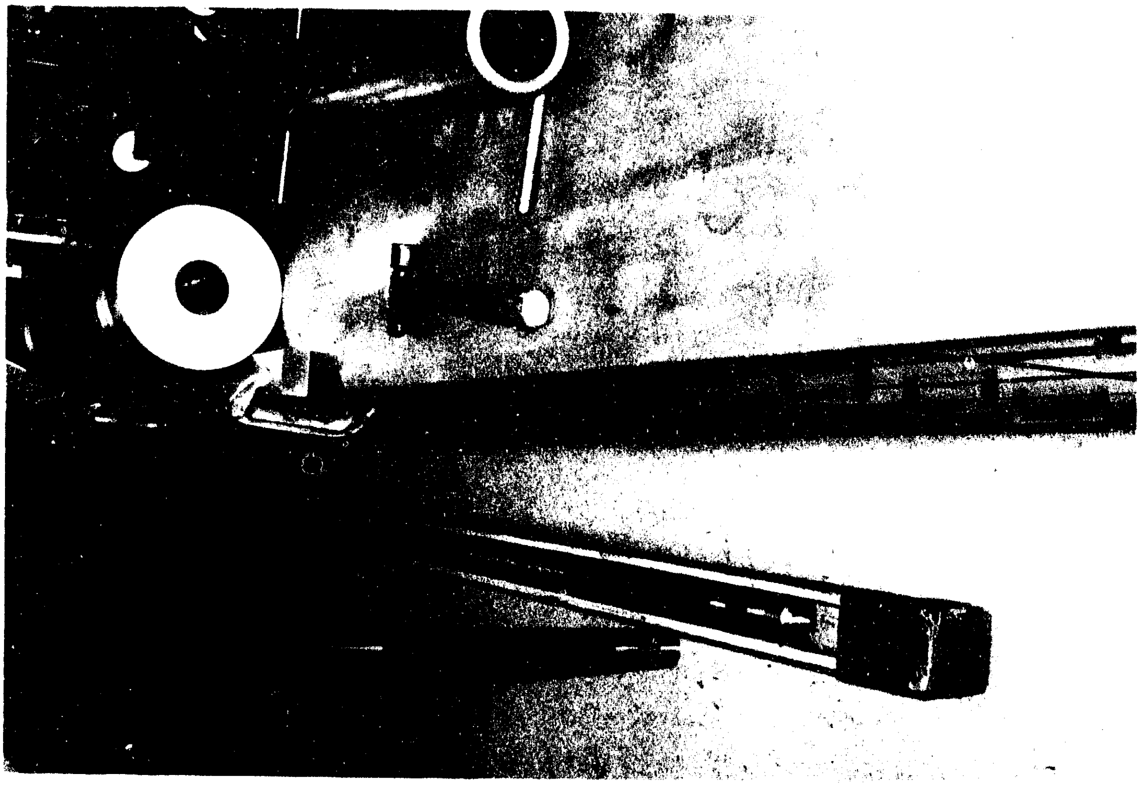


Figure 4.18-6. Probex I (NX) dilatometer (in box) showing expandable membrane (standing upright), aluminum (thick wall), and steel (thin wall) calibration cylinders.

is 91 cm (36 in.) long, 23 cm (9 in.) in diameter, and contains a coaxial cavity that is 7.6 cm (3 in) in diameter. The calibration test procedures and computations were followed as prescribed in the manual provided by the instrument manufacturer.

These initial tests on the aluminum test cylinder yielded results that underestimated Young's modulus for aluminum by about 20%, indicating that the test apparatus was not performing properly. The instrument was drained of its pressurizing fluid (water), and the flexible membrane was removed for inspection of the internal parts of the instrument. Some water was observed in the upper well of the membrane beyond the o-ring seal on the upstream side. In addition, a shallow but persistent helical groove was observed along the upstream portion of the shaft that crossed over the upper o-ring seat. Suspecting a possible source of leakage and a probable cause for underestimating Young's modulus for aluminum, the instrument was returned to the manufacturer on 3/8/89 for inspection of the machining flaw and for repair.

The dilatometer was returned on 3/23/89. Inspection of the shaft revealed that, except for the rims of the o-ring seat, the helical groove had been ground off. During tests of the instrument, the manufacturer noted some loss of fluid (<1 cc) but claimed that this small amount would not adversely affect the performance of the instrument. We repeated all of the tests and again observed small amounts of water (2 cc) where there should not be any. The manufacturer agreed to inspect and test the instrument at no cost to us except for transportation. Before shipping the device on 4/21/89, all o-rings on the shaft, initially supplied by the manufacturer, were replaced by a new batch purchased in Denver. These new o-rings, although of the same dimensions as the "old" ones, appear to be somewhat stiffer.

The manufacturer subjected the dilatometer to three sets of tests: membrane test on a manufacturer-supplied shaft, shaft test in a steel model of the membrane, and membrane-shaft test on the dilatometer as performed numerous times before by both parties. No leaks were detected in any of these tests. Moreover, routine tests found the instrument to be in calibration. The dilatometer was returned on 7/17/89. We repeated our series of tests and observed no leaks. Apparently, the new o-ring batch provided an effective seal. However, tests in the aluminum cylinder still yielded an underestimated value for Young's modulus for aluminum.

The results to date are

2/24/89	E	= 47,300 MPa	(6.86×10^6 psi)	(23% low)
4/4/89	E	= 36,300 MPa	(5.27×10^6 psi)	(41% low)
7/19/89	E	= 36,500 MPa	(5.29×10^6 psi)	(41% low)

Work will continue to improve the performance of this instrument, for example, by finding ways to increase the inherent stiffness of the fluid.

Three-Dimensional Anisotropy Testing

Development work on a true triaxial compression apparatus (Figure 4.18-7) has progressed steadily during the last six months. Four additional proximeter-transducer assemblies were purchased from the Bentley-Nevada Corporation, and work began to design and build null-balance circuits for all six proximeters. Work also progressed on the design of zero-offset circuits for three pressure transducers. Sample preparation techniques have been developed to obtain four 35-mm- (1.4-in.-) oriented cubes from the annular wall of oriented overcores produced during prototype in situ stress testing. This series of oriented cubes is required to fully characterize the directional moduli (Young's modulus and Poisson's ratio) and anisotropy in the overcore sample. The results are to be compared and contrasted with the results obtained with the borehole dilatometer and the biaxial-loading tests on overcores, each of which produces average values of Young's modulus and, as for the latter, partial estimates of property anisotropy.

In Situ Stress Measurements

Stress measurements to date in the G-Tunnel (demonstration and laser drifts) have been only partially successful and are incomplete, pending the drilling of IS-1 in the CBI alcove.

The main problems were the closeness of fractures (Figure 4.18-8), the time-consuming "standard" drilling procedure, and the lack of time (due to scheduling of other prototype tests) to complete site IS-3. The latter two problems are resolvable. In order to obtain an adequate overcore success rate of say 75%, it will be necessary to very accurately locate the least fractured rock intersecting the EX borehole using the borehole video camera. Even then, some fractures will be present in the overcore sample that were not intersected by the EX hole. This problem can be minimized by drilling the entire length of the EX pilot hole first. Zones that look acceptable based on the camera survey are noted and are rapidly reached with the tricone bit. Zones that appear questionable are avoided.

The stress-relief overcoring method of stress measurement appears to be a viable method for use in the ESF, provided the changes in techniques previously noted prove successful.

The testing activities to date have been very helpful in training all personnel involved in those techniques necessary to obtain optimal results in difficult rock conditions.

Future Activities

The activities that need to be started or completed in fiscal year 1990 are as follows:

- Scheduling of approved stress measurements and associated borehole testing in the G-Tunnel.

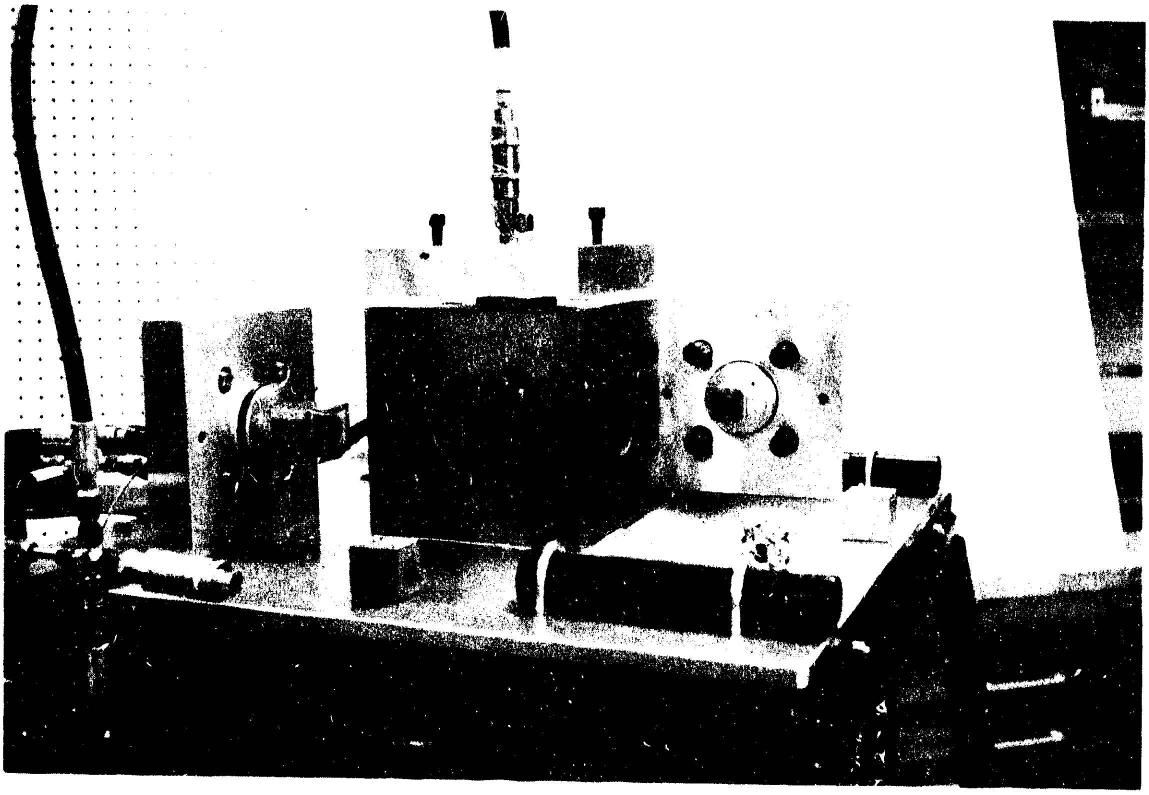


Figure 4.18-7. Triaxial compression apparatus showing adjustable pressure ports and cubical rock test specimens.

Figure 4.18-8. Section of NK core from IS-2 in Demonstration Drift showing closeness of fractures.

- Calibration of the triaxial stress cell and testing of cubical tuff samples.
- Laboratory and field testing of the NX borehole dilatometer. Modification and testing of the EX dilatometer (SCM cell). It is hoped that either or both instruments can be used, as necessary, in the ESF.
- Preparation of a report on the results of laboratory and field prototype investigations in the G-Tunnel.

4.19 Diffusion

General Test Description

The diffusion test proposed for the ESF will measure the rate of solute diffusion into water-filled (or partially filled) pores of the tuffs in the unsaturated zone at Yucca Mountain. In situ measurements of diffusion can be used to derive diffusion coefficients for use in performance assessment calculations. Solute diffusion is likely to be an important mechanism for retarding the water-borne transport of nonsorbing radioactive species.

Prototype diffusion tests are being conducted at the G-Tunnel at the NTS. These tests involve the pressurized injection of a tracer into the tuff at the end of a shallow borehole. After a predetermined period, the tuff surrounding the injection zone is overcored. The resulting core is sectioned and analyzed for tracer concentrations. The distributions of the tracers are used to calculate the in situ diffusivities of solvents in two tuffs (welded and nonwelded) in the unsaturated zone.

Purpose and Objectives

The purpose of prototype testing is to perform all of the operations that will be required in the ES diffusion test to ensure that the procedures and apparatus will function as planned. The test requires the use of drilling and overcoring techniques that are not routine. Pneumatically inflated packers will be in continuous use for periods of several months. Solutions containing tracers will be injected into the tuff using a remote injection system, with the rate and pressure of the injection carefully monitored. Bromide tracers have been used in comparable laboratory experiments, but there is a need to investigate the use of other possible tracers. The conduct of the test, extraction of core, and subsequent analysis of the tracer distribution will be governed by written procedures that need to be developed. The objective of the prototype testing is to ensure that all aspects of the proposed test methodology are viable and to prepare and issue the required written procedures.

Support Required

Diffusion tests will involve both field work at the GTUF and laboratory work. Field work will require dry drilling (using air for cuttings removal) of a vertical access hole and of a smaller hole for injection of tracer at the end of the access hole. A neutron moisture logger will be used to monitor moisture content in the access and tracer injection hole. It might be necessary to inspect the bottom of the access injection hole with a boroscope, to verify the absence of fracture. The injection of the tracer will require mechanical equipment consisting of a sample injector, an inflatable downhole packer to isolate the injection zone, several feet of pipestring for placing the injection apparatus and the packer into the hole, and tubing to deliver nitrogen to the packer assembly. Electronic equipment will be used to monitor and control both the tracer injection and the downhole packer. The electronic control system will be equipped with an alarm system to warn the operator of malfunctions.

At the end of the injection period, the injection zone will be cored, and the sample delivered to the laboratory. Conventional equipment will be used in the laboratory for sectioning and subsequent analysis of the core.

Detailed Test Description

Prototype tests will be conducted in the two rock units that are exposed in the GTUF, which are representative for experimental purposes, of the tuffs that will be exposed in the ESF. The welded Grouse Canyon member of the Belted Range tuff will be used for prototype testing of techniques planned for the welded Topopah Spring Member of the Paintbrush tuff, and the Tunnel Bed 5 tuff will be used as a substitute for the nonwelded tuffaceous beds of the Calico Hills tuff.

The diffusion test requires the pressurized injection of a fluid that contains tracers into a small-diameter hole drilled into the bottom of an access hole. Both the access hole and the injection hole must be cored to allow examination of the tuff. Because the test is designed to obtain data representative of tuff along the flow paths to the accessible environment, it is necessary to conduct the test in rock that has not been significantly altered by excavation of the shaft or drift. Further, the experiment assumes relatively homogeneous unfractured rock, and the injection zone should therefore be relatively free of fractures.

When the injection hole has been successfully completed, a packer assembly will be placed in the hole to isolate the injection zone from the rest of the borehole. Inflation of the packer is maintained by nitrogen gas under pressure. A fluid injection line passes through the packer to permit injection of the tracer into the bottom of the hole. At least two diffusion periods will be used: a relatively short period (about three months) to evaluate the effectiveness of the complete system and a relatively long period (about one year) to obtain data for determining the solute diffusivities in the tuff.

At the end of the diffusion period, the injection and packer system is removed from the borehole, and the access hole is reamed to a larger diameter. A cylindrical core is then taken from the tuff surrounding the injection hole, which encompasses part or all of the tuff where the tracer was injected. The core is sectioned, and each section crushed and leached with water to extract the injected tracer. The spatial distribution of tracer within the core will be used to calculate diffusion coefficients.

Historical Perspective and Background

Measurements of diffusion of solutes will be conducted in the laboratory, using samples of tuff collected from Yucca Mountain. However, it is difficult to preserve the integrity of the tuff during the coring, and many fractures could be introduced into the sample as a result of the coring. In addition, it is difficult to simulate the ambient rock stress in laboratory experiments and to preserve the ambient water content and water chemistry during sample collection.

Confidence in the representativeness of the calculated diffusion coefficients will be enhanced if experiments are conducted in situ. Because the experiments proposed for the ESF have not been previously conducted in the unsaturated zone, the necessary methods and procedures have not been developed. Thus, field work in the GTUF was a necessary prerequisite to ESF diffusion tests.

Measurements of the type proposed for Yucca Mountain have been performed at the Stripa Mine in Sweden as part of the Swedish nuclear waste disposal program.[21] A mixture of three nonsorbing tracers was injected into the granitic rock matrix for times of 3 months, 6 months, and 3.5 years to measure in situ diffusivities. The field test results were compared with laboratory measurements. This work has helped guide the measurements proposed for Yucca Mountain. The field conditions differ so greatly between the saturated granite of interest in Sweden and the unsaturated tuffs at Yucca Mountain that the concepts are the main features shared by the two sets of measurements.

Evolution of Test Design

The design of the diffusion test is based on calculations made with the aid of a transport and diffusion computer model.[22] A simulation was performed of the radial movement of the tracer from the center of a cylinder. Tracer concentrations were calculated in sampling regions as illustrated in Figure 4.19-1. Tracer concentrations in each region were simulated for several different values of diffusivity. The computer simulation of the diffusion test used values for moisture content, porosity, diffusivity, and other rock properties that are representative of the tuffs to be exposed in the ESF. Prototype testing in the GTUF is expected to yield similar results because the tuffs exposed in the G-Tunnel have physical properties similar to those that will be encountered in the ESF.

A key aspect of the computer modeling of the diffusion test is the evaluation of the effect of errors in the measurement of tracer concentrations on the calculated values of the diffusivity. Simulations of these effects, combined with a statement of the desired accuracy in the diffusion coefficient, allow a stipulation of the required concentration of the tracer and the associated analytical accuracy for measurement of the tracer concentrations in the extracted core. The computer simulations of the diffusion experiments have demonstrated that even relatively large errors (up to 50%) in measurement of tracer concentrations will not have a significant effect on calculated diffusion coefficients.

A recognized uncertainty that could invalidate the results of diffusion tests is the possible presence of fractures in the tuff surrounding the injection zone. The analysis of the test assumes homogeneous material, and the presence of a fracture could invalidate this assumption. The injection hole will be inspected before the test for the presence of fractures. However, the total absence of fractures within the sampled region and the effect of any fractures present will not be established until after the test is completed. One anticipated result of the prototype testing is the determination of the effects that fractures have on the

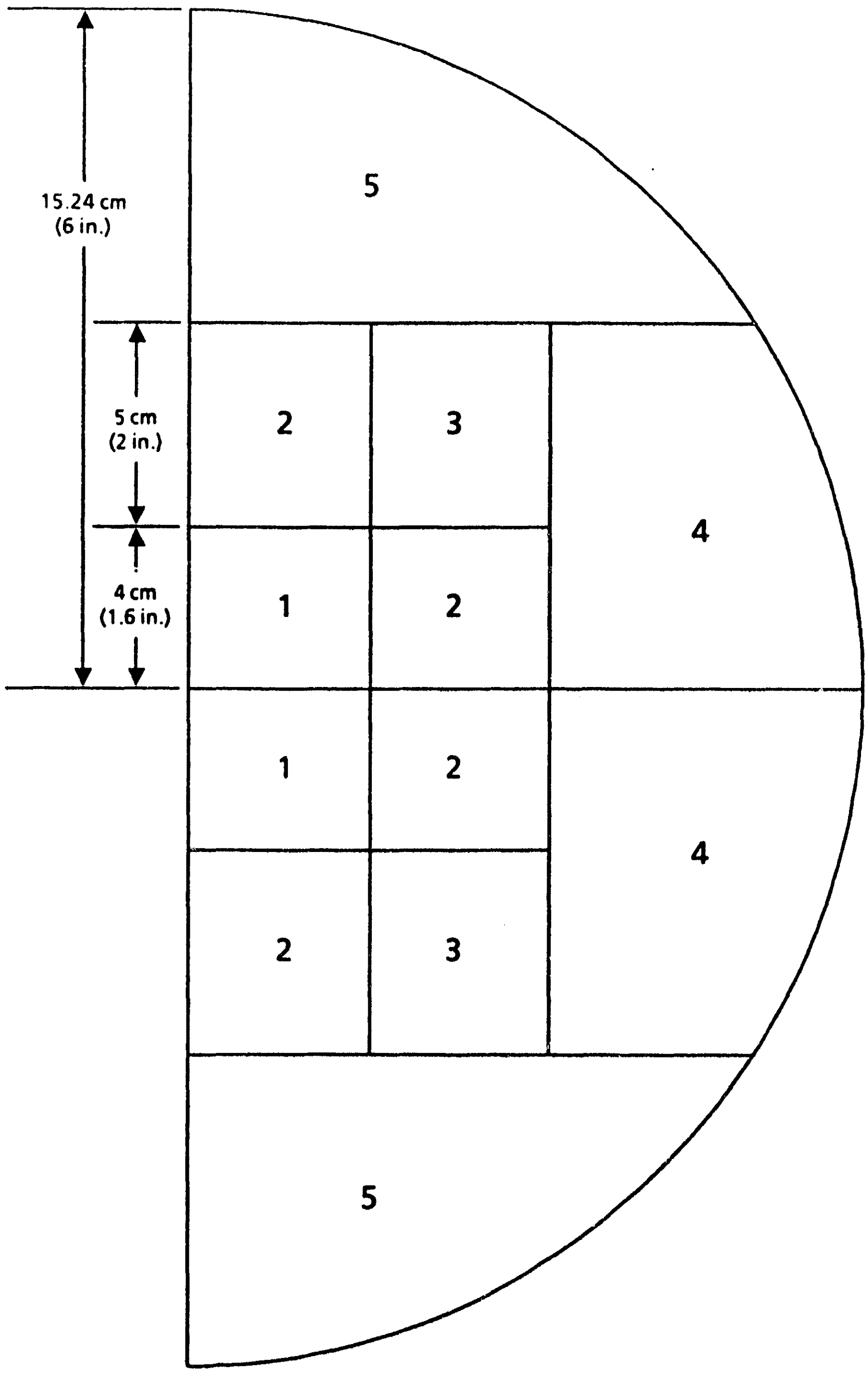


Figure 4.19-1. Diagram of sample locations.

experimental results and on the possible methods for interpreting tracer distributions associated with fractured material.

Another concern in undertaking this test is the effect of introducing the tracers in an aqueous solution. In this case, tracers can move into the tuff by advection as well as by diffusion. Calculations were performed[22] in which solute transport into the tuff was compared for pure diffusion in one case with diffusion plus advection in a second calculation. The 1×10^{-3} g cm^{-3} concentration profile after a year's time had moved 31% farther into the Topopah Spring tuff from the edge of the injection hole under the combined effects of advection and diffusion than under diffusion alone. The difference was 12% for the Calico Hills tuff in the same type of comparison. These calculations indicate that the effects of advection will have to be removed before the effective diffusion coefficients are calculated from the data.

