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A TECHNICAL APPROACH TO RESOLVING ISSUES ON ROCK MECHANICS AS APPLIED TO DEVELOPMENT OF A NUCLEAR WASTE REPOSITORY IN A CRYSTALLINE ROCK FORMATION

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Systems Integration
Basalt Waste Isolation Project

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1.0 INTRODUCTION

1.1 SUMMARY

This paper summarizes the technical efforts for resolving issues on rock mechanics as applied to development of a nuclear waste repository in a crystalline rock formation. This section provides background information and definitions pertinent to rock mechanics. Section 2.0 presents the rock mechanics issues related to licensing, design, and construction of a waste repository. Section 3.0 presents the technical approach to the resolution of issues and concludes that a multi-faceted approach involving principally site characterization, laboratory testing, numerical modeling and analysis, and in situ testing and monitoring is required. While this technical approach is directed to further scientific understanding and quantification of the phenomena involved accompanying the thermal heating of rock from nuclear waste, it is emphasized that formulation of a design basis for an engineered rock structure will precede the development of a large waste repository. The design process of an engineered structure would require:

- Establishment of a field data base of the behavior at various scales for purposes of selecting appropriate constitutive relations of the rock mass-discontinuity system, stress and displacement boundary conditions, and ultimate strength;
- Numerical modeling and analysis verification over the short term for prediction of rock mass behavior over the long term;
- Selection of appropriate design loads, temperatures, and safety factors which will form a design basis for the repository.

Section 4.0 summarizes the status of resolution activities in the areas of thermomechanical effects, coupled thermal, mechanical, and hydrological phenomena, mine-induced fracturing, mine stability, and seismicity. Section 5.0 gives a concluding statement.

Under the present project plans, technical activities are proceeding on multiple fronts involving field, laboratory, and numerical modeling and analysis studies of the important phenomena related to the disposal of radioactive waste in crystalline rock. The advancement of the state of the art in rock mechanics from these activities will culminate in the risk analysis and the formulation of a design basis for repositories.

1.2 BACKGROUND

The term "crystalline rock" applies to a wide variety of rocks including igneous and metamorphic, but excluding sedimentary rocks. The crystalline rock types presently under consideration in the National Waste Terminal Storage (NWTS) Program of the United States include basalt, granite, and tuff.

The rock mechanics technical issues are essentially of equal importance for each of these rock types. Rock mechanics encompasses a wide range of phenomena that are used to assess the redistribution of forces and displacements accompanying an excavation. Because nuclear wastes are heat generating, rock mechanics aspects in repository design are extended to include not only the excavation of the subsurface facilities, but also the stress redistribution resulting from heat transfer from the waste to the surrounding rock.

Traditionally, in rock mechanics, excavations are designed for rock mass stability using empirical design guidelines (Barton and Others, 1974) and field experience, neither of which is well based on scientific principles. Such an approach is not fully appropriate for the design of a nuclear waste repository. In this case, significant scientific quantification of rock mechanics principles must be made prior to their application.

2.0 TECHNICAL ISSUES

2.1 IDENTIFICATION OF TECHNICAL ISSUES

The U.S. Department of Energy has initiated a number of programs and task force reviews to identify and discuss the technical issues with respect to the long-term management of nuclear wastes. In March 1978, President Carter established an Interagency Review Group (IRG) to formulate recommendations for establishment of a United States' policy on the long-term management of nuclear waste and supporting programs to implement this policy. The IRG consisted of members from 14 governmental agencies, which interacted with the interested public, industry, academia, and state governments through open debates and distribution of draft reports. The IRG forwarded a final report to the President in March 1979 (IRG, 1979). The IRG report clearly focused the United States' activities on the management of nuclear wastes.

The United States government implemented the IRG recommendations of involving the earth science community to aid in the development of a coherent plan to resolve the technical issues concerning nuclear waste management. An Earth Sciences Technical Plan (ESTP) Working Group was established by the U.S. Department of Energy (DOE) and the U.S. Department of the Interior. The ESTP is presently in draft form and identifies major earth science technical issues (ESTP, 1979).