Conduct of Test

A readiness review was conducted by the Yucca Mountain Project Office on April 18, 1988, and the implementation of a criteria letter for field support of this task was approved on May 16, 1988. Air coring of access holes was begun on June 20, 1988. Three vertical boreholes (two in welded tuff, and one in nonwelded tuff) were completed to depths of approximately 9 m (30 ft) by the end of August 1988.

Some difficulties were experienced with core recovery and proper centering of the injection hole in the bottom of the access hole. Modifications to the drilling and coring equipment were implemented to facilitate the drilling and coring. However, additional development is needed, particularly with regard to retrieval of small-diameter core from the injection hole. Successful core recovery is important from an experimental perspective to allow for direct observation of the presence of fractures in the injection zone. A boroscope was used successfully to inspect the condition of the injection hole and to inspect for the presence of fractures in the walls of the injection hole. However, visual observations are not sufficient to instill confidence that no fractures are present.

When the first borehole in welded tuff was completed, temperature and neutron probe measurements were made to monitor the rate of reestablishment of ambient conditions in the tuff surrounding the borehole. It is important, for proper conduct of the test, that temperature and moisture conditions surrounding the borehole be at ambient conditions. The measurements showed that the air coring raised rock temperatures only slightly above ambient temperatures and that ambient temperatures were re-established within one hour after completion of drilling. Neutron probe measurements were made in the other two boreholes. No significant effects of the air coring were observable in the neutron probe data. Thus, the air coring did not appear to dry the tuff in the walls of the borehole to the extent that any moisture re-equilibration could be observed over a month's time.

Tracer injection equipment was placed in one borehole in welded tuff and in one borehole in nonwelded tuff. Downhole testing of the packer assemblies revealed some pressure leaks that required correction. More extensive testing of the apparatus before downhole placement is required for future tests. Nitrogen losses to the tuff surrounding the injection zone, where overpressure is .01 mPa (1.5 psi), would require replacement of the nitrogen supply every two weeks during the test. This was considered excessive, and a decision was made to run the tests without pressurization in the chamber below the packer assembly. The reason for the overpressure was to provide a means to detect any failure of the packer to seal the borehole. Monitoring the pressure in the packer was found to be sufficient for this purpose. The control instrumentation in the exploratory shaft will be modified as a result of this prototype testing to facilitate operating in the current mode.

By the end of September 1989, the injection and control apparatus was determined to be working correctly in both holes, and tracer injection into both holes was initiated. Overcoring of the borehole in the nonwelded tuff was started in January 1989. After nearly three weeks of work, the overcoring had progressed to a depth of 3 m (10 ft), and the core recovery had dropped to zero. A depth of 10.5 m (34.5 ft) with good core recovery was required for successful completion of this prototype test. Additional diffusion does not impair the conduct of this test, so the packer was reinstalled. A different type of drill rig has been ordered, which is expected to permit the successful overcoring of both prototype diffusion test boreholes.

Future Activities

The overcoring portion of the prototype testing in the G-Tunnel will be undertaken after delivery of the equipment that is currently on order. The two cores from this test will be shipped to Los Alamos, sectioned, and analyzed for tracer concentrations. The data will be analyzed to determine the in situ effective diffusivities. Laboratory experiments will be performed with similar pieces of the nonwelded and welded tuffs into which the tracers diffused in the G-Tunnel. The results from in situ and laboratory tests will be compared with each other and with the calculations of the expected results to help improve the accuracy of diffusion modeling. Procedures for the exploratory shaft diffusion test will be written, based on field experience gained in prototype field work performed in the G-Tunnel.

4.20 Evaluation of the Engineered Barrier System

General Test Description

The emplacement of high-level nuclear waste into tuffs or any geologic medium will result in the deposition of large amounts of heat into the rock in the vicinity of the waste containers. Furthermore, the waste will generate heat over an extended period. The long-term effects of this heat deposition are unknown, but they must be evaluated to understand and predict the response of the waste package and the natural environment during the period required for waste isolation.[23]

Of particular interest are the relationships between the thermal load and the initial flow of fluid and gas away from the heat source, and then the flow back toward the source as the waste cools; the relationship of thermally-induced stress changes to flow behavior; and the chemical alteration that can occur because of heating, drying, and rewetting of the rock. Testing will be conducted in the ESF to gain an understanding of the near-field effects of heating and cooling a rock mass around a simulated waste package. The prototype test is being conducted before the ESF testing in order to validate and refine the test design, equipment, and methods. The testing will facilitate the collection of field-scale data that can be used to test computer models[24] and the underlying assumptions about physical processes in unsaturated welded tuff.

The prototype test of the engineered barrier system consists of a series of laboratory and field tests to be conducted in the G-Tunnel by LLNL.

Purpose and Objectives

The primary purpose of the prototype test is to evaluate the technical feasibility of defining the hydrologic and thermomechanical behavior of the near-field rock mass during a heating and cooling cycle of a simulated waste package.

Specific objectives of the test are

- the evaluation of the effectiveness of various measurement techniques for monitoring hydrologic and thermomechanical responses under realistic conditions;
- the provision of data that can be used to improve understanding of the hydrologic and thermomechanical responses of welded tuff around a heat source; and
- the development and evaluation of technical procedures under realistic field conditions so that final procedures can be prepared for ESF testing.

One of the potential benefits of prototype testing is the establishment of an acceptable degree of flexibility in producing procedures and test plans, while maintaining an adequate level of specification. This balance between specification and flexibility will allow the latitude necessary for professional judgement, while ensuring that testing is successful and well documented.

Support Requirements

REECo and H&N will support the work. This support consists of the drilling of boreholes for the installation of heaters and instrumentation and the operation of testing equipment.

Detailed Test Description

The prototype test involves field and laboratory investigations. Laboratory testing is used to investigate various grouting materials used to seal or isolate sections of boreholes. Laboratory tests will also be used to calibrate and test instruments before deployment in the field. Field work will be conducted in four phases. The first phase involves determination of baseline geologic and hydrologic conditions at ambient temperatures. During the second phase, heat is applied to the rock according to a predetermined thermal-loading schedule. The objective of this phase is to monitor various parameters as the temperature in the rock mass increases. The cool-down period is the third phase, during which the application of heat is decremented to simulate gradual cooling of the waste. Of particular significance are the measurements obtained when the maximum drying occurs at the end of the heat phase and when the temperature of the rock mass begins to drop below the boiling point of water. The final stage is referred to as the post-thermal stage and involves the monitoring of the rock mass during a period following the cessation of heating.

The first test is designed to simulate a horizontal waste-emplacement scheme. It is expected that the vertical-emplacement configuration will be implemented in subsequent prototype tests. To simulate the horizontal scheme, the heater is oriented horizontally parallel to a small-diameter heater alcove (Figure 4.20-1). Boreholes, drilled at various orientations relative to the heater, contain the instruments that gather data describing various properties of the rock and fluids (Figure 4.20-2). The instruments that will be emplaced in the boreholes are borescopes and borehole videocameras used before testing to map fracture locations and orientations, psychrometers or air-humidity gauges (to determine the water potential of the rock); thermocouples (for temperature measurement); neutron-density and gamma/gamma-density logging tools (for moisture content measurement); pressure transducers (to monitor air pressure inside sealed boreholes); data-acquisition and recording equipment; and inflatable packers, flow meters, and pressure transducers (for gas permeability measurement). Performance of the instrumentation will be evaluated based on recorded data, visual inspection, and, if necessary, post-test calibration. Data

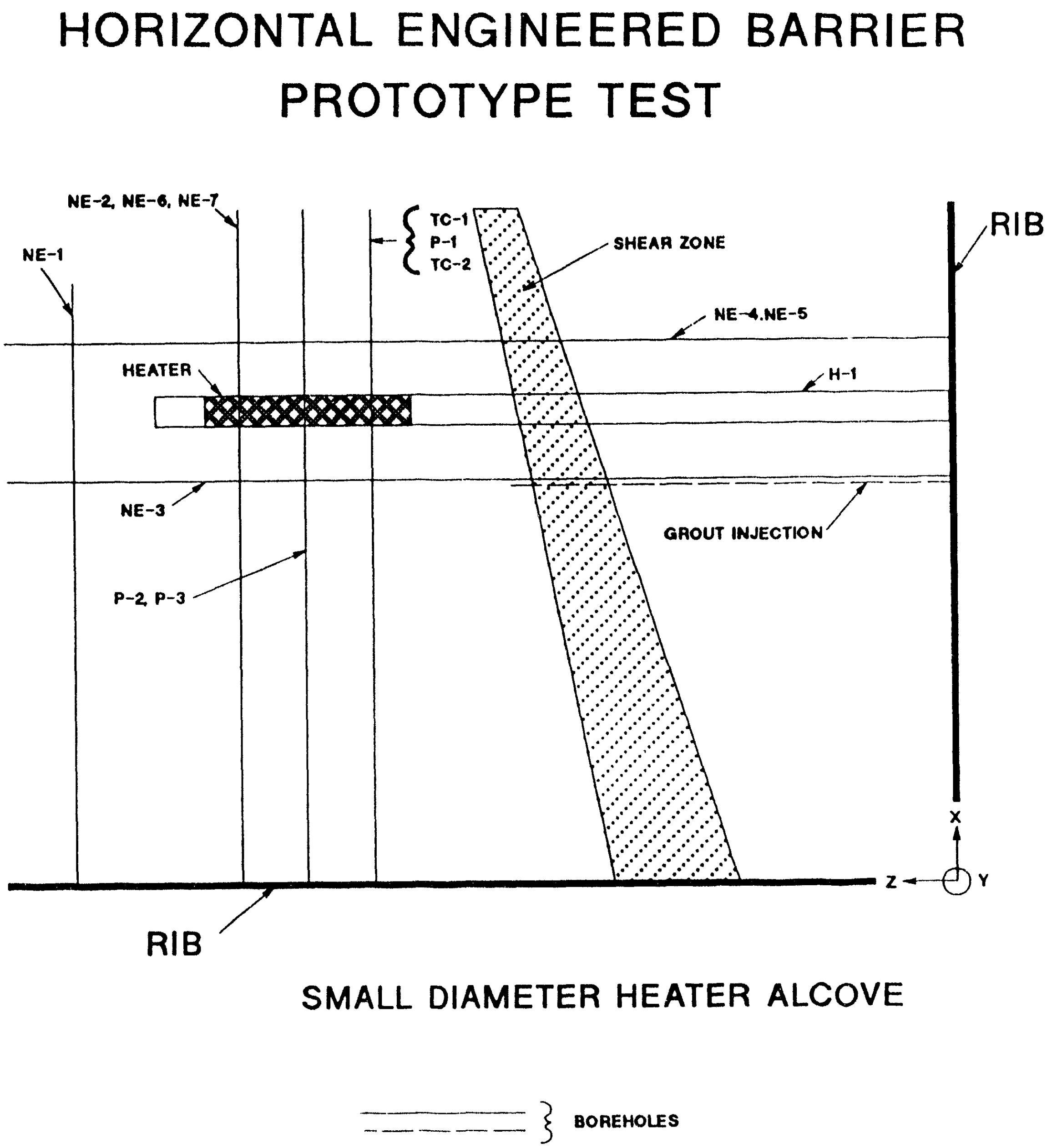


Figure 4.20-1. Plan view of the borehole layout (the location of the rock mechanics incline and the small-diameter heater alcove in the G-Tunnel are shown for reference).

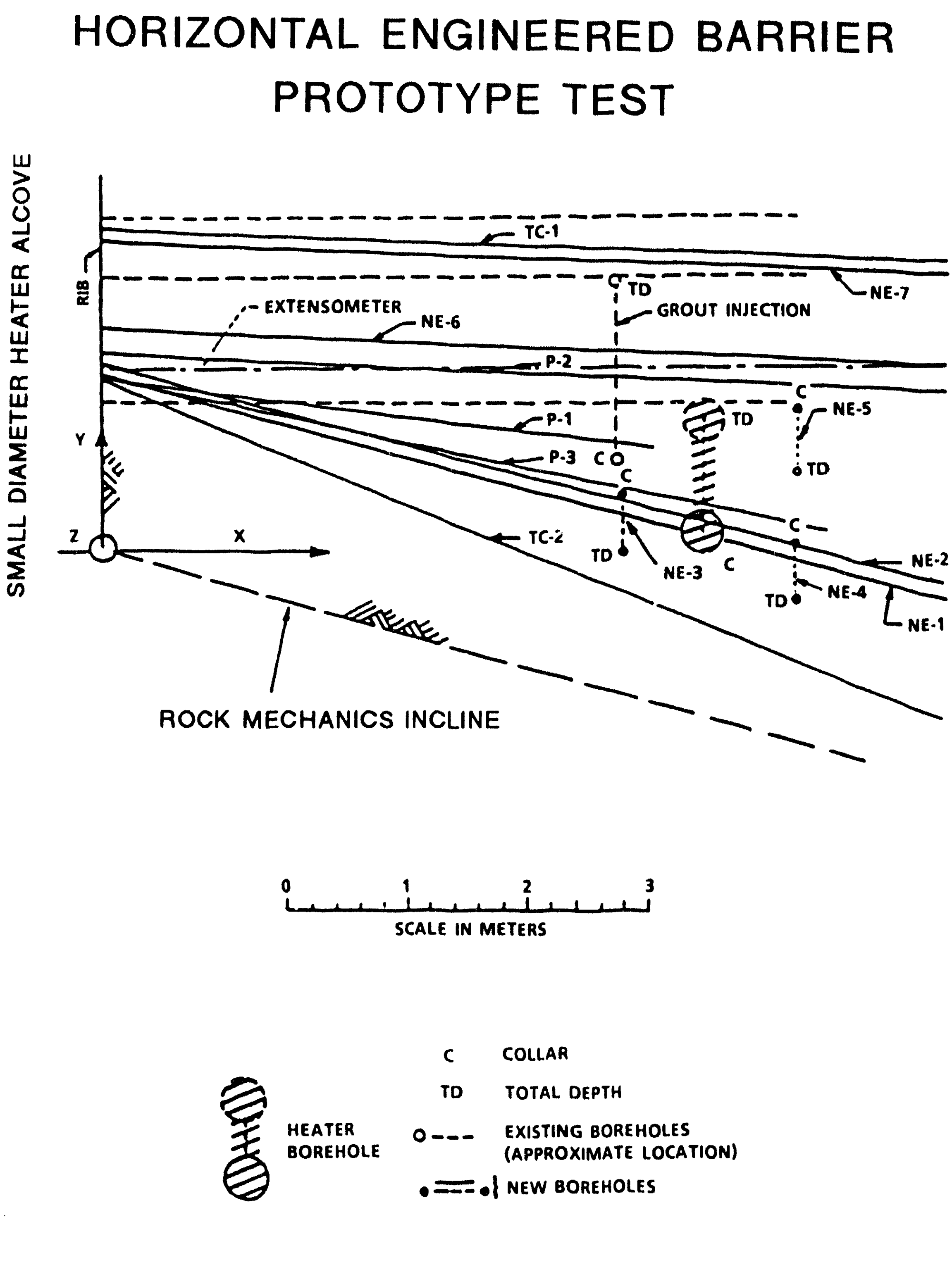


Figure 4.20-2. Cross section view of the planned borehole layout (this view is parallel to the azimuth of the rock mechanics incline).

obtained during the heating and cooling cycle will be used to infer the hydrologic and thermal environment around the heater borehole, and, ultimately, to assist in the development of models. Following the test cycle, a number of the grouted and sealed boreholes will be overcored to allow inspection and assessment of the condition of the seals and the instrumentation.

The testing includes the following sequence:

1. Perform scoping calculations in support of the development of test plans.
2. Develop specifications and preliminary procedures for calibration, installation, and operation of test components.
3. Fabricate or procure test components.
4. Calibrate sensors and other equipment before installation.
5. Install test components.
6. Conduct pretest gas permeability measurements and begin collecting preheat baseline data from all measurement systems.
7. Conduct the test.
8. Conduct gas permeability measurements along the heater emplacement borehole after the heater is removed (these measurements allow a comparison of pre- and post-test gas permeabilities).
9. Evaluate instrument performance based on recorded data, visual inspection, and, when necessary, post-test calibration.
10. Interpret the data to infer, for use in model development, the hydrologic and thermal environment around the heater emplacement borehole.
11. Overcore two of the grouted and sealed boreholes to allow visual inspection of the seals.

Historical Perspective and Background

The prototype tests are being conducted in the G-Tunnel in the Grouse Canyon welded tuff layer, which has properties similar to those expected for the Topopah Springs welded tuff unit in Yucca Mountain.[25] These prototype tests are designed to evaluate the performance of measurement techniques and hardware under conditions similar to those in the ESF. The hydrologic environment expected to develop around a heater during thermal loading is shown schematically in Figure 4.20-3. With time, the heat will dry the partially saturated rock near the emplacement borehole. The water vapor formed will be driven by vapor pressure gradients through the matrix until it intersects a fracture; it will then move down-gradient along the fracture as noted in laboratory work performed.[26] The water vapor will condense where temperatures are sufficiently cool. Part of this water might move into the matrix because of capillary tension; the remainder might stay in the fracture, held by capillary forces, or it might flow along the fracture down-gradient. The percentage of water that moves into the matrix will depend on the degree of saturation of the matrix, matrix hydraulic conductivity, and contact time between fracture water and matrix. When the dried region is allowed to cool, it is expected to slowly re-wet because of pore pressure and saturation gradients that develop in the rock around the heater.

Measurements of several parameters are needed to characterize the response of the rock mass in the near-field environment surrounding the heater.

- Rock mass temperatures will be used in reconstructing the thermal response of the rock and in evaluating the performance of test equipment during the test.
- Rock mass gas pressure and atmospheric pressure will be used in reconstructing the flow regime of the air and water vapor in the rock mass.

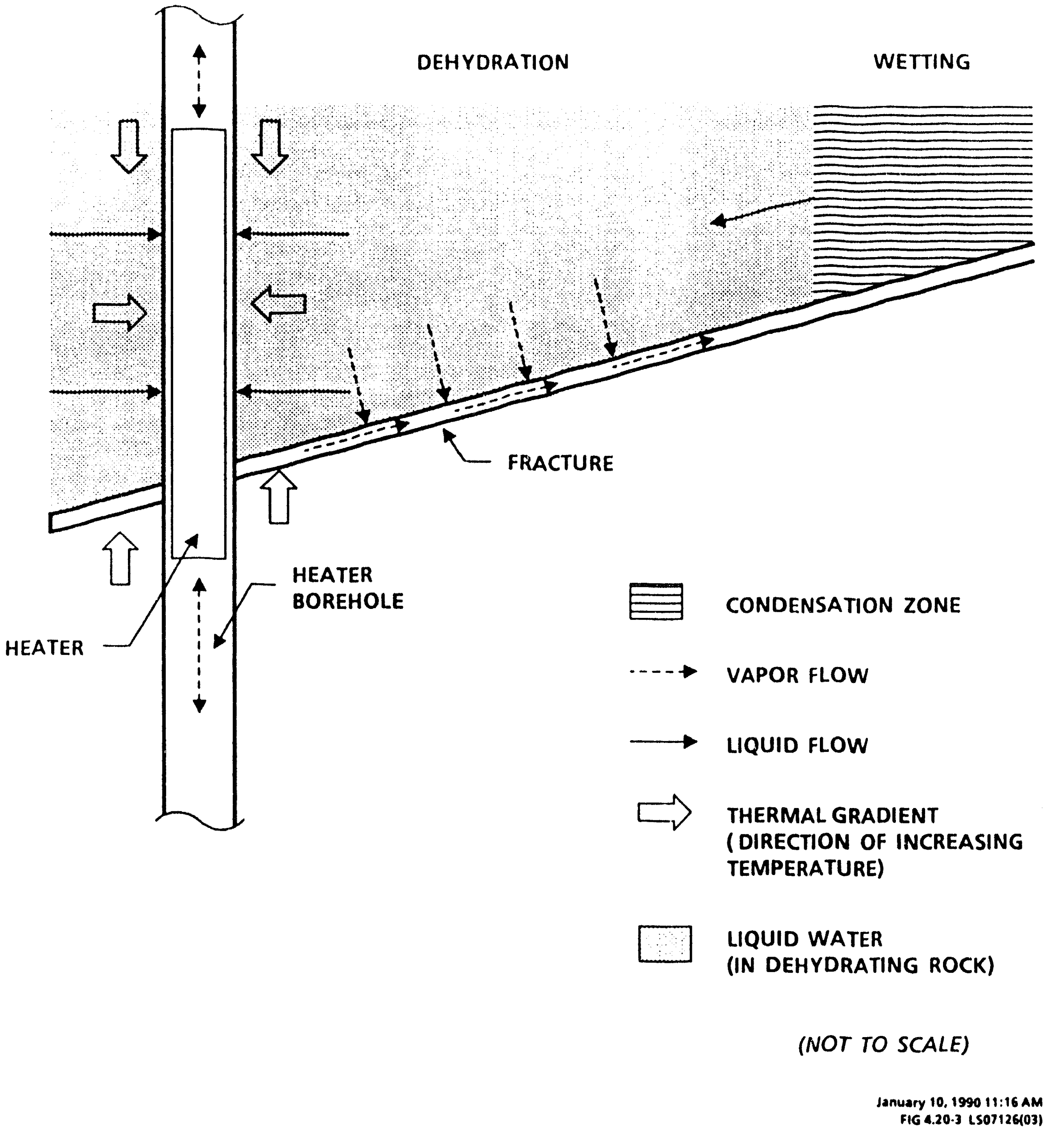


Figure 4.20-3. Schematic representation of a probable hydrologic scenario in partially saturated welded tuff subjected to a thermal load.

- Cross-hole measurements of the relative dielectric constant of the rock and single borehole measurements of thermal neutron counts will be used to infer the spatial and temporal changes in moisture content of the rock mass.
- Air humidity measurements in the rock mass will be used to calculate pore pressure gradients that drive the movement of liquid water within the rock mass. Changes in moisture content and pore pressure information will be used to reconstruct the flow regime of liquid water in the rock mass. Spatial variations in moisture content will be used to infer the flow paths of the liquid water and to define regions that are losing or gaining water as a function of time.
- Air permeability measurements will be used to detect changes in the permeability of rock surrounding the emplacement borehole. These measurements were made along the heater borehole as soon as all of the other boreholes were drilled and sealed. The measurements will be repeated after the heating sequence is completed and the heater removed from the borehole.
- Fracture locations and orientations will be measured in all of the boreholes by borescope and/or borehole videocamera surveys performed before the heater is energized. These surveys will be repeated along the emplacement borehole after the test is completed. This information is needed to understand the effects of heating on the stability of emplacement borehole walls and to help interpret changes in fracture permeability caused by the heating and cooling cycle. The information will also aid in interpreting the flow regime of vapor and liquid water in the rock mass as inferred from other measurements.

Evolution of Test Design

The test utilizes an accelerated thermal cycle to examine the effects of thermal pulse heating and cooling. The initial thermal loading for the 3-m (9.8-ft) heater is approximately 3 kW (1kW/m) and will be applied for approximately 4 months. This initial thermal load per unit length of emplacement borehole is set higher than the loading expected for a typical spent fuel container (0.4-0.7 kW/m) in an attempt to increase the volume of rock to be thermally disturbed in the relatively short period available for prototype testing. The higher thermal loading will create sufficiently high rock temperatures to drive two-phase fluid flow. The duration of heating is based on the criteria of heating the rock mass so that the boiling point isotherm moves approximately .65 m (2 ft) radially from the heater borehole wall. This spatial extent of heating will affect a volume of rock large enough to include several fractures.

In order to better characterize the response of the rock mass, two of the measurements have been added since the original test concept was developed. They are the gas pressure and air permeability measurements. The orientation and spacing of boreholes not specified in the original test concept have also evolved. These spacings and orientations will be modified as needed before implementing Engineered Barrier System (EBS) testing in the ESF.

Conduct of Test

Work in the prototype test of the EBS for the horizontal configuration has progressed to Phase 3, which involves measurements and data acquisition during the cool-down cycle. Preparation for the start of the testing occurred during the middle and later months of 1988 and included alcove drilling and wiring; the drilling, grouting and sealing, and video inspection of boreholes; tests of seals; safety inspection; cross-hole logging; heater test; and the calibration and inspection of instrument packages. The heating cycle and data acquisition were initiated in August 1988. Data acquisition has continued concurrently with the performance of neutron and electromagnetic logging and the decremental turn-off of the heaters, which began in late March 1989. Thus far, the testing has refined and tested most of the equipment and procedures needed to perform the test of the engineered barrier system.

Moisture Content

Plots of moisture content versus radial distance from the heater's center show that during the early stages of heating (five days after start of heating) rock at higher elevations generally shows a greater increase in moisture content than rock below the heater at the same radial distance. This asymmetry in response was unexpected, and the reason for it is unclear at present. It might be due to differences in fracture density adjacent to various monitoring holes. It might be related to a higher initial moisture content (from drilling water) below the heater. It might also be an indication of the tendency of the steam to move upward preferentially because of buoyancy.

In summary, the neutron data for the rock directly above the heater showed an early wetting episode (i.e., increased moisture content) followed by slight drying episodes. The data from directly below the heater showed evidence of a higher degree of drying early, and then continued drying with time. Rock to either side of the heater borehole, whether higher or lower in elevation than the heater, showed an early wetting episode that later dissipated. For locations closer to the heater, a drying episode followed, and for the rock farthest from the heater, continuing increases in moisture were observed.

Temperature

Temperature data collected after approximately seven weeks of heating are illustrative of the thermal responses observed in the testing. The thermal gradient is larger near the heater, which indicates heat transfer by conduction. The temperatures above the heater container are greater than those below the heater, which might be related to the temperature on top of the heater's can being greater than that at the bottom.

There are a few thermocouple locations that are cooler than the remaining locations for values of the radial distance less than 1 m (3.3 ft). At these locations, fractures were mapped in close proximity (within a few centimeters) of the thermocouple locations. This close proximity suggests that the depressed temperature values near the heater borehole are caused by fractures. At least two explanations can be postulated. First, the fractures create more permeable flow paths for vapor to escape the system. As water is converted to vapor and allowed to escape, energy is removed from these locations. This energy is therefore not available to elevate the rock temperatures. Second, the fractures also create flow paths along which drilling water moves downward. Borehole P-3 is lower in elevation than P-2 (Figure 4.20-2). The matrix adjacent to these fractures might have imbibed some of the drill water, thereby increasing the initial saturation near the fractures. This elevated saturation would also tend to depress the local temperature for the same reason stated in the first explanation.

Water Flow

The thermal loading exerted by the heater dries the partially saturated rock surrounding the emplacement borehole. Vapor pressure gradients drive water vapor into pressure sinks such as the emplacement borehole and fractures (Figure 4.20-3). Water vapor might also move along fractures toward the emplacement hole or outward and condense where temperatures are sufficiently cool. Moisture entering the heater emplacement borehole is being collected to provide a measure of the resistance to vapor transport toward the heater relative to the resistance to transport away from the heater as a function of time.

An insignificant volume of water was collected within the first two weeks of the experiment. Thereafter, the rate of water collection has been approximately 0.1 liters per day, which is less than the value predicted by the scoping calculation (approximately 0.5 liter per day).

The reasons for this discrepancy are unclear at present. One possible explanation is that the packer temperature at the intake point for the system is below the dew point. This might have caused some vapor to condense, pond, and possibly drain into fractures, instead of entering the center pipe at the packer. However, relative humidity measurements in the emplacement borehole, using a Humicap sensor on the back surface of the packer, show that the relative humidity remained below 100%, except during the first four days of heating. On the other hand, temperatures measured directly on the packer near the borehole wall are generally about 9° C lower than Humicap temperatures. These results suggest that following the first four days of heating no condensation occurred at the Humicap location, yet temperatures at some points on the packer were below the dew point, and condensation might have occurred at those points. Another possible reason for the discrepancy is that the scoping calculations assume an infinitely long heater. This assumption would cause a substantial overestimation of the steam produced. Additional work is in progress to evaluate the impact of this assumption.

Summary of Results

The test confirmed elements of the conceptual model of predicted environmental conditions.[27] Test results confirm that a dry zone develops around the heater borehole, and the degree of drying increases with proximity to the heater. A "halo" of increased saturation develops adjacent to the dry region and migrates away from the heater as rock temperatures increase. Some of the fractures intercepting the heater borehole increase the penetration of hot-dry conditions into the rock mass. A buildup of pore gas pressure develops in rock regions where vigorous evaporation is occurring. The air permeability of the fracture system exhibits a strong heterogeneity.

The test also yielded some surprises in terms of environmental conditions. The temperature above the heater container is approximately 30° C higher than below the container. This condition might be a consequence of hotter air accumulating at the top of the container; it might also be related to the higher moisture content present below the heater borehole. The amount of steam predicted by scoping calculations to invade the heater borehole is much less than that expected. The reason(s) for this discrepancy is not known at present; it might be a consequence of an inadequate system used to collect and condense the steam or a result of the calculation's assumption that the heater is infinitely long.

The instrumentation's performance for the various sensors used exhibits considerable variability. As expected, temperature measurements made with thermocouples and RTDs show that both types of sensors are sufficiently rugged and accurate. Similarly, neutron and gamma ray tools were rugged enough to withstand temperatures of up to 70° C (manufacturer's specification); in borehole locations where temperatures are above 70° C, the probe is removed periodically to allow probe temperatures to drop below 70° C. Another sensor exhibiting reliable performance is the Humicap capacitance sensor used to measure air humidity in the heater's borehole.

Laboratory measurements of air humidity made with the microwave resonator showed that in principle the technique is sufficiently sensitive. However, field results to date suggest that its calibration curves have shifted. The reason for these shifts is not well understood. These resonators will be recovered upon completion of the test for further evaluation and testing. Air humidity measurements made with thermocouple psychrometers appear to imply a hydrologic scenario consistent, in a qualitative sense, with that expected a priori. However, at present, it has not been demonstrated that these sensors can provide absolute measurements of suction over the range of relevant temperature conditions. Gas pressure transducers used during the early part of the test showed a significant change in their calibration characteristics as pressures changed. These sensors have since been replaced with those from a different manufacturer, and the problem appears to have been solved.

Future Activities

Measurements will continue for approximately two to three months after the heater has been turned off. After that, a few of the test boreholes will be overcored to recover sensors, grout/liner seals, and rock samples that have been perturbed by the test for post-test examinations. The numerical simulations will be repeated assuming a heater of finite length. Upon the completion of the EBS testing for the horizontal emplacement configuration, a second prototype test will be conducted using a vertical borehole in welded tuff for heater emplacement. As the testing is completed over the following months, methods will be finalized for use in analogous tests to be performed in the ESF.

4.21 Air Coring

General Test Description

USGS hydrologists are concerned that water, which is introduced into formations during drilling operations necessary to conduct ESF tests, could invalidate the hydrologic data obtained from many of the ESF tests.[28,29] Core drilling is normally accomplished by using water or a mixture of water, air, and a foaming agent as a circulating medium, the purpose of which is to reduce the likelihood of drill rods becoming stuck or lost in the hole. The process of air coring is being evaluated as a substitute for water drilling in the ESF because the use of air as the circulating medium eliminates the potential for introducing water into the drilled formations.

Air coring shares some basic concepts with standard drilling techniques. As the hollow-core bit rotates, rock is pulverized and must be removed from the hole. Compressed air is introduced through the hollow drill stem, the rock dust is blown from the area of the drill bit, carried from the hole in the air stream, and collected at the surface.

The air-coring tests will be conducted in fractured welded tuffs in the G-Tunnel. The tuffs in the G-Tunnel have fracture densities and compressive strengths similar to those expected in the ESF and are believed to represent a drilling environment that is analogous to that expected during ESF drilling. The prototype air-coring test is a field operation to drill two holes, but it uses data from other prototype tests in which five holes were cored to determine preliminary standards of equipment performance. The two holes are used to demonstrate the effectiveness of the drilling technique and the acceptability of dust collection methods in limiting or eliminating air contamination and health hazards.

Purpose and Objectives

Numerous tests are planned in the ESF to acquire data on geologic, hydrologic, geomechanical, geochemical, and waste-package environment properties to contribute to site characterization at Yucca Mountain. The diverse nature of the testing will require the drilling of several different types of holes. The most recent compilation shows that more than 300 holes totaling more than 3050 m (10,000 ft) of air-cored hole are required to support ESF testing requirements.[1]

There is extensive information on horizontal drilling, air mixes (i.e., air foam and air mist) and hard rock environments. However, documented experience pertaining to horizontal air coring in hard fractured rock in a mine environment is meager. The purpose of the prototype air-coring test is to develop air coring into a viable cost- and time-effective technique, to refine the technique for application to the specific needs of the ESF testing program, and to train the personnel needed to perform the drilling.

The air-coring prototype test has the following objectives:

- Obtain samples as near to natural conditions as possible;
- Determine hole stability through zones that are unstable and may not stay open or that are so highly fractured the cuttings bind up the drill rod and cause related problems;
- Produce cores from holes in highly fractured or unstable rocks for the validation of coring systems, the evaluation of core recovery efficiency, and for testing required by other prototype activities;
- Develop and evaluate procedures to operate instruments and logging devices in unstable holes;
- Evaluate dust control systems for dry underground drilling relative to operational interface with drilling

systems, air requirements, collaring requirements, and health and safety concerns;

- Validate the ODEX method (a system that provides stability for horizontal holes in highly fractured rock) for use underground during intermittent coring. This objective is contingent upon the availability of a rig capable of percussion drilling underground;
- Determine optimal rig performance by identifying and correlating the drilling equipment that is appropriate for the coring, boring, and percussing requirements of other prototype test activities;
- Evaluate commercially available equipment for coring, determine what depths can be achieved successfully within specified cost and time parameters, and determine what, if any, modifications can be made to available equipment to enhance performance;
- Determine penetration rates for coring in hard, fractured tuff;
- Evaluate hole stabilization by advancing the casing intermittently with coring;
- Record real-time data on drilling parameters, such as bit thrust, RPM, air-system requirements, and vibration;
- Evaluate impact of space constraints on operating procedures;
- Develop specific, efficient operating parameters before beginning operations in the ESF;
- Evaluate safety concerns;
- Develop estimates for drilling operations so that ESF planning is realistic;
- Provide information on air coring to PIs of other prototype tests;
- Evaluate volume of particulates and cuttings generated, hopper-size requirements for coarse particles, time cycle for hopper dumping, and procedural adequacy for removing collected drilling products from the immediate work area;

and

- Evaluate engineering/design for each drilling-related system function in advance of experiments in the ESF.

Support Required

The NTS contract will provide engineering support, labor, and construction equipment with supplies to accomplish the work.

Detailed Test Description

As part of the prototype test, two horizontal holes 45.7 m (150 ft) long and 15.2 m (50 ft) long are air-cored in the densely welded, fractured tuff in the G-Tunnel drift to simulate the difficult drilling conditions at Yucca Mountain. The 15.2-m (50-ft) hole (AC-1) is used primarily for the validation of the methods and equipment for dust collection, and the 45.7-m (150-ft) hole (AC-2) is intended primarily to collect data to evaluate the effectiveness of the air coring technique, although both types of information are collected from both holes. AC-2 was purposely sited in unit B of the Grouse Canyon member in the GTUF because this unit contains extremely hard lenses of flattened pumice fiamme and represents arguably the most difficult drilling environment. Figure 4.21-1 illustrates the major drilling and dust collection equipment.

Historical Perspective and Background

A review of current technology through professional contacts and literature was supplemented with an examination of assorted case histories. These case studies provided information relevant to the objectives and requirements of the prototype air-coring test. There is extensive information on horizontal drilling, air mixes (i.e., air foam and air mist) and hard rock environments. However, documented experience is meager for air coring horizontally in hard fractured rock in a mine environment.

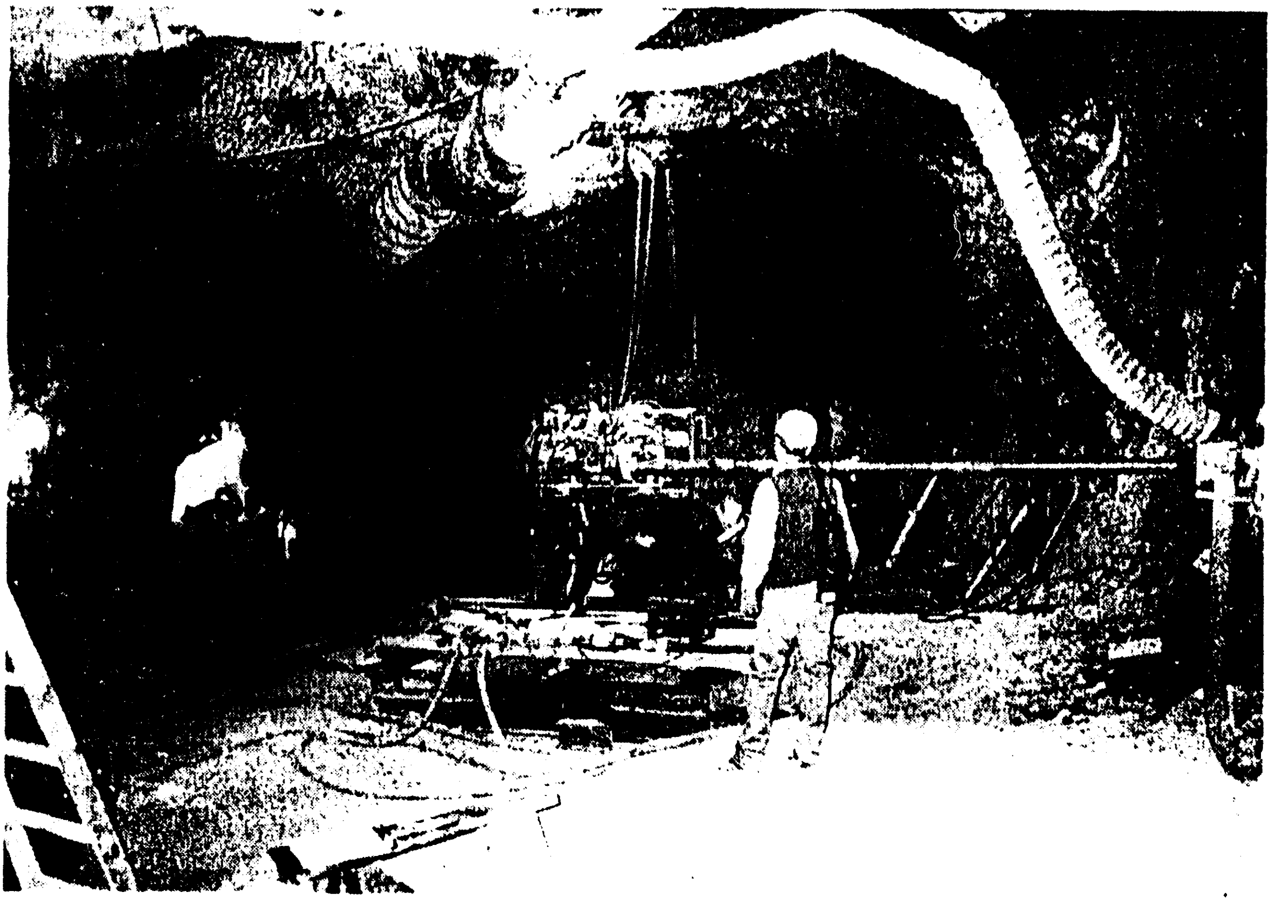


Figure 4.21-1. Horizontal air-coring equipment setup in the G-Tunnel.

A review of dry-drilling case histories[30-34] suggests that downhole-air percussion hammers could dry-drill densely welded tuff at rates in excess of 91.4 m (300 ft) per shift. In cases where core is not required but accurately drilled holes are needed, the downhole hammer drilling technique could reduce drilling time by approximately 80%. The potential cost benefits merit further investigation.

Four of the most pertinent case histories are summarized below. Each case attempted dry drilling, three horizontally and one vertically.

1. Case History 1. The first case involved prototype horizontal drilling in limestone for eventual application to underground stimulation and production of bitumen from adjacent tar sands.[35] The Alberta Oil Sands Technology and Research Authority tested a prototype rig on the surface by drilling into a limestone face using air with a dual-pipe system. After a meter (few feet) of penetration, trouble began when circulation was lost to fractures. Mud was then used as the circulation medium, and a depth of 91.4 m (300 ft) was ultimately achieved. The introduction of mud precluded further evaluation for application to Yucca Mountain.

2. Case History 2. The second case study addressed vertical air coring in the Bandelier tuff near Los Alamos, New Mexico.[30] The Bandelier air coring and the G-Tunnel test involved similar rock type, air circulation medium, and a wireline retrievable coring system. The Bandelier hole was completed to 64.0 m (210 ft), but the vertical orientation presented different hole-cleaning problems than those experienced in horizontal coring. The extensive equipment modification, control of compressor pressure and volume, and less restrictive dust control requirements were unlike the G-Tunnel test. Certain aspects of the test in Bandelier tuff are applicable and were taken into consideration in designing the prototype air-coring test. However, other parameters (e.g., different bit designs, horizontal coring, thicker overburden) needed to be addressed for application to Yucca Mountain.

3. Case History 3. The third case, similar to case 2, required air-cored holes in the Bandelier tuff near Los Alamos, New Mexico.[31] Five horizontal holes for monitoring were dry-cored using wireline core retrieval beneath a solid-waste disposal pit. The operations went mechanically well using a Longyear-44 drill rig. The holes deviated from the vertical as a result of soft zones of nonwelded tuff and reworked tuff.[32] Joints were often filled with clay or caliche, which probably assisted in containing the air circulation. The softer rock, filled fractures, and variable control of air volume and pressures allowed relatively easy drilling. Longer core barrels up to 6.1 m (20 ft) long were used to produce 63% core recovery. This case history was found after the prototype air-coring test was completed. Although the information was not used in designing the G-Tunnel test, it is summarized here because of its relevance.

4. Case History 4. The fourth, and most relevant, case history was hole UE-25h#1, which was cored at Fran Ridge near Yucca Mountain from December 1982 to January 1983.[33] One objective for this hole was to develop horizontal air-coring techniques in the welded tuff of the Topopah Spring member.

The drilling-related problems encountered at Fran Ridge are summarized below.

- Loss of air to fractures, causing failure to clean the hole of cuttings;
- Hole sloughing, jammed drill rods, and damaged drill bits;

- Serious drill string vibration, causing bit failure, poor penetration rates, and poor core recovery; and
- Highly fractured rock, causing core barrels to jam.

Observations and recommendations on the Fran Ridge experience[34] were considered in designing the prototype air-coring test.

Prototype Air-Coring Test Rationale and Design

This test evaluated standard drilling techniques, which were modified slightly for air circulation, to determine if they could meet ESF requirements. Based on the evaluation of case histories, an ideal match of equipment for prototype testing was recommended.[34]

Evolution of Test Design

A multipurpose drill was originally recommended, but a standard core drill (Longyear-38 electric/hydraulic) was ultimately chosen from the available drills at the Nevada Test Site.

Conduct of Test

The prototype test has been completed and is considered to have been successful in demonstrating the viability and the applicability of air coring to needs in the ESF. The results of the test show that in many ways dry drilling is more difficult than wet drilling, but with proper training of personnel and the correct equipment, it is technically and economically feasible.

Many drilling components and procedures were evaluated and refined as part of this test. The impregnated bits exhibited exceptional durability, achieving 36.6 to 48.8 m (120 to 160 ft) of core per bit in densely welded tuff. The average hole production rates were 1.8 to 2.4 m (6 to 8 ft) per bit in welded tuff and almost 6.1 m (20 ft) per bit in deep holes in nonwelded tuff. A carbide bit drilled approximately 20% faster in nonwelded tuff than did the impregnated bit and almost 250% faster in welded tuff. Core recovery was approximately 97% in densely welded tuff and approximately 95% in nonwelded tuff.

General findings of the work are that

- the presence of fractures greatly influences the length of continuous core that can be recovered;
- low-pressure (82.7 KPa [120 psi]) mine air is adequate for normal air coring;
- drilling air volume increases with psi, the occurrence and characteristics of fracture zones, and is often reduced by core blockage and/or poor hole cleaning;
- the loss of drilling air volume due to friction increases with hole depth and reduces the flushing volume of air available for flushing;
- the volume of flushed drilling air (and cuttings) that enter the dust collector must be regulated by the driller for best operation; approximately 20.4 m^3/min (730 cfm) of air are needed to drill the holes while running a dust collection system and using an electric-powered drill; and
- the RPM of the drill bit should be decreased with depth to facilitate smooth drilling; approximately 60 RPM is considered optimal when using carbide bits in nonwelded tuff.

Table 4.21-1 provides a general summary of drilling results, modifications that were made and evaluated during the test, and recommendations for other modifications to equipment and procedures to make the process more efficient. The summary indicates the scope of evaluation and extensive development that occurred as a result of this prototype testing.