2.2 ROCK MECHANICS ISSUES

Rock mechanics issues have been identified in the draft ESTP for mined geologic disposal of radioactive waste and are discussed below.

2.2.1 Are Thermomechanical Effects Adequately Understood?

An understanding of the thermomechanical effects of the placement of radioactive waste in rock is an important aspect of repository development, since the actual thermal loads that the rock mass will be subjected to are unprecedented in the field of rock structures excavated in crystalline rock. More specifically, this understanding requires development of information in the following areas:

- Thermal Conductivity/Diffusivity--The scalar influence of jointing as well as the influence of moisture, temperature, and stress on thermal conductivity and diffusivity must be determined.
- Thermal Expansion Coefficient--The scalar influence of jointing as well as the influence of temperature, stress, thermal cycling, and chemical change on the thermal expansion coefficient must be determined.
- Deformation Modulus--The scalar influence of jointing as well as the influence of temperature, stress, blast damage, and moisture changes on the deformation modulus must be determined.
- Rock Mass Strength--The scalar influence of jointing as well as the influence of temperature, confining stress, blast damage, and moisture on rock mass strength must be determined. A definition of failure must be developed which recognizes post-failure response of rock once ultimate strength is exceeded.
- Temperature Limits--Temperature ranges must be established for which there is confidence in predicting long-term response. Temperature levels for which chemical and moisture changes produce unacceptable changes in rock structure must be determined.

2.2.2 Are the Effects of Coupling the Thermal Hydraulic and Thermal-Mechanical Phenomena Adequately Understood?

An understanding of the thermal-mechanical-hydrological effects of the placement of radioactive waste in rock is an important aspect of repository development. More specifically, this coupled effect requires development of information in the following areas:

- Hydraulic Conductivity--The effect of stress, chemical alteration, temperature, fluid pressure, and fracture development on hydraulic conductivity must be determined.
- Fluid Pressure--The influence of fluid pressure on rock mass strength must be determined since the generation of pore pressure can reduce effective stresses transmitted in the rock mass.
- Phase Changes--The influence of potential phase change on stability and heat transfer from the waste to the rock mass must be determined.

2.2.3 Are Induced Fractures by Mining Adequately Understood?

The development of mining-induced fractures is dependent on rock type, the rate and method of drilling and blasting, in situ stress fields, and design geometry. Minimizing induced fractures is most important where potential conduits for groundwater migration can be created. The shaft and major subsurface access drifts are areas of concern. Specific areas which require understanding are:

- Rock Mass Permeability--The change in permeability of the rock mass surrounding the opening must be determined as a function of initial stress, rock quality, design geometry, rock mass strength (peak- and post-failure), and water pressure.

- Grouting--The ability of grouting techniques to reestablish pre-disturbance states or sufficiently reduce permeability must be assessed.

- Rock Support--An evaluation of rock support systems must be made in order to determine their relative abilities to preserve rock integrity and minimize time dependent fracturing.

- Excavation Methods--A comparison of drilling and blasting must be made in order to determine mine-induced fractures associated with the various methods.

- Thermal Influence--The impact of rock fractures on thermally induced stresses must be determined and criteria developed to provide a design limit for such stresses.

The factor which is common to the geomechanical and geohydrological properties is the influence of discontinuities. The principal problem in rock mechanics arises from the fact that sampling at a small scale may ignore weaker or more compliant discontinuities at a larger scale (Bieniawski, 1968 and Bieniawski and Van Heerdon, 1975). The approach that is needed is to perform various tests at geometric scales ranging from laboratory size to room size in order to assess at what level sampling will be representative of the large repository scale and rock mass behavior.

2.2.4 Are the Effects of Seismic Events on the Operational Repository Adequately Understood

The issues relating to seismic events include both the influence of regional seismicity on the repository and any change in seismicity induced by construction of a waste repository. The following issues have been identified:

- Magnitude and Return Period--The magnitude and return period of various seismic events which could cause subsurface structural damage at the repository level must be determined.

- Analytical Techniques--Analytical techniques need to be developed to adequately model seismic/rock structure/rock support interactions as well as the statistical evaluation of magnitude and return period of the repository level.

- Thermally Induced Fracturing--Thermal loads may result in thermally induced fracturing of the rock mass and, thus, alter the dynamic response of the structure. Consideration must be given to altered dynamic response due to potential thermal fracturing.

- Blast-Induced Fracturing of the Rock Mass--The use of explosives in rock excavation could potentially lead to overbreak where smooth-wall blasting is not effective. Consideration must be given to altered dynamic response due to blast-induced fracturing.

- Micro-Seismic Events--The impact of changes in the regional stress field around a repository upon the frequency and magnitude of micro-seismic events needs to be determined. Baseline conditions must be determined.

- Induced Seismicity--The impact of thermal loading and openings such as shafts, access drifts, and rooms on seismic activity must be determined. Acceptable limits must be determined.

2.2.5 Are Mine Stability Issues Adequately Understood?

The issues of repository stability relate to the combination of geo-mechanical, hydrological, and seismic phenomena. The resolution of these issues requires development of information in the following specific areas:

- Operational Safety--Criteria must be developed to ensure a safe working environment in the subsurface. The role of artificial roof support must be assessed.

- Waste Retrieval--Design criteria must be developed for combined mechanical, seismic, and thermal loading such that stability can be ensured during the retrieval period.

- Repository Integrity--The consequences of rock mass failure around an opening in hard rock must be determined. This is particularly relevant to the design of engineered barriers where rock failure could induce gross permeability changes in the rock mass and could initiate flowpaths to the biosphere.

- Regional Integrity--An assessment of away-from-repository stress and strain conditions must be made with respect to the impact on changes on regional hydrology, seismicity, and surface displacement.

2.3 DEVELOPMENT OF ROCK MECHANICS CRITERIA

In addition to the issues identified in the preceding section, investigations are needed to select rock mechanics design criteria such that a safe, long-term isolation repository would result. The selection of design criteria requires the formulation of a design basis. The design basis would:

- Identify the periods of construction, operation, retrieval, and final isolation;
- Identify the design temperatures of the source waste to be placed in the repository for the various time periods;
- Identify the procedure for determination of acceptable levels of stress;
- Identify the combination of geomechanical, geohydrological, seismic, and thermal events which result in a most severe test of repository or substructure integrity during the various time periods;
- Identify the load factors associated with geomechanical, geohydrological, seismic, and thermal loads to provide adequate design margin for the repository or substructures for the various time periods;
- Identify the methods by which the design can be verified by numerical modeling and analysis over the long term or field verification over the short term.

3.0 TECHNICAL APPROACH TO RESOLUTION OF ISSUES

3.1 OVERALL ROCK MECHANICS PROGRAM

Activities on five broad fronts are required for adequate resolution of the issues enumerated in Section 2.0. These areas of specialization include:

- Site characterization must answer the question of what are the rock mass conditions (fabric structure, hydrology, stress, and temperature) before repository construction;
- Laboratory tests must identify phenomena and allow measurement of properties of components of the rock mass under controlled conditions;
- In situ tests must be undertaken to demonstrate interaction of rock mass components to evaluate large-scale phenomena, to characterize rock mass properties, to validate computer models, and to verify design assumptions;
- Numerical models must be developed, modified, and applied to evaluate the significance of rock mechanics phenomena and for support of risk assessment, predictive analysis of in situ tests, and for repository design;

- Design applications include definition of rock mechanics criteria, evaluation of artificial rock support schemes, and implementation of rock mechanics criteria and data into a design basis for waste repositories.