Among the major safety-related findings of the test are that

- the handling of drill rods, cables, and air hoses requires considerable attention to ensure they do not become entangled in moving machinery;
- air lines, valves, and gauges should be elevated and somewhat remote from highly trafficked passages to keep workers from tripping on them;
- the number of personnel in the immediate area of the drilling should be kept to a minimum;
- if a dust leak does occur, confined spaces present a potentially more hazardous environment than would be present in larger spaces;
- moving machinery in confined spaces requires extreme caution because personnel have a greater chance of being trapped between machinery and drift walls; and
- noise levels are more damaging in a confined space than in a larger area.

Future Activities

Results from this test show that only minor changes need to be made to render air coring even more efficient, time effective, and safe. The prototype test core holes were done with a traditional core drill, but the Multipurpose drill (MPD) is recommended in order to reduce the setup time required for future drilling and to facilitate the use of down-the-hole (DTH) air percussion drilling of several holes from one setup. A MPD should provide increased operating efficiency in several respects.

1. Mobility. A self-mobilizing MPD is capable of being moved and set up in much less time than a drill that is loaded onto and moved about by a mine mucking machine.

TABLE 4.21-1

EQUIPMENT RESULTS AND RECOMMENDATIONS

Equipment	Plan	Modifications or Changes	Results	Recommendations
Drill rig	Longyear LY-38 Electric/ Hydrostatic.	None.	Better control than with air motor. Sufficient torque. This rig worked well for holes requiring several different sizes from RWT to HQ and will be used for overcoring with a 12-in. bit.	For NQ and HQ dry-cored holes, this is ideal rig. The electrical power is quiet, nonfluctuating; it provides necessary power and saves a considerable volume of air that would be needed if air power were chosen. For example, air power LY-38 uses 875-1000 cfm; LY-24 uses 500 cfm.
Drill rig substructure	I-Beam platform was rock-bolted to floor beams, cross-stacked, and welded.	None.	Not perfectly stable, very time-consuming setup. Several welds were broken during vigorous drilling activities.	1. Design modular base for faster, more stable setup. 2. Look into self-mobilizing modular base. 3. Procedures need to be written that would help determine the ideal drill height or distance from hole collar.
Dust collector	New Atlas Copco DCT-90/9504. Modify as needed.	Used Atlas Copco DCT-90/9504. 1. Added upper chamber air charger. 2. Added exhaust adapter to vent line. 3. Added sound-deadening materials. 4. Built stand.	Excellent. 1. Helped clean unit. 2. Prevented exhaust dust contamination. 3. Lowered decibels to acceptable levels. 4. Awkward to mobilize.	For ESF 1-DCT-90 or 9504: one smaller unit for small holes; one larger unit for possibly large percussion holes. 1. This item is currently on most new models. 2. Add exhaust to vent line (as tested). 3. Add sound-deadening material on exhaust area of dust collection system (as tested). 4. Design stand that mobilizes more easily.

TABLE 4.21-1

EQUIPMENT RESULTS AND RECOMMENDATIONS
(continued)

Equipment	Plan	Modifications or Changes	Results	Recommendations
Dust collector (continued)		5. Adjusted flushing air to keep bag in vacuum mode.	5. A. Prevented leaks. B. Vacuum helped clean hole in fractured area.	5. Do as tested.
	Modify collar pack-off.	6. A. Added spider arrangement for fastening pack-off to wall.	6. A. Worked well.	6. A. Use as built and tested.
		B. Designed rubber pack-off for rod seal.	B. Works well when rubber wipers are in good shape.	B. Use as built, modified, and tested; order factory-built rubber wipers.
		C. Brought mine exhaust line to spider area to exhaust minor fugitive dust leaks.	C. Keeps fugitive dust safely contained during time of leak to shutting down of air for repairs.	
				7. Plan for site-specific dust collectors to be used in ESF drilling.
Bits	Test (all) diamond-set, diamond-impregnated, diamond-geoset, carbide.	Varied type of cutting surface, matrix materials diameters of bits, revolutions per minute, and weight on bits. Only one face discharge bit tested so far.	Excellent bit life on impregnated bits used in welded tuff. Expect 120-160 ft on each bit.	Use impregnated bits for all moderate and densely welded tuff. Rotate 60-120 rpm.
	Wide waterways flared on the outside diameter (O.D.) were chosen. Some face discharge bits were ordered.		Penetration rate averaged 7.7 ft per shift in welded tuff.	The nonface discharge bits far exceeded expectations, and future tests may show superior performance over face discharge design in hard rock.

TABLE 4.21-1

EQUIPMENT RESULTS AND RECOMMENDATIONS
(continued)

Equipment	Plan	Modifications or Changes	Results	Recommendations
Bits (continued)			Impregnated bits will dull or self-sharpen at different depths when passing through formations that vary in hardness, abrasiveness, and fracture frequency. The bit was pulled and sharpened when drill rate slowed to ~2.5 min per in. in densely welded tuff. Softer matrix will self-sharpen more easily than the harder matrix but will wear out more quickly.	Face discharge bits help retain the integrity of cores in soft formations. Order bits with wide waterways, flared, and with hardened O.D. Bit diameters. Impregnated bits should self-sharpen, but if they slow down too much, pull and resharpen them.
			Geoset and carbide bits drill ~17% faster in nonwelded tuff than do impregnated bits.	Use carbide or geoset bits in nonwelded tuff.
			Face discharge bit plugged.	Others should be tried.
			Actual bit measurements were up to 10/1000 in. from specification.	All bits need to be accurately measured before use and remeasured when returned. This information needs to be kept in a log book at bit locker.
			Diamond-set bits not tried yet.	Set bits are not expected to hold up as well as impregnated bits, but they will be tried in the future.
Reaming shells	Bit diameter plus 0/1000 in. and 5/1000 in.	Tried diamond set 5/1000 in. larger than bit diameter.	Good results; should get three bits per remaining shell.	O.D. should be bit diameter plus 5/1000 in.

TABLE 4.21-1

EQUIPMENT RESULTS AND RECOMMENDATIONS
(continued)

Equipment	Plan	Modifications or Changes	Results	Recommendations
Stabilizers	Full hole three-wing.	Added three air courses milled as deeply as permissible with spiral-welded stab.	These worked very well. They somewhat reduce hole-cleaning efficiency, and rotational torque increases, but they keep hole straighter and keep down vibrations when properly spaced.	Stabilizers are necessary if accuracy is important.
	Determine optimal spacing.			More study on proper spacing should be done.
Core barrel	Longyear HQU3.	1. Modified by splitting the inner barrel and using a Lexan liner inside it.	1. One split tube worked well. One distorted.	1. Use as modified for anticipated drilling. For very soft formations, the barrel can be remachined to allow more air volume to reach bit.
		2. Drilled two relief holes in head above liner area.	2. This stopped the Lexan liner from being crushed.	2. Use as modified.
		3. Modified pump-in head.	3. Made pumping-in better.	3. 4. Use as modified. Plan for further testing of shoe designs.Use as modified.
		4. Adjusted shoe stand-off for best air flow with each bit type.	4. This worked well, but testing of different shoe configurations could reduce core-blocking problems.	
	J. K. Smit RWT core barrel.	J. K. Smit XRP core barrel.	Did not perform well (as used). It may perform better if used according to plan.	Try to get sample core according to plan.

TABLE 4.21-1

EQUIPMENT RESULTS AND RECOMMENDATIONS
(continued)

Equipment	Plan	Modifications or Changes	Results	Recommendations
Core barrel (continued)		Change to EW core barrel with inner barrel.	This did not work as well as when first used, but it did perform as expected when plan was followed.	If any PI wants this size, follow the plan written for RWT barrel in the Air-Coring Test detailed test plan.
Lexan poly-carbonate liner	Thin polycarbon-ate inner liner and plastic caps for sealing each end.	Had early problems with crushing. They were eliminated by modifying the head adapter.	No problems after modifications. Worked well. Ends were sealed ~3-4 min after retrieval. Physical property data suggest moisture content is protected.	Use these any time good-quality core is wanted. Liners preserve in situ condition and protect core from damage usually associated with dumping core.
Running/ retrieving tools	Factory underground. Run/retrieval tools.	1. Modified for running dry. 2. Built special tool for running inner barrel back into dry vertical hole.	1. Worked well. 2. Worked well.	1. Use as modified. 2. Use as built.
Drill rods	HCQ Longyear 3-1/2 in. O.D. 5-ft length.	None.	Excellent; good strong rod.	Use for all HQ holes and large O core. Use for casing while coring RWT or EW size end hole. Clean before initial use. Have shorter rods on site.
	EW 5-ft length.	These were used for coring small holes for diffusion test.	This worked. Better than using HQ for turning small core barrel.	Use as planned and tested with HQ rods as casing and stabilizers built for use inside HQ rod.
Swivel	Air-water. Large flow.	King 21-aluminum with 1-1/2 in. passage.	Excellent air flow. Lightweight.	Use in future. Large flow passages needed for air drilling.

TABLE 4.21-1

EQUIPMENT RESULTS AND RECOMMENDATIONS
(continued)

Equipment	Plan	Modifications or Changes	Results	Recommendations
Hydraulic-operated drill rod holding device	Not planned.	Not used.	It would have increased drill rod handling efficiency and reduced health hazards. It eliminates working on a platform.	This item should be used for vertical drilling. It would allow rods to be added and removed between drill head and hole collar. The drill head could then swivel to the side for core retrieval, while the holding device safely held the drill rods.
Data gauges	psi-air gauge.	Changed location.	Excellent indicator of drilling conditions.	A must; use in future.
	cfm-air gauge #1. cfm-air gauge #2.	#1-air line to drill rods. #2-air line to dust collector.	Excellent indicator of hole conditions/core blocking.	A must; use in future.
	Pulldown.	On rig.	Hard to read but valuable.	A must; use in future.
	Pullback.	On rig.	Hard to read but valuable.	A must; use in future.
	rpm gauge.	We added to rig.	Not accurate.	Get better type or count with stopwatch.
	Torque.	On rig.	Good indicator of hole cleaning.	A great help. psi and cfm gauges should be located where driller can see them while drilling.
Survey tools	Sperry-Sun.	None.	Fair; not as accurate as laser sitings.	Use for future readings where accuracy is not critical and quick inexpensive surveys are needed. Additional information on surveying methods is succinctly described by The Robbins Company (1984).
Video survey	Video inspection and recording of drill holes USGS/SNL	None.	A. Excellent resolution. B. Clean hole quality apparent.	Use in holes where geologic information is needed. Excellent detail of the hole wall is possible by using downhole video cameras with panning and side-scan capabilities such as that used to examine AC-2 by Odum (1988).

TABLE 4.21-1

EQUIPMENT RESULTS AND RECOMMENDATIONS
(continued)

Equipment	Plan	Modifications or Changes	Results	Recommendations
Video survey (continued)			C. Allows optimal packer placement. D. Found localized moisture not seen in core (non-Lexaned).	
Miscellaneous	Miscellaneous tools. HQ funnel adapter for diffusion test.	Built workhouse/ pipestand. Built crude model at welding shop.	Very helpful. Worked fairly well.	Use stand, have pipe vise on location, and have a good assortment of pipe wrenches. To machine an adapter, use drawings as furnished before test and as requested by PI.
Multipurpose drill.	Ingersoll-Rand CMM-2 Electric/ Hydrostatic (if funded).	Not funded.	Not applicable.	This drill would reduce mobilizing and setup time; could core drill, bore, and run down-the-hole hammers. These factors would greatly increase the efficiency of operations in the ESF. Some minor modifications are recommended to allow for hole parallelism and to ease core retrieval.
Available mining air	1500-3000 cfm at 115 psi.	Two Quincy 1500 cfm x 125 psi compressors were available. Usually only one was running. Other underground equipment was running on the same air system. Used cfm gauges and controls to vary the cfm for flushing.	cfm of air was adequate most of the time, but air pressure fluctuated. This was adequate for coring moderate and welded tuffs. However, being able to reduce air pressure at drill, as well as cfm, would help core recovery in very soft formations.	For electrically powered drill: Have approximately 600 cfm available for hole cleaning plus 130 cfm dust collection system operations. Total = 730 cfm. For air-powered drill: Have 600 cfm for hole cleaning plus 130 cfm for DCS; 1000 cfm for rig power. Total = 1730 cfm.

TABLE 4.21-1

EQUIPMENT RESULTS AND RECOMMENDATIONS
(concluded)

Equipment	Plan	Modifications or Changes	Results	Recommendations
Available mining air (continued)				Electric power is recommended, if possible. An air booster compressor is recommended if down-the-hole hammer drilling is used. An alternative would be electrically powered compressors positioned underground. These, however, add considerably more heat to the underground environment than do booster compressors.
		Water traps located in the mine air lines were drained daily.	Water was not visible at drill site after this practice was begun.	Drain water lines as tested.

Time savings would be appreciable and the level of safety would increase.

2. Function. The MPD would be able to function both as a heavy-duty coring machine and as a heavy-duty rotary drill. The rotary drilling function allows the use of DTH air percussion hammers, dual-wall drilling, ODEX drilling, tricone drilling, hole opening, and large-diameter overcoring. With the addition of a hole-parallelism attachment, multiple parallel holes can be drilled without having to move and reset the drill. The MPD has been recommended as an essential part of prototype and ESF testing but to date has not been funded.[35-37]

To make the MPD drill more efficient, however, the following modifications are recommended:

- Add a hole-parallelism attachment;
- Modify for off-hole lead swing out or through-the-head wireline core running;
- Add dual-speed hydraulic top head motor feature;
- Evaluate MPD on some planned prototype tests under wet- and dry-drilling conditions;
- Test dual-wall and ODEX drilling methods with core bits, cone bits, and hollow DTH; and
- Evaluate the MPD/MPD and DTH system, recommend modifications if necessary, and integrate them into ESF planning.

Areas where improvements are needed are refinement of some aspects of rig logistics, including the placement, mobilization, setup, sealing, and safety of rig operations. Further equipment refinement is recommended to test other drills that are to be used in ESF work, develop a hydraulic rod-holding device, develop a mobilization package, develop modular drill setup, develop adequate torque and weight control gauges, improve parts of core-barrel assembly, further evaluate specific properties of bits and bit design, and refine in-hole stabilizers. Improvements in the data collection and calculation methods are needed to improve the accuracy of hole surveys. A method needs to be developed to improve the uniformity of hole logs and notes. Methods for overcoring should be refined to enhance the probability of success, reduce bit costs, save time, and provide better-quality core.

4.22 Dust Hazards Associated with Air Coring

General Test Description

USGS hydrologists have recommended that drilling done at Yucca Mountain be performed with air as the circulating medium rather than other drilling fluids because of concerns that water-based drilling fluids could effect the hydrology of the site. Air coring is not a well-developed technology; another prototype test, described in Section 4.21, addresses the technical feasibility of air coring in fractured, welded tuff. A concern associated with air coring is the potential creation of a significant health hazard to workers because of the increased generation of airborne dusts and fibers that would normally be mitigated by a drilling fluid such as water. The prototype dust hazards test was conducted to determine the nature and extent of the exposure conditions during air coring and if air contaminants can be sufficiently controlled using available dust control/collection equipment so that compliance with health and safety standards are achieved.

Purpose and Objectives

The prototype dust hazards test is necessary to ensure that air coring performed during site characterization activities at Yucca Mountain can be performed safely. The objective of this test was to (1) evaluate the potential exposure of workers and investigators to airborne silica, zeolite fibers, and nuisance dusts so that the proper controls (engineering controls, administrative controls, and physical protection devices such as respirators) can be incorporated into procedures for projects involving air coring at the ESF and (2) to evaluate the effectiveness of commercial dust control equipment when attached to the drilling apparatus during air coring.

Support Required

The Industrial Hygiene Group (HSE-5) at Los Alamos performed the sampling and analysis portions of the test in coordination with the Industrial Hygiene Group of REECo, except where noted otherwise. The Geological/Geochemistry Group (EES-1) at Los Alamos provided two bulk mineral samples of Yucca Mountain zeolites for analysis of fiber content. A third sample of Nevada zeolite was purchased from a mineral supply house. The commercial sample was confirmed to be a suitable reference sample by EES-1 for HSE-5 analysis. These samples were used to evaluate fiber content and as reference samples for comparison with samples collected during the air coring portion of the test. Instruments used for sampling were calibrated by the Los Alamos calibration laboratory, and statistics support was provided by the Los Alamos Statistics Group (A-1).

Elemental analysis of particulate samples was performed by the Elemental Analysis Corporation. Data Chem supplied PVC membrane filters used for total dust measurement, determination of the respirable fraction of suspended particulates, and crystalline silica sampling. Data Chem also performed the silica analysis.

The FSN G-Tunnel geologist identified the geological unit that was air-cored during the test as being unit B of the Grouse Canyon member welded tuff. Drilling was performed by Los Alamos personnel.

Detailed Test Description

The test was divided into four tasks. The first task was an analysis of bulk samples from the test site to determine the potential for the production of crystalline silica and zeolitic fibers during coring, as these materials have been shown to cause serious health effects in animals and, based on epidemiologic information, are likely to cause similar effects in humans. Second, the efficiency of dust control and collection equipment was evaluated. The third task was collection of air samples during a prototype air coring project in the G-Tunnel to assess exposure conditions to airborne crystalline silica and zeolite fibers when the selected dust control/collection equipment was in use. The final task was to provide recommendations for operating procedures and health and safety requirements during air coring for ESF studies.

The bulk analysis task was performed to ensure that HSE-5 analytical personnel could recognize, identify, detect, and measure the occurrence of the suspected zeolites (erionite and mordenite) in the field-collected samples. The three reference samples were examined by scanning electron microscopy (SEM) to assess morphology and by energy dispersive X-ray (EDX) analysis to assess elemental composition. The samples were viewed by SEM at nine magnifications, from 20 to 10,000 times the actual size, to determine the location and visibility of fibers and fiber content. Appropriate fields were photographed to compare with field-collected samples. The erionite samples were examined in both the bulk and milled state. EDX spectra were obtained for selected portions of the samples for comparison with spectra of field-collected samples.

A pre-test review of the efficiency of the dust collection equipment was conducted. The efficacy of these controls were then assessed during the drilling test. Characteristics of the dust collector system that were evaluated included expected collection efficiency, airflow/pressure drop characteristics of the system blower, effectiveness of filter cake removal, seal design characteristics, and potential for secondary release of particles. General exposure controls that were considered were subdivided into the following three categories:

1. Emission source controls, such as local exhaust ventilation, process controls, equipment modifications,

wet methods, enclosure of dust producing equipment, and housekeeping;

2. Controls in general airspace, such as employee isolation and dilution ventilation; and
3. Breathing zone controls, such as respirators and supplied air islands.

Fugitive emission sources and direct sources of dust emissions other than the actual drilling process were identified to the extent possible before and during the test so that all emissions could be reduced where feasible.

The field air-sampling task included collecting air samples during the air-coring test, and sample analysis and data evaluation. Samples were collected in two ways. A personal sampling pump connected to a filter cassette was attached to the lapel of workers involved in the drilling operation. Sampling pumps attached to filter cassettes and Anderson cascade impactors were positioned in the tunnel at various sites of interest, such as near the drill penetration site or on the dust collector. The filter membrane cassettes were capped and transported to Los Alamos, or elsewhere, as described below, for analysis following collection of samples. The material collected was weighed and subjected to SEM and EDX analysis for zeolite determination. Fiber content was further quantified by phase contrast microscopy. Cassettes used for obtaining crystalline silica samples were returned to Data Chem (the supplier) for x-ray diffraction analysis in accordance with the method required by the National Institute of Occupational Safety and Health. Additional elemental analysis was performed by Elemental Analysis Corporation using photon-induced x-ray emissions to determine sample content of the elements sodium through uranium. Particle size distribution of samples was determined by analysis of the Anderson cascade impactor samples at Los Alamos.

Historical Perspective and Background

As mentioned previously, USGS hydrologists have recommended air coring (also known as dry drilling) at the Yucca Mountain site because introduction of drilling fluids could potentially affect the site's hydrologic characteristics. The dampening effect of drilling fluids reduces the dust hazard created by the drilling process. Air coring is associated with a greater dust hazard and, therefore, this prototype test was undertaken to determine if air coring could be performed safely using a variety of dust control and exposure control methods.

The extensive site characterization that has been performed at Yucca Mountain has indicated concentrations of silica in the rock ranging from 20% to more than 70%. Inhalation of crystalline silica is associated with the disease silicosis, which has a long latent period; therefore, it is important that exposure to silica be controlled because it is not immediately apparent when a dangerous exposure level has been achieved. Estimates based on available data indicated that allowable exposure levels might be approached or exceeded during air-coring operations. Confirmation was needed that available exposure controls could achieve exposure levels consistent with established occupational exposure levels for silica during air-coring projects at Yucca Mountain. Another concern was the presence of natural zeolites. While currently there are no exposure standards for zeolites, some zeolites are fibrous and may be associated with an asbestos-like disease. While the most studied of these, erionite, has only been found in one borehole, mordenite, which has characteristics similar to erionite, has been found more extensively at Yucca Mountain.

Commercial dust collection equipment is available for drilling operations. Two-stage collectors, consisting of a baffled-inertial separator followed by a bag- or envelope-type fabric filter, are reported by various manufacturers to have collection efficiencies ranging from 95.0 to 99.9% by weight. The Atlas Copco dust collector, the DCT90, chosen for the test is reported by the manufacturer to have a collection efficiency of "nearly 100%" for particles smaller than 5 mm in diameter.[38] The actual collection efficiency, however, would depend on operating conditions. Because the collector is designed with a collar to surround the drilling stem, fugitive emissions and dust sources outside the collar, such as those due to vibration of the equipment, would contribute to greater dust exposure than these reported efficiencies might indicate. Actual exposure conditions needed to be determined during a drilling procedure that approximated conditions at the Yucca Mountain site.

Conduct of Test

The bulk analysis task was performed. Two of the three zeolite samples contained free fibers and aggregates that were considered potentially respirable. Milling decreased fiber size and increased the number of free fibers. To confirm identification of mordenite and erionite, SEM, EDX, and x-ray diffraction analyses were needed.

Pre-test evaluation of the dust collection equipment indicated that actual airborne concentrations during the test might approach, or exceed, allowable concentrations for silica dust. Therefore, in addition to the dust collection equipment to be installed on the drill shaft exhaust system, further measures were implemented for the field test, including dilution ventilation to reduce fugitive emissions; workers were fitted with respirators and trained in work practices to reduce dust emissions; exhaust air from the dust collector was ducted to the main exhaust system; and traffic in the test area was limited.