Activities in each of these fields are required prior to development of an underground waste repository. The following discussion summarizes the general technical approach.

Site characterization will be required to assess the relative ranking of candidate sites from the rock mechanics viewpoint. Comparisons are needed on the basis of in situ state of stress, geophysical rock mass properties, rock mass strength and deformational properties, large-scale and small-scale rock mass discontinuities, seismicity, and groundwater hydrology.

The use of laboratory testing allows for the determination of constitutive thermomechanical and hydrological properties of intact crystalline rock. Laboratory testing is valuable because of the controlled nature of scientific experiments. Relationships between important variables can be determined, while secondary variables can be randomized (Wilson, 1952). A high degree of standardization exists in the performance of laboratory tests allowing for meaningful comparisons of rock properties of one site with those of other sites.

In situ testing is required due to the fundamental problem of modeling discontinuities in rock mechanics. Relationships between strength, deformational properties, and permeability are strongly dependent on the scale of the rock mass structure. Large-scale in situ tests allow for assessment of the reduction in magnitude of strength and stiffness properties with increasing rock mass volume.

Numerical models must be developed and applied to properly account for in situ material constitutive properties, thermal force, and displacement boundary conditions and geometry of the rock mass structure. The use of numerical models is important because they are the only means available to assess the long-term effects of waste storage for which no data will be available. The comparison of results from in situ tests will be used to verify all numerical modeling aspects over the short term. Having identified the important physical laws governing thermal, mechanical, and hydrological behavior of the repository and verifying constitutive relations, numerical models can be used for parametric studies of long-term effects.

The culmination of the above activities is the design applications process and establishment of a design basis. The analysis, design, and construction of a waste repository will require technical judgment in assessing predictive capability. It is accepted that greater design margin will be required for those elements that are less capable of prediction. Once all investigations are complete, there should exist a general scientific consensus that the design basis for a waste repository is conservative.

In addition to those activities required for analysis, design, and construction of a repository, monitoring during construction, operation, and post-decommissioning is essential to resolution of long-term rock mechanics issues.

3.2 PROGRAM RESPONSIBILITY

The resolution of the rock mechanics issues is pursued in the United States at two levels, through generic and site-specific studies in the DOE-sponsored programs. The ONWI has responsibility to develop the scientific base and technology common to all the host rock types. Site-specific programs in rock mechanics are undertaken by the Basalt Waste Isolation Project (BWIP) for basalt and the Nevada Nuclear Waste Storage Investigation for granite and tuff programs. The ONWI coordinates participation in international cooperative programs. Major participants in the United States' programs for crystalline rock media are shown in Table 1.

The U.S. Geological Survey is represented directly on the ESTP committee, provides major technical and personnel assistance for a variety of site characterization programs directed by ONWI and the site-specific programs, and has ongoing independent technical programs to develop scientific data of a generic nature to support the NWTS.

The U.S. Nuclear Regulatory Commission (NRC) has responsibility to issue licenses and must review the technical issues associated with radioactive waste disposal. They are supporting an independent research and development program to identify rock mechanics issues associated with the NWTS Program so that they can set acceptance criteria and develop the methodology to adequately review the license applications. At the present time, DOE and NRC research and development programs are independent, although communications are maintained through published status reports.

3.3 SITE-SPECIFIC ROCK MECHANICS PROGRAMS IN THE UNITED STATES

Described in this section are current programs at specific sites in granite, tuff, and basalt.

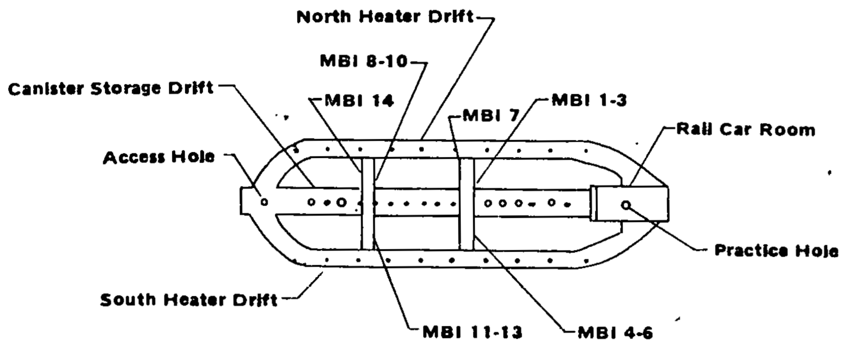
3.3.1 The Spent Fuel Test in Granite at the Nevada Test Site

The effect of nuclear spent fuel is being evaluated in granite at the Nevada Test Site (NTS) (Figure 1). The primary objective of this in situ test is to evaluate the feasibility of safe and reliable emplacement, short-term storage, and retrieval of spent fuel assemblies at a depth of 420 meters in a typical granite. In addition to the primary objective, information will be obtained on the suitability of granite as a storage medium for repository design. The test is being conducted in a newly mined tunnel adjacent to an existing tunnel.

TABLE 1. Major Rock Mechanics Participants in National Waste Terminal Storage-- Hard Rock Programs

	Granite NNWSI	Basalt BWIP	Tuff NNWSI
Site Characterization	ONWI, Savannah River, IC	Rockwell, USGS State Agencies	Sandia
Laboratory Tests	LLL, LBL, IC	FSI	Sandia
In Situ Tests	CSM, USGS, IC, NTS (LLL), Savannah River	Rockwell	NTS (Sandia)
Numerical Models	LBL, LLL, ONWI	Rockwell/D&M/UM	Sandia
Design Applications	IC	KP	--

BWIP - Basalt Waste Isolation Project
CSM - Colorado School of Mines
D&M - Dames & Moore
FSI - Foundation Sciences, Inc.
IC - International Cooperation
KP - Kaiser Engineers/Parsons Brinckerhoff Quade & Douglas, Inc.
LBL - Lawrence Berkeley Laboratory
LLL - Lawrence Livermore Laboratory
ONWI - Office of Nuclear Waste Isolation
NTS - Nevada Test Site
NNWSI - Nevada Nuclear Waste Storage Investigation
Rockwell - Rockwell Hanford Operations
Sandia - Sandia Laboratories
UM - University of Minnesota
USGS - U.S. Geological Survey