The field test was performed during the prototype air coring project in the G-Tunnel. Dust emissions were observed around the

DCT90 collar at the drill site and at the site of attachment to the collection bay. A hand-held photometer's reading indicated the emissions were above allowable exposure levels. The test was stopped, the tunnel cleared by the ventilation system, and modifications to the collection system were made to reduce these fugitive emissions. The final test results indicated that the dust collection equipment and other exposure controls were effective in reducing air emissions to acceptable levels. Crystalline silica was not detected in airborne particulate samples but was detected in dust collected by the DCT90 filters, indicating the DCT90 was effective in reducing silica exposures.

Likewise, no zeolite fibers were detected in airborne particulate samples. Diesel exhaust particulates, presumably arising from machinery exhaust, were detected by personal samplers. All of the controls used (DCT90, dilution ventilation, respirators, work practices to reduce dust emissions) were considered to contribute to the highly effective control of dust hazards during the prototype test.

Future Activities

The dust and exposure controls used during the prototype test are recommended for all air coring projects at Yucca Mountain. The specific recommendations are detailed in the Final Dust Hazard Assessment Report prepared by HSE-5 personnel at Los Alamos.[2]

4.23 Radon Emanation

General Test Description

Radon is a gaseous decay product of uranium that decays, in turn, to form radioactive particulates that pose a health hazard when inhaled. The rate of radon emanation from the potential repository host rock is needed to assess overall radiologic exposure of workers in the repository and to assess off-site releases of radiation caused by construction and operation of the repository. (These requirements are stated in the Site Characterization Plan;[39] Sections 8.3.5.3 and 8.3.5.4.) It is also important to ensure that the airflow in an underground space is sufficient to keep radon concentration at an acceptable level.

The rate of emanation of radon from a rock mass is influenced by many factors, including temperature; air pressure; properties of the matrix, such as gas permeability, gas pressure, and moisture content; and the characteristics of the fractures. Under these complex conditions, multiple field measurements of radon concentrations are invaluable. In the ESF, several types of radon measurements are planned. These measurements are spot measurements at working areas around the facility, continuous monitoring of the ventilation air at the outlet, measurements in sealed boreholes at ambient and at elevated temperatures, and measurements in a drift with regulated airflow. Drift measurements, which are the focus of the prototype radon emanation test, are intended to show the relationship between radon concentration and rate of airflow.

In the radon emanation prototype test, a recently mined drift in the G-Tunnel will be sealed off, and a ventilation system capable of flushing the sealed space will be installed. Radon concentrations and atmospheric conditions will be monitored while equilibrium is established. This equilibrium level will be compared with control measurements on an intact sample and in a sealed borehole. The chamber will be repeatedly flushed and allowed to re-equilibrate in order to establish a relationship between airflow rate and radon concentration. The prototype test will be conducted in the G-Tunnel to take advantage of the available facilities and to obtain preliminary data on radon emanations from a jointed, welded tuff rock mass.

Purpose and Objectives

The purpose of the radon emanation prototype test is to develop procedures and evaluate equipment appropriate for the environment expected in the ESF, for measuring radon emanation rates, and for determining the relationship between airflow and radon concentration in drifts. Equipment and procedures developed in the prototype test will be available for radon emanation tests to be conducted in the ESF and will ensure that these tests can be performed successfully in the limited time available to conduct experiments in the ESF.

Specific objectives of this prototype test are to

- develop testing logistics, including creating an airtight seal across a drift in welded tuff and installing a variable-flow ventilation system;
- evaluate and develop, if necessary, instrumentation for monitoring radon concentrations and other environmental parameters, including calibration procedures;
- verify the approach to assessing the relationship between airflow and radon concentration; and
- obtain preliminary information regarding the concentrations of radon in openings in welded tuff.

Support Required

Personnel from SNL will be responsible for the majority of field activities associated with the radon emanation prototype test. SNL personnel will be assisted by one or more subcontractors, who have not yet been identified. Technical and field assistance may be sought from subcontractors to SNL. REECo staff, under the general direction of the field coordinator, will construct the airtight bulkhead, install the ventilation system, and assist in instrument installation.

Detailed Test Description

The radon emanation prototype test will consist of three components: measuring radon emanation from a piece of intact core, measuring radon concentrations in a borehole, and monitoring radon in a drift.

Measurements from a piece of core will be done in a laboratory over a short period of time. Pre-existing core from the vicinity of the drift measurements will likely be available.

Measurements within a borehole will consist of sealing off the end of a borehole and running a sampling tube from the sealed area to a continuous radon monitor outside the hole. Readings will be made at regular intervals, several times daily, over a period of several months. A pre-existing borehole might be available for this use.

Drift measurements will require continuous monitoring of radon concentrations, airflow, air temperature, air pressure, and relative humidity in a sealed chamber. First, the airflow will be stopped for several weeks to a month to determine the variation of radon concentration with respect to the uncontrolled variables (temperature, pressure, humidity). Next, the chamber will be ventilated at a slow rate, and all parameters measured to determine the steady-state radon concentration at that flow. This second step will be repeated several times at various flow rates.

Historical Perspective and Background

Methods of measuring radon emanation in underground excavations were developed for use in uranium mines. Research in this area stopped in the 1970s when mining of uranium in the United States was curtailed. The magnitude of underground measurements differs from the measurements made in structures and soils on the surface. Where surface surveys measure radon in the range of tenths of picoCuries per liter (pCi/l), unventilated uranium mines might register radon in the range of 1,000 to 100,000 pCi/l.[40] Numerous methods exist for measuring the radon or radon daughter concentrations in grab samples. Instrumentation for continuous monitoring of radon concentrations was developed in the 1970s by the Bureau of Mines (USBM) for use in uranium mines. Since then, the concept has been commercially developed for use in surface applications.

Radon concentrations in the G-Tunnel and in the ESF will fall somewhere between those on the surface and those in uranium mines. It is not clear whether the commercially available continuous radon monitors can be used in the G-Tunnel or in the ESF because radon levels in these areas might saturate highly sensitive detectors. Preliminary grab samples and further investigation are needed to determine the answer. An alternative approach is to refurbish several continuous monitors that were developed and assembled by the USBM and that have been stored unused for a number of years.

Evolution of Test Design

The initial test configuration was proposed by Mine Ventilation Services, Inc., a subcontractor to SNL, in 1987. This plan included only the drift measurement study, which has not changed in basic concept. The need for radon measurements from intact samples and in boreholes, where conditions are more easily controlled, was realized later. The original plan proposed to use the old USBM monitors. Since this plan was presented, preliminary comparisons between USBM monitors and more modern commercial monitors have been made, but this investigation is not yet complete.

Conduct of Test

Current plans are to conduct the prototype test in the G-Tunnel demonstration drift after the controlled blasting suite of tests is completed. The test is still in its conceptual stages. No instruments or equipment have been procured.

Future Activities

Future activities will include finalizing an experiment procedure, writing contracts for laboratory and field assistance, writing the criteria letter, performing a preliminary survey of radon concentrations in the G-Tunnel using grab samples and continuous monitors, and, once the test is approved, acquiring equipment and instruments and performing the test.

4.24 Prototype Vertical Seismic Profiling Test

General Test Description

Determining the orientation and spacing of fractures is an important component of the site characterization activities planned for the ESF at Yucca Mountain. The design of the repository and the assessment of the waste isolation capabilities of the natural barriers require a thorough characterization of the geometry of subsurface discontinuities such as faults and fractures. Data on fracture spacing and orientation provide needed input for both the prototype test program and certain tests planned for the ESF. The tests model the response of the repository and the surrounding environment to the emplacement of high-level nuclear waste.

As part of the characterization activities, a series of boreholes will be drilled and instruments will be installed in them to gather data for various studies. One such study involves the use of vertical seismic profiling (VSP) to characterize fractures and other subsurface discontinuities. In VSP, the ground surface is vibrated, which sends sound waves into the subsurface. The waves are reflected and refracted by discontinuities such as fractures, faults, and depositional surfaces and then recorded by instruments (geophones) located in boreholes. Through computer analysis, characteristics such as fracture spacing and orientation may be inferred. Thus, the properties of fractures, observed directly in boreholes, may be extrapolated throughout the subsurface in the area between boreholes.

The prototype VSP test will take place in the vicinity of Well G-4 at Yucca Mountain. Major activities in the testing program include solving logistics problems associated with the seismic equipment, such as ensuring that the large vehicle-based vibrators can gain access to the site to be vibrated, preparation of the site, and evaluation of the data gathered to refine the seismic profiling techniques.

Purpose and Objectives

The purpose of the prototype seismic profiling test is to develop and test the techniques that will be needed for seismic profiling during site characterization and to anticipate and solve logistical problems. Completion of the prototype test will mean that seismic profiling can be accomplished efficiently during site characterization activities and that the data generated are adequate for the intended purpose.

The specific objective of the prototype work is to test the VSP techniques for mapping the fracture (density, orientation, and distribution) and lithologic characteristics between boreholes and underground workings at the potential Yucca Mountain repository site and to relate the seismic results to the hydrologic response of the repository block. The work is part of the exploratory shaft experiments. Verification and calibration of the fracture mapping using VSP will be done by comparing the seismic results with the fracture mapping done by the geologists in the exploratory shaft and drifts. A second objective is to provide a data base that will allow us to calibrate and relate the seismic wave properties to the actual fracture and lithologic patterns observed in the boreholes and underground workings and how they control the hydrologic properties. This will provide a means to extrapolate the fracture, lithologic, and hydrologic properties to the surrounding units using sources placed at the surface.

The overall objective of the work is to test the VSP/tomographic methods for providing information that could be used in combination with surface geologic mapping, drill-hole studies, and ESF geologic data to construct a three-dimensional geologic framework for the entire repository. That is, use the data gained from the VSP studies, coupled with the geologic results, to provide a means to extrapolate the ESF hydrologic, geochemical, geomechanical, and geophysical properties from specific sites (i.e., boreholes and underground workings) to the entire repository. Prototype VSP field and modeling work is the first step to accurately define the appropriate VSP field and data processing procedures.

Upon completion of this work, one of the most important results will be an evaluation of the VSP/tomographic technique. If successful, this method could prove to be a valuable tool in the characterization and licensing of the repository. Because VSP is based on techniques that have been thoroughly tested and used in the petroleum industry (i.e., reflection profiling), the method could easily meet the accountably and quality assurance requirements. The most important result, however, may be the link between the fracture characteristics as inferred from the seismological results and their utility in inferring the hydrological properties of the media.

Support Required

The USGS will be supported in this investigation by REECo, which will support site preparation work, and FSN, which will provide a Dresser Atlas boom truck and services. The vibrators, VSP tool, and recording services will be procured from an outside service contractor. Lawrence Berkeley Laboratory is providing overall technical management and guidance for this project.

Detailed Test Description

The procedure for the seismic profiling experiment involves placing a geophone in a well and recording the seismic signals generated by the vibrators. A geophone is a device that is attached to the side of the borehole to convert vibratory motion to electrical impulses, which are transmitted to a recording station. The vibrators remain at one site as the geophone is moved incrementally from the bottom to the top of the well. After the geophone reaches the top of the well, the vibrators are moved to a new location, and the geophone is moved through another cycle from the bottom to the top of the well. A total of twelve sites will be occupied by the vibrators, and four vibrators, two P-wave and two S-wave, will be used during the experiment. Using two vibrators increases the strength of the acoustic signal to the geophone and, thus, the resolution of the VSP process.

The equipment used for this work will be standard geophysical exploration tools that are available from commercial sources and are widely used in the petroleum industry. Therefore, the equipment is well calibrated, and all standards are easily maintained and traceable. No special fabricated equipment is required. The equipment and procedures used for the study are as follows:

(1) A three-component wall lock geophone. This will be used to gather the VSP borehole data. The frequency range covered by this instrument is from 8 Hz to 300 Hz. The actual data range will depend on rock parameters and will be likely to be from 10 Hz to 70 Hz. The geophone is lowered into the borehole and locked at 10-m (33-ft) intervals in the well. During the time in which the phone is locked in the well, the surface seismic source is activated to produce seismic waves that travel through the earth and are sensed by the geophone.

(2) Seven-conductor wireline and hoist truck. This will be used to support the geophone in the well and to transmit the data to the surface for digitization and recording.

(3) VSP recording system and in-field processing system. This will be used to record the data on 9-track magnetic tape and to preprocess the data in the field for quality control.

(4) P-wave vibrator. This will be used to generate compressional waves at the surface of the earth for the VSP survey.

(5) S-wave vibrator. This will be used to generate shear waves at the surface of the earth for the VSP survey.

(6) Support equipment and vehicles. Equipment such as a diesel fuel trailer, a small 6-kW generator, and vehicles to transport personnel to and from the field will also be required.

The prototype field experiment at Yucca Mountain will address the applicability of seismological techniques for mapping fracture content and structure. There will be two phases to the prototype testing, an initial phase to map the area around the ESF, and a more extensive phase to map in more detail surrounding fracture sets.

The concept behind the field experiment is relatively simple. We will provide P-wave and S-wave energy sources (vibrators). These sources will be positioned at intervals along lines trending radial from G-4. The offset distances will be every 100 to 250 m (328 to 820 ft) (depending upon access), with up to 3 offsets along each line.

At each offset, we will vibrate the P-wave source and the S-wave source. The S-wave source will be vibrated parallel and then perpendicular to each line. Each vibration sequence will be done for each geophone level in the well. The geophone spacing will be every 20 meters in the well. This combination of offset spacing and geophone spacing will yield an approximate pixel size of 20 meters. In reality the raypaths will not be straight but curved due to velocity changes. The area sampled will be extending below the water table. We are purposely extending the survey below the water table to determine the seismic signature and sensitivity to P- and S-waves of the saturated zone relative to the unsaturated zone. Preliminary examination of well logs in wells surrounding this area show generally an increasing velocity with depth, but intermixed with low velocity zones. There is also a very-near-surface high-velocity zone. Before we actually carry out the field work, we will model the area with ray-tracing programs to determine the optimum placement of sources and receivers. Data from available well logs will be used for this purpose.

In addition to the field work, there is an effort to develop the necessary modeling and interpretational codes for the data analysis and processing of the data. Data from available VSPs in fractured rock are being used for this effort. The seismic modeling and processing work is ' 'ng carried out at LBL's Center for Computational Seismology CCS has a complete set of commercial and custom VSP an flection processing software developed in-house. In addition to this software, LBL also has a complete set of modeling and ray tracing programs.

Once the data have been acquired, the anticipated processing sequence will be as follows:

(1) The data will be demultiplexed and displayed for editing.

(2) The data will be "de-spiked." (The geophone may slip in the hole, causing it to shake and put a spike on the data. After correlation with the sweep, these spikes cause a ringing nature in the data. Therefore, it may be necessary to remove the spikes with a special editing

program: however, careful field procedures will minimize the need to do this.)

(3) After de-spiking, the data will be filtered with a bandpass Butterworth filter to enhance arrivals.

(4) The data will be correlated with the recorded sweep.

(5) The data will be plotted for visual inspection. At this point, we will look at the individual shots for each offset and each orientation. This is in preparation for stacking the data.

(6) The noisy shots will be discarded.

(7) The data area will be stacked and displayed.

It is then necessary to separate the Horizontal Shear Wave (SH) arrival from the Vertical Shear Wave (SV) arrival for each orientation of the vibrator. This is accomplished by rotating the data into the planes of propagation. This may be accomplished by knowing the orientation of the geophone, either from looking at the P-wave arrival or by actually having a gyro or tilt meter on the geophone itself.

Once the data have been rotated into the appropriate planes, it is possible to pick the various arrivals (SH, SV, P from both orientations of the shear-wave, and the P-wave vibrator). Then the data are ready for tomographic analysis. Before the data are collected, it is difficult to tell the exact sequence of processing, but our goal is to map the anisotropy in the SH, SV, and SV/SH velocities and, if possible, the variation in the amplitudes. With these quantities, we will then be able to infer fracture density and orientation through the fracture stiffness and anisotropy theories mentioned previously. The frequencies at which we will be working provide a relatively gross picture of the rock; however, if the technique is successful, it will provide a method for characterizing the geologic and hydrologic parameters of the entire repository block at a much finer scale by using higher frequencies and finer sampling. In this way, we are using methods that are well developed in the petroleum industry to test some relatively new concepts in interpreting the behavior of seismic wave propagation.

Four activities have been identified as part of the prototype test. A major activity is to provide the support needed to ensure access to vibrator field sites at Yucca Mountain. It may be necessary to grade a path for transporting the seismic equipment to the field sites. Grading may also be needed to create a reasonably level site for the vibrators. The vibrators are all-terrain vehicles that are meant to operate in rough terrain. Because sites are chosen to minimize requirements for site preparation, the main concern at Yucca Mountain is whether or not the vibrator can be driven to the site. However, many of the sites are near roads or in terrain accessible by four-wheel drive vehicles and require little or no preparation. A second activity is to provide a support truck for the wire-line truck to suspend the sheaves that hold the wire line for the VSP tool. These trucks are normally used instead of a drill rig to support the wire-line surveys. In some cases, a tripod adequately supports the wire line for the VSP survey. The third activity involves removing the casing from Drill Hole G-4. The geophone placed in the borehole must be coupled to the rock in a manner that ensures that adequate acoustic energy reaches the geophone and that the acoustic energy is not altered as it passes from the rock to the geophone. To ensure this, the casing for Drill Hole G-4 is being removed from the well so that the geophone can be placed directly in contact with the rock exposed in the borehole. The fourth activity is to provide the vibrators, VSP tools, and recording system for the prototype work. These will be procured from an outside service contractor.

Historical Perspective and Background

At Yucca Mountain, Barton and Larsen[41] have mapped fracture traces on exposed pavements and have begun to develop a model of the fracture system, which includes two types of fractures: cooling and tectonic. They have investigated the fractal nature of this system which could lead to a mathematical description. Scott and Bonk[42] have described the fracture system on a larger scale, including Basin- and Range-style normal faults and higher density faults associated with major shear zones. Also, these authors have pointed out that the degree of fracturing is a function of the degree of welding. Such observations must be incorporated into one or more conceptual models of the fracture system at NTS on an appropriate scale for comparison with field data. This scale is not necessarily the same as the pixel size used for VSP tomographic analysis. These studies are being carried out at the surface and from limited borehole data. During the ESF construction, detailed mapping will give fracture and structural properties at the drift walls. However, a technique is needed to reliably extrapolate the data to zones between the available drifts and boreholes as well as to zones outside of these areas. Prototype VSP testing will refine the fracture detection techniques as they apply to the Yucca Mountain geology. The calibration of the method will occur during the ESF phase of the VSP work. At this point, the VSP results of fracture characteristics can actually be compared with the fracture patterns existing in the underground workings.

One of the most crucial needs in the design and implementation of an underground waste isolation facility is the detection and characterization of fractures in zones away from boreholes or subsurface workings. The fracture network will significantly affect the hydrological and geomechanical response of the host rock. From underground workings, we may be able to examine fractures directly and predict the local hydromechanical behavior. However, a major problem exists in trying to extrapolate this characterization to unexposed regions. Geophysical methods may help solve these problems. VSP methods may offer a useful technique for characterizing fractured media. By performing a tomographic analysis of VSP data, it may be possible to map the fracture density and structure. These data can then be used in hydrologic or geomechanical models of fracture networks to predict the behavior of the rock mass. VSP will be evaluated as a tool for determining fracture content and structure in the potential repository area. Supporting research on the relationship between seismic signatures of fractures and the hydrologic properties of fractures will contribute to understanding the relationship between seismic response and hydrologic behavior. In this way, the prototype work will evaluate VSP tomography as a tool for determining the geologic and structural framework of the repository area and relating this information to the hydrology and mechanics of the media. If the technique is successful, it will provide a method for characterizing the geologic and hydrologic parameters of the entire potential repository block, thus providing a more complete data set to characterize the overall hydrologic and geomechanical properties of the potential repository.

Several points must be kept in mind. First, the principal area of study is in unsaturated rock, and previous surface seismic reflection work has indicated a non-reflective environment.[43] Examination of P-wave VSP surveys in well G-1 and G-4 (single offset) indicates that the problem is not so much attenuation as it is a lack of reflective boundaries, as indicated by the lack of any strong upgoing arrivals in the VSP data. This is a very important point. The rock clearly transmits energy, but does not coherently reflect energy. Therefore, we selected a method that utilizes a point-to-point transmission of energy rather than one that relies on reflected energy. We hope to show that fracture characteristics can be inferred from the way in which this energy is partitioned among the various seismic waves. The targets of the survey are the fracture sets within the welded tuffs, brecciated zones, and if possible, differences in the lithophysal zones. Geologic mapping in this area indicates generally dominant north-south direction to the fracture sets.[42] We of course will also be targeting faults, with the Ghost Dance fault as the main target. The target zones will be areas around the ESF and G-4 borehole. We also expect to see a difference between the saturated zone and unsaturated zone, especially in the P/S velocity ratios.

Fracture detection using P- and S-waves in VSP studies is not a new idea.[44] It is becoming increasingly apparent, however, that to utilize the full potential of VSP, three-component data should be acquired. Crampin has pointed out the importance of using three-component data in VSP work, particularly for fracture detection.[45-49] This author and others have pointed out the phenomenon of shear wave splitting and the anisotropy effects of SH versus the SV waves in addition to P- versus S-wave anisotropy.[50] In addition to Crampin's theoretical work on shear wave splitting, there has been some recent laboratory [51,52] and theoretical work[53] that explains shear wave anisotropy in terms of fracture stiffness. The fracture stiffness theory differs from Crampin's theory in that at a fracture, or a nonwelded interface, the displacement across the surface is not required to be continuous as a seismic wave passes. The only boundary condition in the solution to the wave equation is that the stress must remain continuous across an interface. This displacement discontinuity is taken to be linearly related to the stress through the stiffness of the discontinuity.

The implication of the fracture stiffness theory is that for very thin discontinuities such as fractures, there can be significant effect upon the propagation of a wave. Usually seismic resolution is thought of in terms of wavelength as compared with the thickness and lateral extent of a bed or other features. In the stiffness theory the lateral extent is still important, but if the fracture stiffness is small enough, the thickness of the feature can be less than the seismic wavelength. The effect should be even more pronounced in an unsaturated environment, such as at Yucca Mountain, because the stiffness of an unsaturated fracture is less than that of a saturated fracture. Thus, for any given size of fracture, the lower limit of fracture detectability in an unsaturated fracture will be smaller than if the fracture is saturated. Alternatively, if the fractures are fairly uniform, it may be possible to map isolated saturated zones or perched water.

This stiffness theory is also attractive from several other points of view. Schoenberg[54] shows that the ratio of the velocity of a seismic wave perpendicular and parallel to a set of stiffness discontinuities is a function of the spacing of the discontinuities as well as the stiffness. Thus, given the stiffness and the velocity anisotropy, one could determine the average fracture spacing or density. Or alternatively, given independent information on fracture density, one could determine the fracture stiffness and hopefully relate this stiffness to actual fracture properties, such as discriminating between filled and open fractures or hydraulic conductivity. In any case, there is sufficient reason to expect fracture content and properties to be reflected in the velocity, amplitude, and polarization of the seismic waves.

A link between seismology and hydrology should exist because both the seismic response and hydrology depend on the details of the fracture surface and the geometry of the fracture network. In other words, if this technique is successful, it will be due to the fact that that seismic signature is sensitive to the same geometric parameters which control flow. The main thrust of the research part of this study will be to determine how the fracture geometry influences the propagation of the seismic waves. To the extent that we can determine how the geometry of the fracture system influences the seismic behavior, we can also determine the hydrologic significance of the same geometry. This in turn will lead to a more realistic model of the groundwater system. Although the emphasis of this research is currently in seismology, the background for this work includes the details of both flow and mechanics in individual fractures, as well as an understanding of the fracture network geometry, and the principles of measuring average behavior.

Evolution of Test Design

As stated, there are really two parallel efforts in this project: (1) the design/implementation of the field work and the processing/interpretation of the resulting data, and (2) the development and integrations of the seismic and hydrologic models for interpreting the overall performance of a subject rock mass. The major modifications of the work involve the actual location of the offsets to be used for the prototype work. This is due to limitations on access and the present placement of the ESF. All other activities are proceeding as originally planned.

Conduct of Test

Upon commencement of the project, the available data from the site, VSP, and well log will be used to model the proposed study area. This involves synthetic studies to model the appropriate source and receiver distances, sweep parameters, and other survey specifications. In order to realistically carry out this work, there has been a considerable effort in developing a code that models anisotropic fractured media.

Also being carried out is the planning of the actual logistics of the field work (i.e., procure equipment), survey the lines, and transport equipment. The work was originally scheduled for August of 1989, but due to various obstacles, the work has been postponed until early FY 1990. In addition, all documentation (technical procedures, site investigation plan, etc.) and QA activities are either finished or proceeding.

Future Activities

The most immediate task is to perform the actual field work at G-4. Our goal is to do two VSP offsets per day if a single level VSP tool is used and five per day if a three level tool is used. The next task would be to process the data as outlined. The result would be an overall evaluation of the technique, its resolution, recommendations for further work, and our interpretation of the fracture network, structure, and geologic characteristics in the study area.

Running in parallel with this work would be the modeling and code development effort of the project. It is more difficult to place exact deliverables and milestones on this work. However, quarterly progress reports will be made on this work. As mentioned previously, we are striving to link the seismic anomalies to the fracture content and geomechanical properties of the rock. This will involve modeling and analytical work. Success in these endeavors will allow refinement of the hydrologic models.

If the first stage of prototype testing is successful, the next logical step would be to calibrate the results and the method by comparing the results with independent data on fracture characteristics and hydraulic measurements in the study area. This could be done in the actual mining phase of the ESF or comparing the results with new data that will be obtained in the study area through additional logs or other surveys. As the studies progress at the Yucca Mountain site, more and more will be known about the fracture sets and structure. The ground truth, however, will come in mining the ESF and hydraulic measurements in the ESF area. Also, if successful, the technique could be used to study other zones on the edges of the potential repository site, which will not be mined out but could still affect the performance of the potential repository. After calibration, the developed techniques could be applied to a wider area for a more comprehensive analysis of fracture characteristics. This would involve placing sensors in the subsurface workings and doing "cross-hole" type data gathering. During this process there would be parallel efforts in modeling the seismic response of fractures in order to refine the tomographic interpretation. This would involve integrating the displacement boundary conditions into existing ray tracing programs. Advanced work will involve more complicated models, including finite fracture length, effects of multiple fractures, and matrix properties.

If the seismic modeling indicates that seismic response is sensitive to the geometric parameters that control saturated flow, it will be necessary to determine how unsaturated flow is controlled by these parameters. This would necessarily be done in close association with YMPO. Also, we do not expect the geophysics to tell us the location of every fracture. Rather, in each pixel we will have some average property. The use of fracture models, which incorporate geostatistical simulation, is also based on average pixel properties. Thus, geostatistical techniques can be applied to extend the seismic pixel information and relate this extension to hydrologic properties.

4.25 Equipment and Instrument Development and Demonstration

General Test Description

Many of the experiments planned for the ESF use equipment and instruments that require development and demonstration under conditions similar to those at the ESF before they are used in QA Level I data-gathering activities for site characterization. This prototype test is intended to provide information on the adequacy and reliability of equipment and instruments planned for use in the ESF. These activities are part of ongoing rock mechanics research and are being conducted by SNL in the G-Tunnel at the NTS.[25]

Purpose and Objectives

The purpose of this activity is to ensure that experiments planned for the ESF at Yucca Mountain utilize equipment and instruments that are both adequate and reliable for the testing and environmental conditions expected.

The objectives of this activity are to evaluate and demonstrate that the following instruments and equipment are adequate and reliable for future ESF testing:

- high-pressure flat jacks,
- MPBXs,
- remote convergence monitoring equipment,
- ASR equipment, and
- hydraulic chain saws.

In addition to the instruments and equipment listed above, it is expected that other instruments and equipment will require evaluation in the G-Tunnel prior to use in the ESF. These devices will be described as they are identified.

Support Required

Personnel from SNL will be responsible for the majority of field activities associated with this prototype test. SNL personnel will be assisted by one or more subcontractors, who have not been identified. Technical and field assistance might be sought from subcontractors to SNL. REECo staff, under the general direction of the field coordinator, will provide specific assistance by drilling instrumentation holes and other general support.

Detailed Test Description

SNL is currently evaluating high-pressure flat jacks, MPBXs, remote convergence measurement equipment, ASR equipment, and hydraulic chain saws.

High-Pressure Flat jack Testing

This activity includes the development and demonstration, in situ, of high-pressure 34.5-MPa (>5,000 psi) flat jacks. The flat jacks will be placed in smooth saw-cut slots, pressurized, and their performance monitored by displacement-measuring devices mounted on the rock surface and by pressure transducers in the hydraulic pressure system. Displacement devices are necessary to determine the deformation capability of flat jacks. Pressure transducers are necessary to determine the pressure capability of flat jacks. Both parameters are important for future prototype G-Tunnel and ESF experiments (i.e., rock mass response experiment [Section 4.26], plate loading, and heated block experiment).

MPBX Testing

This activity includes the demonstration and evaluation of the

ROCTEST BOF-EX MPBX. This is a relatively new MPBX that has been used with some success on other projects, but was not used during the G-Tunnel mining evaluations experiment. The BOF-EX MPBX will be placed in an NX core hole drilled nominally perpendicular to a saw-cut slot in the nonwelded Tunnel Bed 5 unit in the G-Tunnel. A flat jack will be installed in the slot and pressurized, and then rock mass displacements will be measured for purposes of comparison with the MPBX and with displacement measuring devices mounted on the rock surface. Flat jack pressures will be monitored using pressure transducers in hydraulic pressure lines.

Remote Convergence Measurement Equipment Testing

This activity includes evaluation of remote drift-convergence-measuring equipment. Such equipment includes laser interferometers and other, as-yet-undetermined devices. A remote convergence-measuring device will be mounted on drift surfaces to measure rock mass convergence as a function of time. This type of equipment is desirable because of the time and manpower constraints associated with ESF development. Such a device, if feasible, will have much less impact on construction schedules. Therefore, it will cost less to operate than conventional shaft convergence equipment, such as tape extensometers.

ASR Equipment Testing

This activity includes the demonstration of ASR equipment in the G-Tunnel. Existing ASR technology uses larger core than the small cores planned for use in the ESF, hence, equipment must be developed. The demonstration in the G-Tunnel will assess the ASR equipment used on the smaller Q core. The oriented HQ core will be retrieved from one hole in the G-Tunnel, the ASR equipment attached, and the response of the rock to relief of stresses monitored. This will be repeated for three pieces of oriented HQ core from one hole in the G-Tunnel.

Chain Saw Development

This activity includes the development of hydraulically powered, diamond-tipped chain saws used to cut smooth slots. Smooth slots are required for many G-Tunnel and ESF experiments (i.e., rock mass response, plate loading, and heated block experiments). The reliability of existing chain saw rock-cutting technology is such that continued development and demonstration are required in the G-Tunnel. The chain saw will be used to cut slots for flat jack installation and for other G-Tunnel experiments. In addition, the saw will be demonstrated for cutting a 2-m-deep (6.6-ft-deep) slot and for cutting horizontal slots in the densely welded tuff in the G-Tunnel.

Other Activities

Other development activities will probably occur in the G-Tunnel as SNL's understanding of the requirements of equipment and instruments progresses. These activities will be defined as they are identified.

Historical Perspective and Background

Equipment and instrument development and demonstration are ongoing SNL activities intended to evaluate instruments and equipment that have not been adequately evaluated in other G-Tunnel experiments. Many instruments and pieces of equipment have been evaluated as part of previous G-Tunnel experiments, such as the heated block experiment and G-Tunnel mining evaluations. Others, such as chain saws, have been developed through separate activities. Some of the present developments are in response to inadequacies identified in previous work; others are based on newly identified needs. The intent of this activity is to evaluate instruments and equipment without fielding complete experiments. However, in some cases, related activities might be assembled to resemble a mini experiment to better evaluate equipment and reduce expenditures.

Evolution of Test Design

The test designs described indicate present requirements based on SNL's present understanding of experimental needs. As such, instrument and equipment demonstration and development testing will change as experimental requirements change.

Conduct of Test

Equipment and instrument development and demonstration include activities that are ongoing in the G-Tunnel. High-pressure flat jacks and hydraulic chain saws are currently undergoing development and testing in the G-Tunnel. Flat jacks have been pressurized to about 27.2 MPa (4,000 psi) and deformed to +100% of their original thickness. Hydraulic chain saws are being evaluated as to their reliability in cutting slots up to 3 m (10 ft) in depth and up to 15 mm (5.9 in.) in width.

Future Activities

Future equipment and instrument development and demonstration activities include a continuation of flat jack and chain saw testing. Flat jacks will be demonstrated to a minimum of 34.4 MPa (5,000 psi). Hydraulic chain saws will be demonstrated for cutting 3-m-deep (10-ft-deep) slots. Other activities will be conducted as resources and needs dictate.

Chain Saw Development

This activity includes the development of hydraulically powered, diamond-tipped chain saws used to cut smooth slots. Smooth slots are required for many G-Tunnel and ESF experiments (i.e., rock mass response, plate loading, and heated block experiments). The reliability of existing chain saw rock-cutting technology is such that continued development and demonstration are required in the G-Tunnel. The chain saw will be used to cut slots for flat jack installation and for other G-Tunnel experiments. In addition, the saw will be demonstrated for cutting a 2-m-deep (6.6-ft-deep) slot and for cutting horizontal slots in the densely welded tuff in the G-Tunnel.

Other Activities

Other development activities will probably occur in the G-Tunnel as SNL's understanding of the requirements of equipment and instruments progresses. These activities will be defined as they are identified.

Historical Perspective and Background

Equipment and instrument development and demonstration are ongoing SNL activities intended to evaluate instruments and equipment that have not been adequately evaluated in other G-Tunnel experiments. Many instruments and pieces of equipment have been evaluated as part of previous G-Tunnel experiments, such as the heated block experiment and G-Tunnel mining evaluations. Others, such as chain saws, have been developed through separate activities. Some of the present developments are in response to inadequacies identified in previous work; others are based on newly identified needs. The intent of this activity is to evaluate instruments and equipment without fielding complete experiments. However, in some cases, related activities might be assembled to

4.26 Rock Mass Response Experiment in the G-Tunnel

General Test Description

The prototype rock mass response experiment in the G-Tunnel consists of two activities. A large-scale direct shear test and a large-scale multiaxial compression test will be performed. The large-scale direct shear test will evaluate joint characteristics at field scale, and the compression test will evaluate rock mass response to controlled loading conditions.

Purpose and Objectives

The experiments will assess the feasibility of conducting large-scale rock mass response experiments in the ESF at Yucca Mountain by performing preliminary experiments in the GTUF where rocks similar to those expected at Yucca Mountain are found.

The experiments will be performed in the Grouse Canyon member welded tuff of the Belted Range tuff in the GTUF (Figure 4.26-1) at Rainier Mesa of the NTS. Experiment configuration, geometry, loading techniques, and selection of instruments and equipment will be assessed for use in future ESF experiments. The adequacy and usefulness of the information obtained during this experiment will also be assessed by the PI following post-test analyses of the experiment.

The objectives of the ESF experiments are to measure the rock mass compressive response of large samples of welded tuff in situ and to measure the shear strength and the closure/slip relationship to stress of in situ joints. This information is desirable for the development of sealing relationships and for evaluating rock mass strength. However, these types of experiments are especially hard to conduct, making the development of techniques in the G-Tunnel essential.

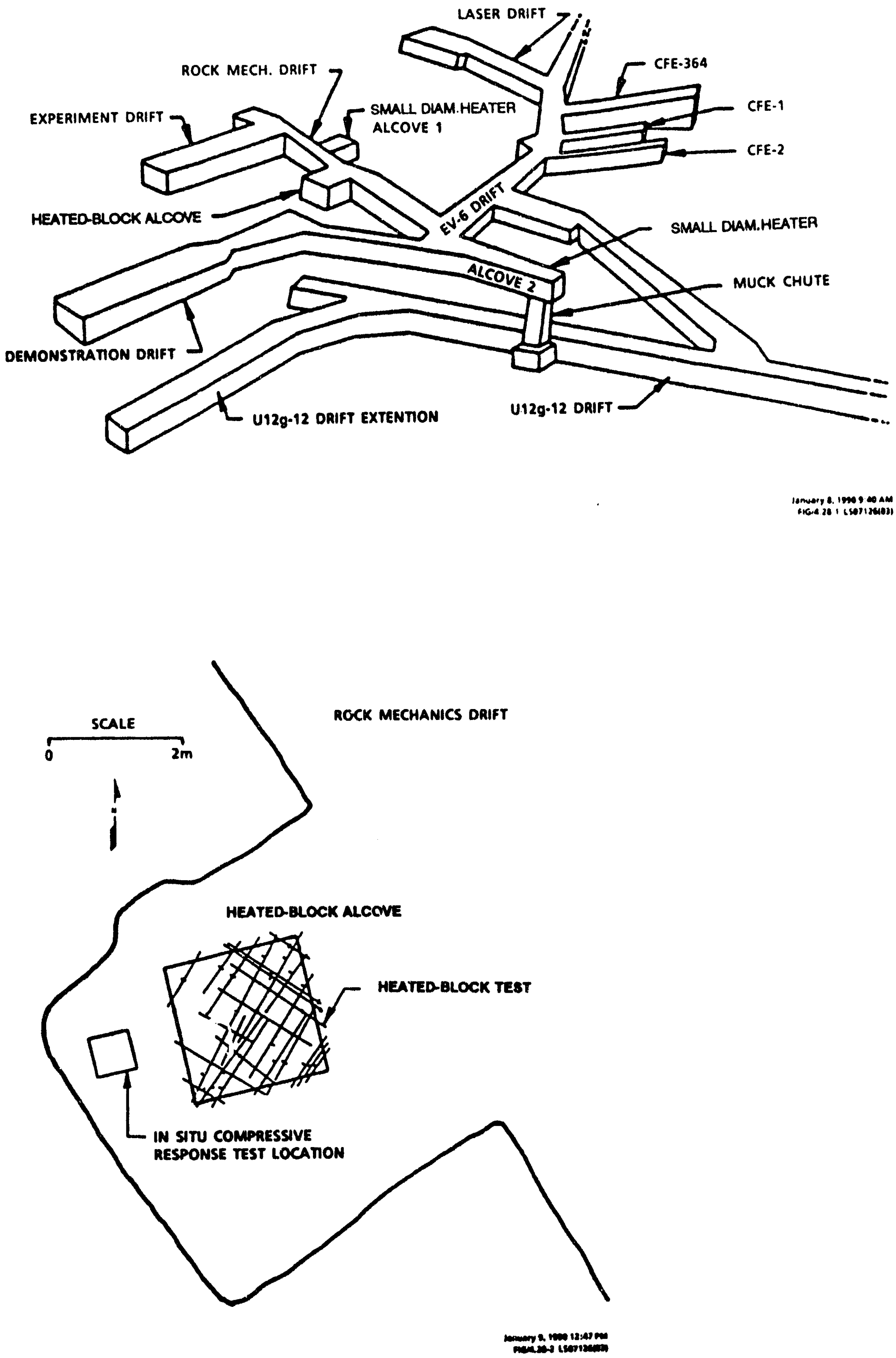


Figure 4.26-1. (a) Schematic drawing of the NNWSI area in the G-Tunnel
(b) Plan view of the Heated-Block Alcove.

The objectives of the prototype experiment are to

- develop and evaluate techniques for conducting large-scale tests in situ for compressive and shear behavior;
- evaluate equipment and instruments that are required for these tests; and
- provide preliminary information on compressive and shear behavior for evaluating models of a jointed rock mass.

Support Required

Personnel from SNL will be responsible for the majority of the field activities under the rock mass response experiment in the G-Tunnel. SNL personnel will be assisted by one or more subcontractors, who have not been identified. Technical and field assistance might be sought from subcontractors to SNL and from REECo staff, who, under the general direction of the field coordinator, will provide assistance by drilling instrumentation holes and other general support.

Detailed Test Description

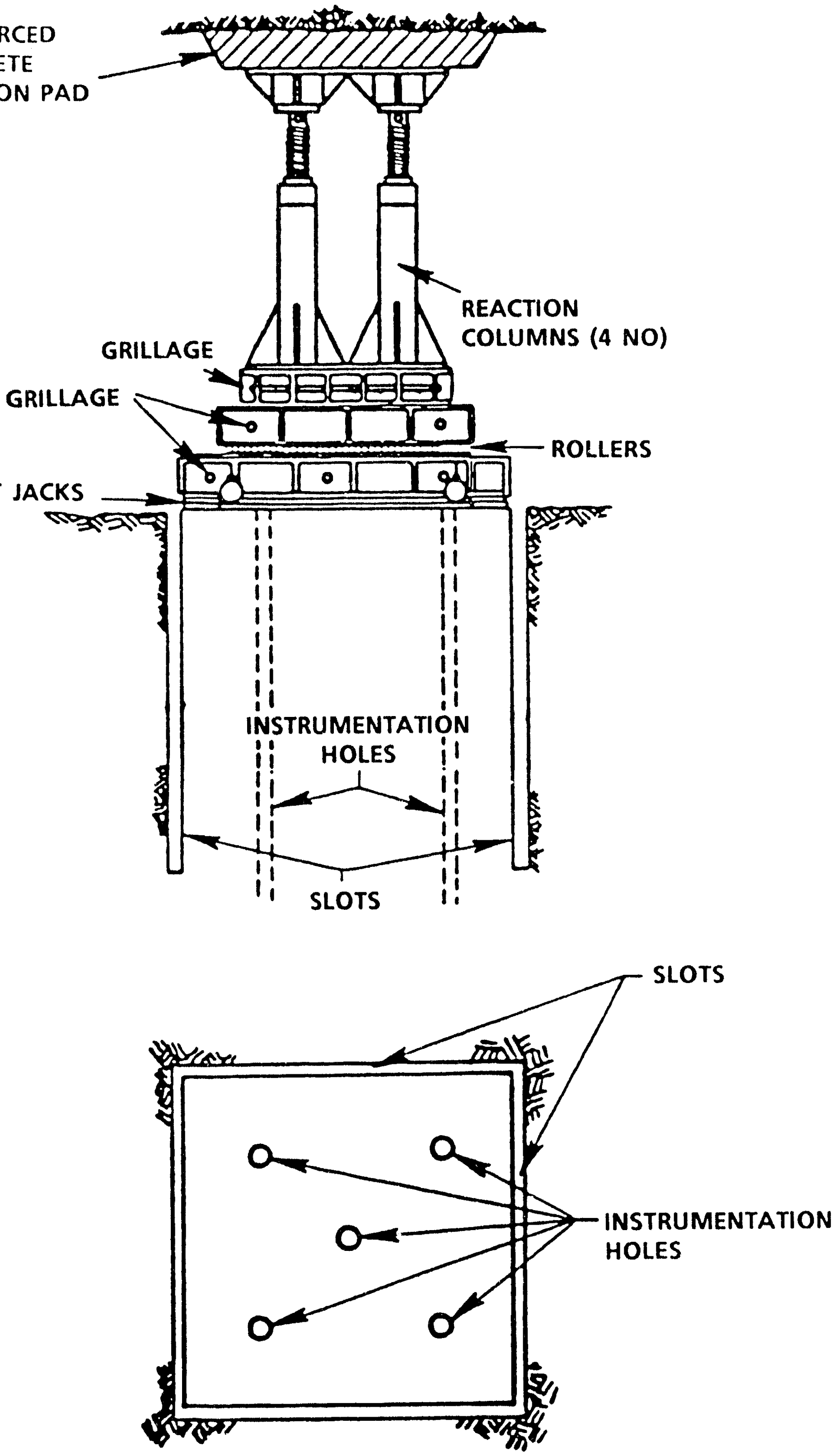
This experiment will be conducted in two parts. The first is the in situ rock mass compressive response test using a large in situ sample that contains as many fractures as possible. The second is the large-scale joint shear response test. These two parts might be conducted simultaneously.

In Situ Rock Mass Compressive Response Test

The in situ rock mass compressive response test performed in the G-Tunnel is intended to provide information to enhance the performance of such an experiment in the ESF. The equipment intended for this experiment is of a developmental nature and must be demonstrated prior to its use in the ESF. This portion of the experiment will aid in determining optimal testing configuration(s) (by analyzing the response of the block and the placement of instruments), scale (by determining if the size tested is large enough to represent the rock mass), and loading for the ESF rock mass response experiments. In addition, the experimental concepts must be proven prior to their use in the ESF.

This portion of the experiment is intended to provide information on the rock mass response to compressive loads so that both numerical models[55-58] and empirical analyses[59] can be evaluated for the potential Yucca Mountain site. The numerical models currently being considered approximate the mechanical response of the rock mass as an elastic, elastic-plastic, or compliant jointed material. These numerical models incorporate an understanding of the physics of the deformation process to provide a quantitative assessment of the stress state and the displacements resulting from mechanically induced loads. The empirical analyses, in general, describe the rock mass response to applied loads incorporating both major and minor principal stresses. As a result, the testing program should, if possible, allow the capability of testing in situ samples with confining pressure. This work in the G-Tunnel will initially concentrate on the compressive response of blocks, with minimal confinement. Subsequent tests in the G-Tunnel will be performed with increasing confinement.

The first of these compressive tests will be located in the floor of an alcove in order to simplify the test. Following analyses of this test, a compressive test in the rib and/or a confined test may be attempted. The configuration of the first experiment is illustrated in Figure 4.26-2. The figure shows a possible layout of instruments for the first in situ rock mass compressive response test in the G-Tunnel. A square cross section



January 9, 1990 12:47 PM

Figure 4.26-2. Conceptual layout of the In Situ Rock-Mass Compressive-Strength Test.

was chosen because of the ease of achieving this shape with the newly redesigned 1-m (3.3-ft) hydraulic chain saw.[60] The use of the saw will allow various block sizes to be tested. Tests[61] indicate that as long as the aspect ratio is greater than about 2:1, the shape of the sample has little influence on the measured strength. Five borehole extensometers will be used to measure the axial displacement of the sample during loading. The borehole extensometers will be BOF-EX extensometers using three linear variable differential transformers (LVDT) each. The middle LVDT in each hole will measure displacement in the middle third of the sample. The top and bottom LVDTs will measure the top and bottom thirds of the sample, respectively. The load will be applied by either high-pressure hydraulic rams or high-pressure flat jacks located between a loading platen and a reaction frame. Displacement transducers will be attached to the loading platen in each of the three principal directions in order to monitor the direction of loading. Vertical displacement transducers will be used to monitor the axial displacement of the sample as it is loaded. These transducers will be used to determine if there is any eccentricity in the axial loads. In addition, the gross lateral displacements in each of the four lateral directions will be measured using either the volume change in the confining flat jacks or long-gauge displacement transducers.

The size of the sample tested in the G-Tunnel will initially be limited to about 0.5 m by 0.5 m by 1 m (1.6 ft by 1.6 ft by 3.3 ft) because of the limitations of the present 1-m (3.3-ft) saw. This saw can cut a slot up to about 1 m (3.3 ft) in depth. In order to maintain a 2:1 aspect ratio, the sides of the block must be no greater than 0.5 m (1.6 ft). In terms of the testing in the G-Tunnel, this is not considered a problem because the information provided by this experiment is of a preliminary nature. Other workers have attempted large-scale in situ compression tests with mixed results. Most of these tests have been on pillars of coal,[62-65] although large-scale tests on other rocks have also been performed.[66-68] Work on cubic pillars of calcareous iron ore suggests that the dimensions of large-scale in situ tests must be such that they comprise at least 10 inhomogeneities or joints in each of the three principal dimensions.[67] Coal is a densely cleated and fissured rock; therefore, the compression tests performed on the material (side lengths up to 2 m [6.6 ft]) probably satisfy dimensional requirements. Unconfined compression tests were performed on triangular prisms of intact diorite up to 2.7 m (9 ft) in length.[66] The work performed on salt was reviewed but did not well represent the behavior of tuff.[68] Capturing 10 homogeneities in the sample might be impractical for the G-Tunnel because the average joint frequency is about 3 to 4.5 per meter (9.8 to 14.8 per foot).[69] This would require a test specimen of about 3 m (9.8 ft), which is probably impractical. As stated before, the G-Tunnel work is preliminary and is intended to demonstrate testing concepts for experiments in the ESF.

In Situ Joint Shear-Response Test

The in situ joint shear-response test performed in the G-Tunnel is intended to provide information to enhance such an experiment in the ESF. This portion of the experiment will aid in determining the optimal configuration(s), scale, and loading for the ESF in situ joint shear strength experiments.

The technique recommended in "ISRM Suggested Methods" (1981)[70] will be modified for the large-scale in situ joint shear response experiments in the G-Tunnel. The shear response experiment will be conducted in a manner that most closely approximates the expected response of the joints at Yucca Mountain. Preliminary information indicates that the predominant joint orientation at Yucca Mountain is near vertical.[71] In order to closely approximate the expected conditions there, the G-Tunnel test should be conducted so that the direction of shear displacement is the same as the expected joint shear direction at Yucca Mountain. Because the predominant orientation of joints in both the G-Tunnel and Yucca Mountain is vertical, shearing along joints in the near field will most likely occur in the vertical direction. The in situ shear test in the G-Tunnel will be conducted in the floor of the heated block alcove in a specially excavated test pit. This will allow shearing of the vertical joints under controlled conditions. Figure 4.26-3 shows the potential location in the heated block alcove for the in situ joint shear-response test. The test pit concept was chosen because this configuration allows access to vertical joints and provides a reasonable support for the reaction frame.

Figure 4.26-4 shows a three-dimensional representation of the test pit and the shearing block. The test pit and shearing block will be delineated using rock saws, and material will be removed by conventional mechanical mining methods. The shear block will be instrumented prior to any excavation in order to measure any changes that might occur in the block/joint interface.

The configuration of the experiment itself is illustrated in Figure 4.26-5. The figure shows a possible layout of instruments for the in situ joint shear-response test. The square cross section was chosen because of the ease of achieving this shape with available saws. The size of the test specimen will initially be guided by ISRM-suggested methods,[70] which require a shearing surface no less than 70 cm by 70 cm (27.5 in. by 27.5 in.).

Experimental Methods

In Situ Rock-Mass Compressive-Response Test Methods

The in situ rock-mass compressive-response test will be conducted using a staged methodology. The first stage will be the uniaxial compression of a 0.5 m by 1.0 m by 1.0 m (1.6 ft by 3.3 ft by 3.3 ft) block of welded tuff. Failure of the rock mass in unit TSw2 (which will be tested in the ESF) may occur at stresses

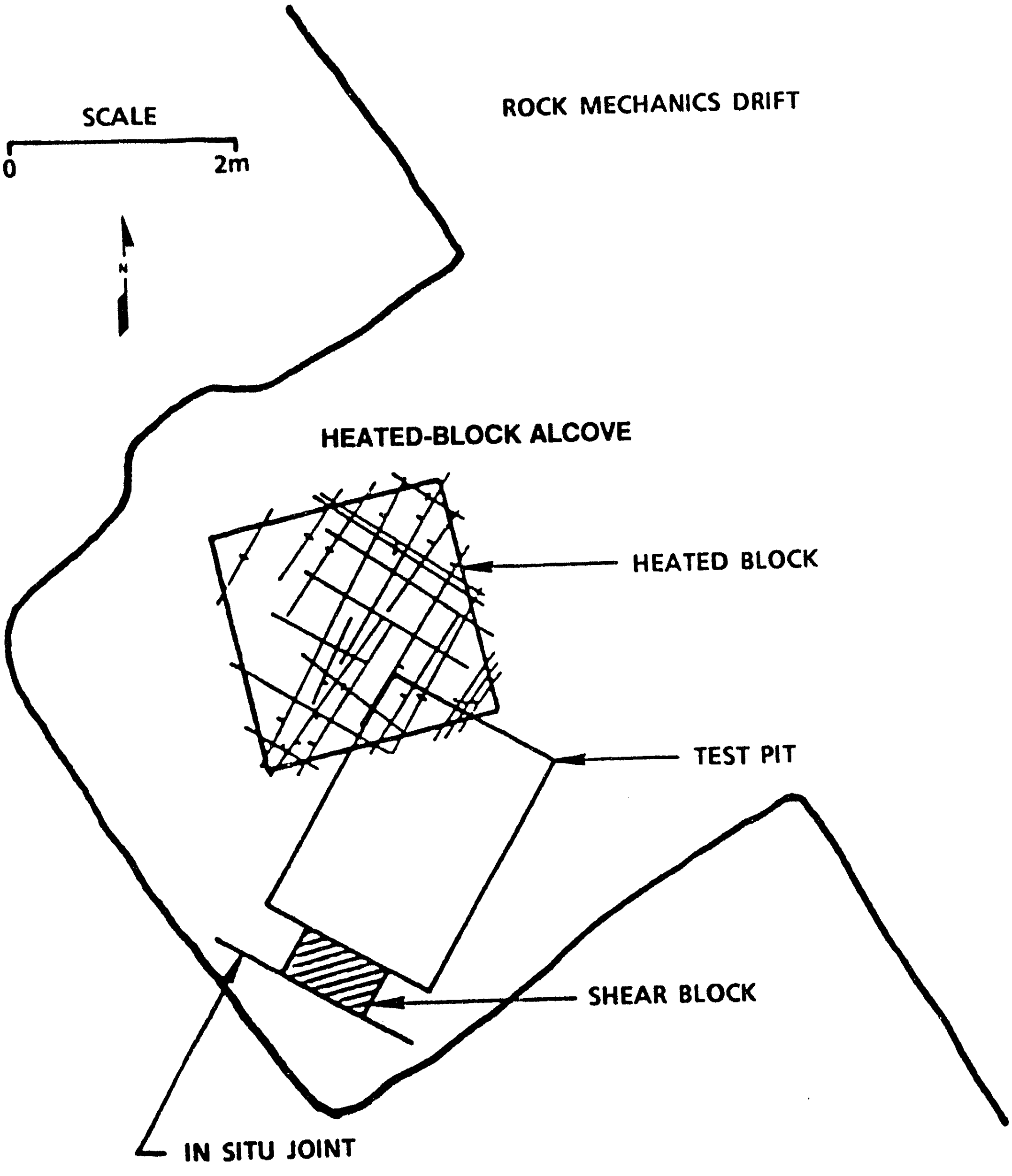


Figure 4.26-3. Heated-Block Alcove showing possible in situ joint shear-response test locations.

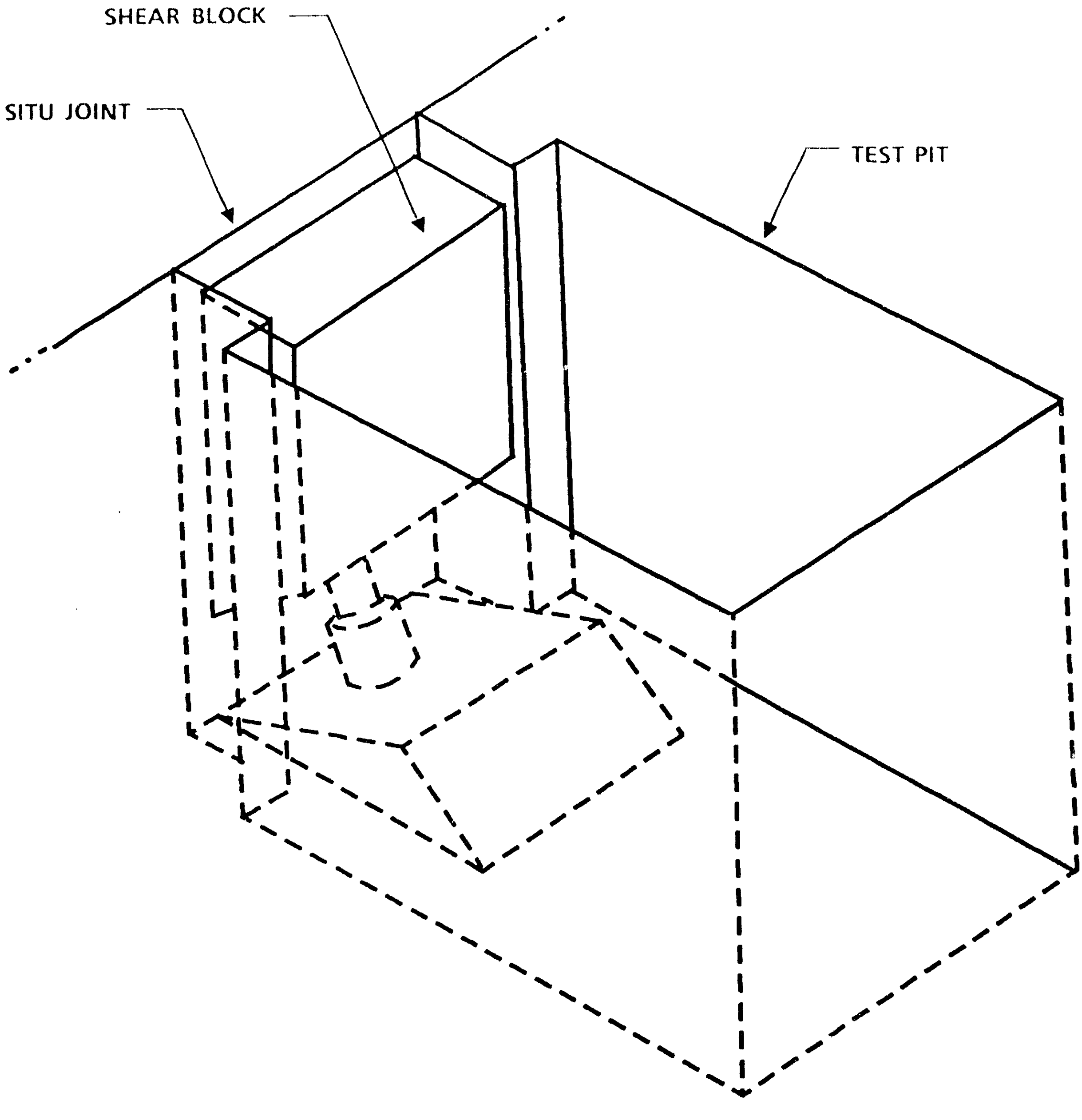


Figure 4.26-4. Excavation of the test pit for the In Situ Shear-Response Experiment.

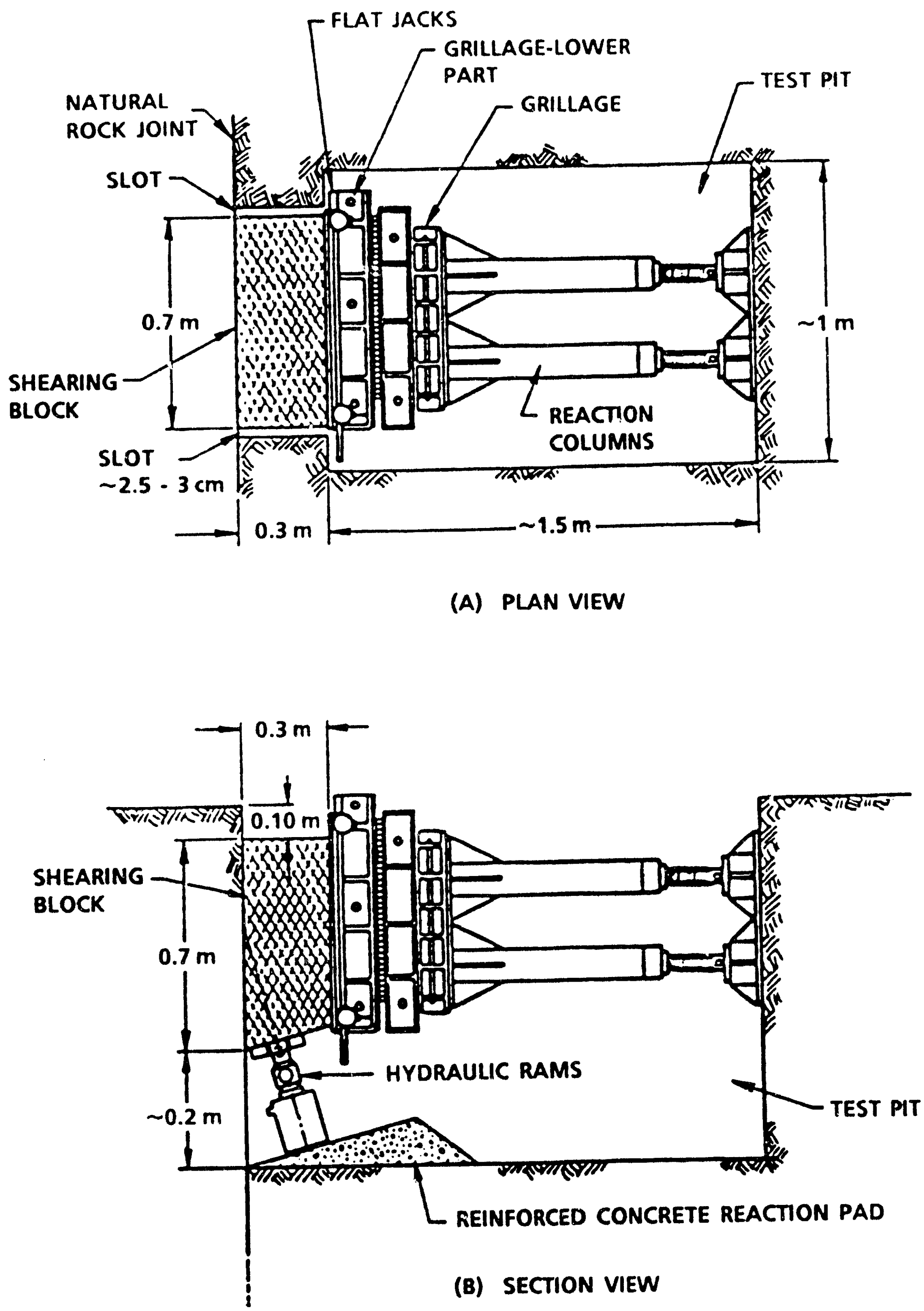


Figure 4.26-5. (a) Conceptual layout of equipment for the In Situ Joint Shear-Response Test, plan view; (b) section view.

as low as 16 MPa (2300 psi).[72] This first stage of the test will provide information to guide second-stage compression tests in the G-Tunnel and the ESF. First-stage testing will also provide information with regard to sample size and loading requirements for second-stage testing.

A detailed geologic characterization will be conducted to define the structure and lithology in the region of the test. This geologic characterization will include at least the location, orientation, spacing, and condition of the joints in the vicinity of the test location. Following the geologic characterization of the test location, a thin, pasty layer of high-strength grout will be applied to the surface. While the grout is still soft, the surface will be finished smooth and planar. Five EX core holes will be drilled parallel to the long axis of the specimen. The five EX core holes will house the MPBXs in the specimen. Following the drilling and MPBX installation, slots will be cut. These slots will be about 1 m (3.3 ft) deep, and they should intersect so as to produce a block specimen 0.5 m by 0.5 m (1.6 ft by 1.6 ft) on a side and 1 m (3.3 ft) deep. The slots will have to be cut twice so as to produce slots at least 10 cm (3.9 in.) wide to allow expansion of the specimen in lateral directions during axial loading. The "piece" of rock that remains after the two slots are cut must be broken out to produce the widened slot. Analyses of the G-Tunnel heated block experiment data indicate that lateral confinement was produced by the axial slot walls during the uniaxial testing.[73]

Following delineation of the block of rock by cutting the slots, the instruments that will measure the reaction of the block to the applied stresses must be installed. These instruments include five BOF-EX MPBXs, surface strain gauges, and displacement transducers in all three principal stress directions. After these instruments are installed and checked, the reaction frame will be constructed. The reaction frame should include the large cover plate as part of its system and should, as a minimum, be capable of supporting up to 226 T mg (5 million lb). Furthermore, it should be as stiff as possible to limit the amount of strain energy that can be stored in it.

The testing itself will first proceed by inserting the confining flat jacks into four slots. These flat jacks and the axial load device will be pressurized to about 2 MPa (290 psi) to provide some confinement of the sample and to "seat" the loading devices and platens. Following this seating, the axial load will be increased at an incremented displacement strain of about 10 x 10^{-6} mm/mm. The axial load will be increased to about 15 MPa (2,175 psi) and then cycled down to 2 MPa (290 psi) with a negative displacement strain of .00001 mm/mm. The axial load will then be increased to about 30 MPa (4,350 psi) and again cycled down to 2 MPa (290 psi). The cycling will continue until either the pressure capacity or displacement capacity of the axial load device has been reached or the bearing capacity of the sample is exceeded. If the sample maintains integrity, then the confining pressure will be increased to 5 MPa (725 psi) and the above process repeated.

In Situ Joint Shear-Response Test Methods

The in situ joint shear-response test will follow the methods outlined in the "ISRM Suggested Methods."[70]

The test block will be cut to the specified size (about 70 cm by 70 cm by 35 cm [27.5 in. by 27.5 in. by 13.8 in.]), using the available 1-m (3.3-ft) hydraulic chain saws developed by SNL.[60] The base of the test block should coincide with the plane of the fracture, and the direction of shearing will coincide with the direction of shearing anticipated under in situ conditions, namely, vertical shearing.

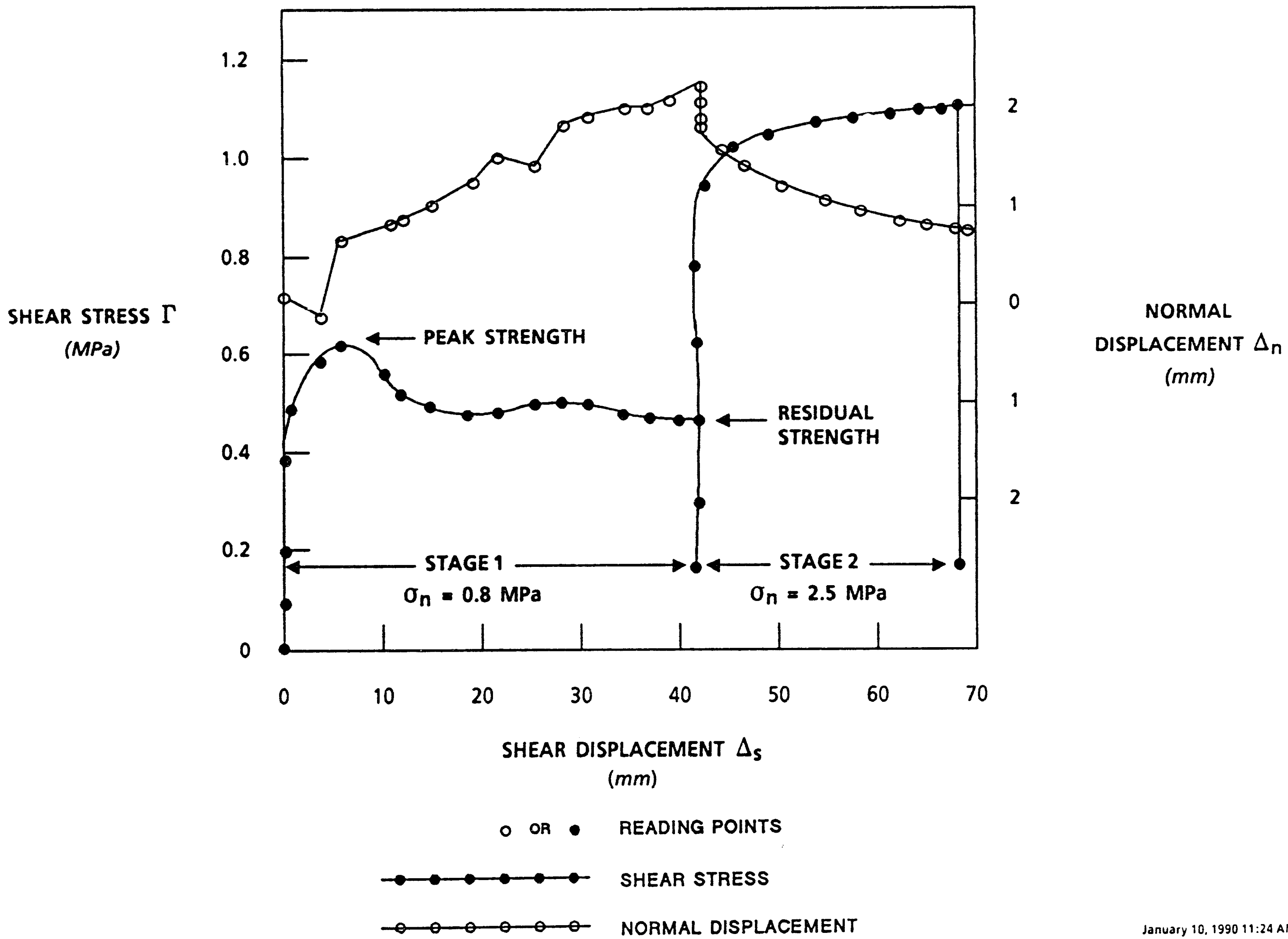
After the equipment and instruments are in place and ready, the normal load should be increased to the full value specified for the first stage of the test. The changes in the joint normal aperture should be recorded.

Following the previous steps, the actual shearing can be started. The purpose of shear testing is to establish values for the peak and residual shear strengths and the normal and shear stiffness of the joint in question. Corrections to the normal load applied with the normal load flat jacks are required because the angle of the shearing load is not zero; consequently, there is a normal component to it.

The shear force is applied either in increments or continuously in such a way as to control the rate of shear displacement. Approximately 10 sets of readings should be taken before reaching the peak shear strength. An example of a stress/displacement graph is shown in Figure 4.26-6. The rate of shear displacement should be less than 0.1 mm/min (.021 in./min) in the ten-minute period before taking a set of readings. This rate may be increased to not more than 0.5 mm/min (.10 in./min) between sets of readings provided that the peak strength itself is adequately recorded.

After reaching the peak shear strength, readings should be taken at increments of 0.5- to 5-mm (.021-to .197-in.) shear displacements as required to adequately define force/displacement curves (Figure 4.26-6). The rate of shear displacement should be 0.02 to 0.2 mm/min (.001 to .008 in./min) in the ten-minute period before a set of readings is taken, and may be increased to not more than 1 mm/min (.039 in./min) between sets of readings.

It may be possible to establish a residual strength value when the sample is sheared at the constant normal stress if at least four consecutive sets of readings show not more than 5% variation



January 10, 1990 11:24 AM
FIG 4.28-8 LS07126(03)

Figure 4.26-6. Shear stress-displacement graph.

in a shear displacement of 1 cm (0.39 in.)

The specimen should be reloaded for each normal stress, and the shearing continued as previously described. This should be continued for all normal stresses of interest. For this experiment, the maximum normal stress of interest is 10 MPa (1450 psi), and the normal load incremental increase is to be 1 MPa (145 psi).

Historical Perspective and Background

Large-scale in situ experiments intended to provide information on the response of rock masses was discussed in the previous section. Early attempts in the YMP to provide this type of information include the G-Tunnel heated block and pressurized slot experiments. These experiments, although somewhat successful, had inherent problems with regard to experimental boundary conditions and stress levels. The planned rock mass response experiment in the G-Tunnel is intended to overcome these limitations.

Evolution of Test Design

The rock mass response experiment is an attempt to improve on techniques and experiments previously conducted in the G-Tunnel. Changes in this approach or the design of the experiment might occur as progress on the experiment is made.

Future Activities

A criteria letter that details the support requirements of this experiment will be written. Preliminary activities that contribute to this experiment will be started.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support and contributions of other individuals that were instrumental in the compilation of this report. Draft technical sections were provided by the respective PIs from the Laboratories (LLNL, SNL, and LANL) and the USGS. Special thanks are expressed to the Organization Technical Leads who coordinated efforts within their organizations. The Organization Technical Leads are R. Craig (USGS), A. Norris (LANL), R. Finley and B. Luke (SNL), and A. Ramirez (LLNL). We would also like to acknowledge M. Wheeler (LATA) for his efforts in preparation of the initial preliminary report draft and figures.

The G-Tunnel field operations effort was consistently supported by A. Veloso (DOE/NTSO), A. Girdley (DOE/YMP), R. Dye and J. Talbutt (SNL), and S. Francis (LANL). Their support and the enthusiastic support of the Nevada Test Site contractors (REECo, FSN, and H&N) contributed to the success of the testing activities conducted.

Finally we would like to thank the following individuals for providing suggestions during manuscript preparation and providing review comments: J. Rowley, N. Elkins, K. Cambern, K. Quintana, A. Thompson, and R. Herbst (LANL).

REFERENCES

1. J. M. Ray and J. C. Newsom, "The Yucca Mountain Project Prototype Air-Coring Test, U12g Tunnel, Nevada Test Site," Los Alamos National Laboratory (September 1988).

2. B. J. Skaggs, L. W. Ortiz, D. J. Burton, et al., "Evaluation of Dust-Related Health Hazards Associated with Air Coring at G-Tunnel, Nevada Test Site," Los Alamos National Laboratory report LA-11594-MS (1989).

3. Los Alamos National Laboratory Exploratory Shaft Facility Test Manager's Office, "The Yucca Mountain Project Prototype Testing Program," Los Alamos National Laboratory status report LA-11665-SR (October 1989).

4. DOE Yucca Mountain Project Office, Procedure AP-5.10Q, "Use of NTS Contractors on the NNWSI Project," Yucca Mountain Project Administrative Procedures Manual, YMP/APM-1, Rev. 60 (August 1988).

5. "Sample Collection of Muck from Excavations at the Exploratory Shaft Facility for Mineralogy-Petrology Studies," Los Alamos National Laboratory Detailed Procedure, TWS-ESS-DP-127 (May 1989).

6. P. Montazer and W. Wilson, "Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada," Water-Resources Investigations report 84-4345, US Geological Survey, Lakewood, CO (1984).

7. John C. Westall, "Reactions at the Oxide-Solution Interface: Chemical and Electrostatic Models," Geochemical Processes at Mineral Surfaces, J. A. Davis and K. H. Hayes, eds., ACS Symposium Series 323, American Chemical Society, Washington, DC, pp. 54-78 (1986).

8. D. B. Kent, V. S. Tripathi, N. B. Ball, and J. O. Leckie, "Surface-Complexation Modeling of Radionuclide Adsorption in Subsurface Environments," Sandia National Laboratories Technical report No. 294, p. 110 (1986).

9. D. Langmuir and J. Mahoney, "Chemical Equilibrium and Kinetics of Geochemical Processes in Ground Water Studies," in Proceedings First Canadian/American Conference on Hydrogeology, Practical Applications of Ground Water Geochemistry, B. Hitchon and E. I. Wallick, Eds., pp. 69-95 (1985).

10. A. Lewis-Russ, "Applicability of Simple and Complex Models of Tracer Adsorption in Water-Rock Systems," presented at the annual meeting of the Association of Ground Water Scientists and Engineers, Houston, Texas (October 31 - November 1, 1989).

11. P. M. Thompson and P. A. Lang, "Geomechanical Instrumentation Applications at the Canadian Underground Research Laboratory," presented at the 2nd International Symposium on Field Measurements on Geomechanics, Kobe, Japan, Atomic Energy of Canada, Limited, White Shell Nuclear Research Establishment, Pinawa, Mantoua Canada, ROE 1L0 (April 6-9, 1987).

12. Site Investigation Plan, "Characterization of Percolation in the Unsaturated Zone: Surface-Based Borehole Investigations," US Geological Survey Investigation Plan USGS-SIP-33436G-01, R0, Denver, CO (1988).

13. T. A. Buscheck and J. J. Nitao, "Fluid Flow and Transport Modeling," Institutional Research and Development FY86, Lawrence Livermore National Laboratory Annual report, UCRL-53689-86, pp. 48-49 (1987).

14. W. Daily, W. Lin, and T. Buscheck, "Hydrology of Topopah Spring Tuff-- Laboratory Measurements," J. Geophys. Res. v. 92, no. B8, 7854-7864 (1989).

15. "Yucca Mountain Project Office of the Exploratory Shaft Facility Title I Design Summary," Yucca Mountain Project YMP/88-20 (December 21, 1988).

16. H. S. Swolfs, "First Experiences with the C.S.I.R.O. Hollow-Inclusion Stress Cell," US Geological Survey OFR 82-990, Denver, CO, 17 pp. (1982).

17. J. R. Aggson, "Test Procedures for Nonlinearly Elastic Stress-Relief Overcores," US Bureau of Mines report of Investigations 8251, Denver, CO, 9 p. (1977).

18. H. S. Swolfs and T. C. Nichols, Jr., "Anisotropic Characterization of Pierre Shale--Preliminary Results," US Geological Survey OFR 87-417, Denver, CO, 9 pp. (1987).

19. V. E. Hooker and C. F. Johnson, "Near-Surface Horizontal Stresses, Including the Effects of Rock Anisotropy," US Bureau of Mines report of Investigations 7224, 29 pp. (1969).

20. J. R. McWilliams, "The Role of Microstructure in the Physical Properties of Rock," Testing Techniques for Rock Mechanics, American Society for Testing and Materials, STP 402, Philadelphia, PA, pp. 175-189 (1966).

21. L. Birgersson and I. Neretnieks, "Diffusion in the Matrix of Granitic Rock, Field Test in the Stripa Mine," Swedish Nuclear Fuel and Waste Management Company (SKB) Technical report 8808 (1988).

22. K. H. Birdsell, L. F. Brown, A. E. Norris, G. A. Cederberg, B. J. Travis, and P. G. Stringer, "Modeling Tracer Diffusion in Fractured and Unfractured, Unsaturated, Porous Media," J. Contaminant Hydrology, v. 3, pp. 145-170 (1988).

23. J. Yow Jr., "Concept for Waste Package Environment Tests in the Yucca Mountain Exploratory Shaft," Lawrence Livermore National Laboratory report UCID-20450, Livermore, CA (1985).

24. K. Preuss, Y. W. Tsang, and J. S. Y. Wang, "Numerical Studies of Fluid and Heat Flow Near High-Level Nuclear Waste Packages Emplaced in Partially Saturated Fractured Tuff," Lawrence Berkeley Laboratory, University of California report LBL-18552, Berkeley, CA (1989).

25. R. M. Zimmerman and R. E. Finley, "Summary of Geomechanical Measurements Taken in and Around the G-Tunnel Underground Facility, NTS," Sandia National Laboratories report SAND86-1015, Albuquerque, NM, p. 143 (1987).

26. W. Daily, W. Lin, and T. Buscheck, "Hydrology of Topopah Spring Tuff--Laboratory Measurements," J. Geophys. Res., v. 92, no. B8, pp. 7854-7864 (1989).

27. A. L. Ramirez and D. G. Wilder, eds., "Prototype Engineered Barrier System Field Tests, Progress Report through November 1, 1988," Lawrence Livermore National Laboratory report UCID-21640 (draft), Livermore, CA (1989).

28. P. Montazer, "Rationale for Air Drilling/Coring in the Exploratory Shaft and Test Chambers" (6 page draft) and "Preliminary Outline of Design Needs for Prototype Air-Coring Tests in G-Tunnel" (5 page draft) with letter (available from authors) from P. Montazer, USGS/Nuclear Hydrology Program to P. Aamodt, Los Alamos National Laboratory, providing input for planning the Prototype Air-Coring Test (1985a).

29. P. Montazer, letter (available from authors) from P. Montazer, USGS/Nuclear Hydrology Program to M. Blanchard, Department of Energy/Waste Management Project Office (1986).

30. D. A. Teasdale and R. R. Pemberton, "Wireline-Rotary Air Coring of the Bandelier Tuff, Los Alamos, New Mexico," US Geological Survey Water-Resources Investigations report 84-4176, Denver, CO (1984).

31. K. P. Larkin and J. L. Speake, "Horizontal Monitoring Holes, Los Alamos, New Mexico," Reynolds Electrical & Engineering Co., Inc. report NVO-410-36 (1976).

32. J. W. Nyhan, B. J. Drennon, W. D. Purtymun, et al., "Distribution of Plutonium & Americium Beneath A 33-Yr-Old Liquid Waste Disposal Site," J. Environ. Qual., v. 14, no. 4, p. 501 (1978).

33. A. E. Norris, F. M. Byers Jr., and T. J. Merson, "Fran Ridge Horizontal Coring Summary Report Hole UE-25h#1, Yucca Mountain Area, Nye County, Nevada," Los Alamos National Laboratory report LA-10859-MS (1986).

34. J. M. Ray and J. C. Newsom, "ESF Drilling Equipment Options: Recommendations and Rationale," unpublished draft document prepared for the Department of Energy/Waste Management Project Office by Los Alamos National Laboratory to assist DOE in planning and logistics for Yucca Mountain Exploratory Shaft Facility drilling requirements (1987b).

35. D. A. Best, G. M. Cordell, and J. A. Haston, "Underground Test Facility: Shaft and Tunnel Laboratory for Horizontal Well Technology," SPE 14333, report prepared by the Alberta Oil Sands Technology & Research Authority for presentation at the 60th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers held in Las Vegas, NV, (September 22-25, 1985).

36. P. L. Aamodt, "Updated Cost Estimates for Prototype Test Drilling Activities," letter dated August 24, 1987 to R. Bullock, FSN, and H. Pedalino, H&N, TWS-ESS-1-8/87-35, Los Alamos National Laboratory, Los Alamos, NM (1987c).

37. J. M. Ray and J. C. Newsom, Appendix A of the "Prototype Test Plans, Revision 1," prepared by Los Alamos National Laboratory for the Department of Energy/Waste Management Project Office (TWS-ESS-1-8/87-36)(1987d).

38. Atlas Copco dust collector, DCT90, TWS-EES-1-LV-09-90-20.

39. USDOE, "Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada," United States Department of Energy, Office of Civilian Radioactive Waste Management, Washington, D.C. (1988).

40. N. H. Harley, I. M. Fisenne, R. G. McGregor, et al., "Measurement of Radon and Radon Daughters in Air," National Council on Radiation Protection and Measurements report No. 97, Bethesda, MD (1988).

41. C. C. Barton and E. Larsen, "Fractal Geometry of Two-Dimensional Fracture Planar through Networks at Yucca Mountain, Southwestern Nevada," in Proceedings of (Bint. Sym. on Fundamentals of Rock Joints), (Bjorkliden, Lapland, Sweden, 1985).

42. R. B. Scott and J. Bonk, "Preliminary Geologic Map of Yucca Mountain Nye County, Nevada with Geologic Sections," US Geological Survey OFR 84-494, Denver, CO, 9 pp. (1984).

43. T. F. McGovern "An Evaluation of Seismic Reflection Studies in the Yucca Mountain Area, Nevada Test Site," US Geological Survey OFR-83-912, Denver, CO, 55 pp. (1983).

44. R. R. Stewart, R. M. Turpening, and M. N. Toksoz, "Study of a Subsurface Fracture Zone by Vertical Seismic Profiling," Geophys. Res. Lett., v. 8, pp. 1132-1135 (1981).

45. S. Crampin, "Seismic-Wave Propagation Through a Cracked Solid: Polarization as a Possible Dilatancy Diagnostic," Geophys. J. Roy. Aston. Soc., v. 53, pp. 467-496 (1978).

46. S. Crampin "A Review of Wave Motion in Anisotropic and Cracked Elastic-Media," Wave Motion, v. 3, pp. 343-391 (1981).

47. S. Crampin, "Effective Anisotropic Propagation Through a Cracked Solid" in Proc. of the First Internat. Workshop on Seismic Anisotropy, Crampin, S., Hipkin, R. G., and Chesnokov, in E. M., Eds., "Geophys. J. Roy. Astron. Soc.," v. 76, pp. 135-145 (1984a).

48. S. Crampin, "Anisotropy in Exploration Seismics," First Break, v. 2, pp. 19-21 (1984b).

49. S. Crampin, "Evaluation of Anisotropy by Shear-Wave Splitting," Geophysics, v. 50, no. 1, pp. 142-152 (1985).

50. P. C. Leary and T. L. Henyey, "Anisotropy and Fracture Zones About a Geothermal Well from P-Wave Velocity Profiles," Geophysics, v. 50, no. 1, pp. 25-36 (1985).

51. L. J. Pyrak-Nolte, L. R. Myer, and N. G. W. Cook, "Anisotropy in Seismic Velocities and Amplitudes from Multiple Parallel Fractures," J. Geophys. Res., in press (1989a).

52. L. J. Pyrak-Nolte, L. R. Myer, and N. G. W. Cook, "Transmission of Seismic," J. Geophys. Res., in press (1989b).

53. M. Schoenberg, "Elastic Wave Behavior Across Linear Slip Interfaces," J. Acoust. Soc. Am., v. 68, no. 5, pp. 1516-1521 (1980).

54. M. Schoenberg, "Reflection of Elastic Waves from Periodically Stratified Media with Interfacial Slip," Geophys. Prosp., v. 31, pp. 265-292 (1983).

55. R. K. Thomas, "A Continuum Description for Jointed Media," Sandia National Laboratories report SAND81-2615, Albuquerque, NM (1982).

56. E. P. Chen, "A Computational Model for Jointed Media with Orthogonal Sets of Joints," Sandia National Laboratories report SAND86-1122, Albuquerque, NM (1987).

57. E. P. Chen, "Two-Dimensional Continuum Model for Jointed Media with Orthogonal Sets of Joints," in Proc. 27th U.S. Symposium on Rock Mechanics, Tuscaloosa, AL, pp. 862-867 (1986).

58. M. T. Blanford, S. W. Key, and J. D. Chiesler, "A General 3-D Model for a Jointed Rock Mass," Constitutive Laws for Engineering Materials: Theory and Application, Elsevier C. S. Desai et al., Eds., pp. 35-46 (1987).

59. E. Hoek and E. T. Brown, "Empirical Strength Criterion for Rock Masses," Journal of the Geotechnical Engineering Div., ASCE, v. 106, no. GT9, pp. 1013-1035 (1980).

60. R. M. Zimmerman, R. E. Finley, R. L. Schuch, and D. J. Dodds, "Development of Diamond-Tipped Chain Saws for Slot Cutting in Welded Tuff," in Proc. 28th U.S. Symposium on Rock Mechanics, Tucson, AZ, June 29-July 1, 1987, pp. 963-971 (1987).

61. N. E. Grosvenor, "Specimen Proportion-Key to Better Compressive Strength Tests," Min. Eng., v. 15, no. 1, pp. 31-33 (1963).

62. H. P. Greenwald, C. Howarth, and I. Hartman, "Experiments on Strength of Small Pillars of Coal in the Pittsburgh Bed," US Bureau Mines Investigation report TP605, pp 12-25 (1939).

63. Z. T. Bieniawski, "Geomechanics Classification of Rock Masses and Its Application in Tunneling," Advances in Rock Mechanics, v. 2, part A, pp. 27-32 (1974).

64. Z. T. Bieniawski, "The Effect of Specimen Size on Compressive Strength of Coal," Int. Jour. Rock Mech. Min. Sci. and Geomechanics Abstracts, v. 5, pp. 325-335 (1968).

65. H. Wagner, "Determination of the Complete Load-Deformation Characteristics of Coal Pillars," Proc. of 3rd Congress of the Int. Soc. of Rock Mechanics, v. 2, pp. 1076-1083 (1974).

66. H. R. Pratt, A. D. Black, W. S. Brown, and W. F. Brace, "The Effect of Specimen Size on the Mechanical Properties of Unjointed Diorite," Int. Jour. Rock Mech. Min. Sci., v. 9, no. 4, pp. 513-530 (1971).

67. H. Jahns, "Measuring the Strength of Rock In Situ at Increasing Scale," in Proc. 1st Cong. ISRM, (Lisbon, Portugal, 1966), v. 1, pp. 477-482 (in German).

68. V. I. Hunsche, I. Plischke, H. K. Nipp, and H. Albrecht, "An In Situ Creep Experiment Using a Large Rock Salt Pillar," 6th International Symposium on Salt, (Toronto, Ontario, Canada, 1983).

69. B. S. Langkopf and P. R. Gnirk, "Rock-Mass Classification of Candidate Repository Units at Yucca Mountain, Nye County, Nevada," Sandia National Laboratories report SAND82-2034, Albuquerque, NM (1986).

70. ISRM, E. T. Brown, Ed., "Rock Characterization Testing and Monitoring: ISRM Suggested Methods," Pergamon Press, Oxford (1981).

71. R. W. Spengler and M. P. Chornack, "Stratigraphic and Structural Characteristics of Volcanic Rocks in Core Hole USW G-4, Yucca Mountain, Nye County, Nevada," with a Section on Geophysical Logs by D. C. Miller and J. E. Kibler, US Geological Survey OFR 84-789, Denver, CO (1984).

72. B. I. Ehgartner, "Empirical Rock Mass Strength Criteria," Memorandum to Distribution, Sandia National Laboratories, Albuquerque, NM, September 24, 1987 (1987).

73. R. M. Zimmerman, R. L. Schuch, D. S. Mason, M. L. Wilson, et al., "Final Report: G-Tunnel Heated Block Experiment," Sandia National Laboratories report SAND84-2620, Albuquerque, NM (1986).

*U.S. Government Printing Office: 1992-774-036/67057

DATE FILMED

4/21/94

END