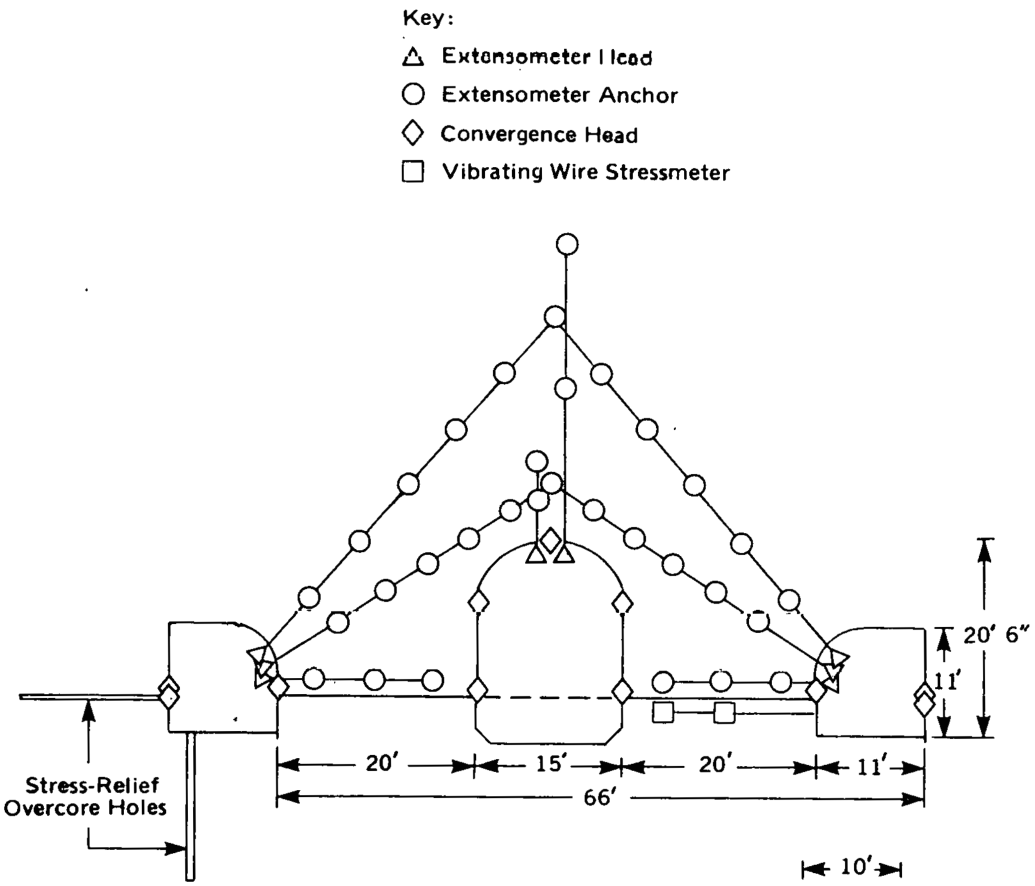


FIGURE 1. Instrumentation Layout, Spent Fuel Test at the Near-Surface Test Facility.

The thermal history of a repository containing a large number of assemblies will be simulated with 11 canisters of spent fuel, 6 electrically heated simulator canisters, and 20 auxiliary electric heaters. The effects on granite of heat alone (from the electric simulators) will be compared with the combined effects of heat and radiation (from the spent fuel). Other measurement programs will evaluate the magnitude of displacement effects from mining (for comparison with thermally induced displacement), the effects of mine ventilation on heat dissipation from the waste, and possibly (as a mid-test add-on) the heat dissipation and stability effects of an in situ heat and radiation field in backfill materials.

Rock temperatures, stresses, and displacements will be measured continually by thermocouples, stressmeters, and extensometers during the storage period at more than 600 locations. These data will be compared with calculated values at each location. In addition, there will be a series of pre-test measurements in the laboratory and in the field. Rock properties (thermal and strength), the in situ state of stress, geologic and hydrologic parameters, seismic phenomena, in situ thermal properties, and the mechanical response of the rock to mining will all be measured.

Throughout the test and at the end, measurements will be made to document differences between the response of the rock to spent fuel and its response to the electric simulators. After the test, rock samples will be recovered from the storage hole walls and studied in the laboratory.

3.3.2 Basalt Waste Isolation Project, Hanford Site

The BWIP (Rockwell, 1979) is presently engaged in a comprehensive program in the major areas of specialization from site characterization through design applications. Subsurface investigations have been carried out by drilling five boreholes to below the potential repository horizon for assessments of rock mass quality. Regional studies are being performed utilizing geophysical surveys (Rockwell Hanford Operations) and seismicity studies (Rockwell Hanford Operations and University of Washington), regional rock mass-discontinuity system characterization, and to generate a scientific data base for relating earthquake magnitudes to return period. Laboratory testing (Foundation Sciences, Inc.) is being performed to determine intact rock mass properties related to density, porosity, thermal diffusivity, thermal expansion coefficient, confined and unconfined compressive ultimate strength, Brazilian tensile strength, and elastic moduli.

The in situ testing program is presently being implemented at the Near-Surface Test Facility (NSTF) (Figure 2) to assess the influence of scale on rock mass properties. The tests include jointed block tests for the very near field, canister-scale heater tests for the near field, and a proposed accelerated room test for the far field.

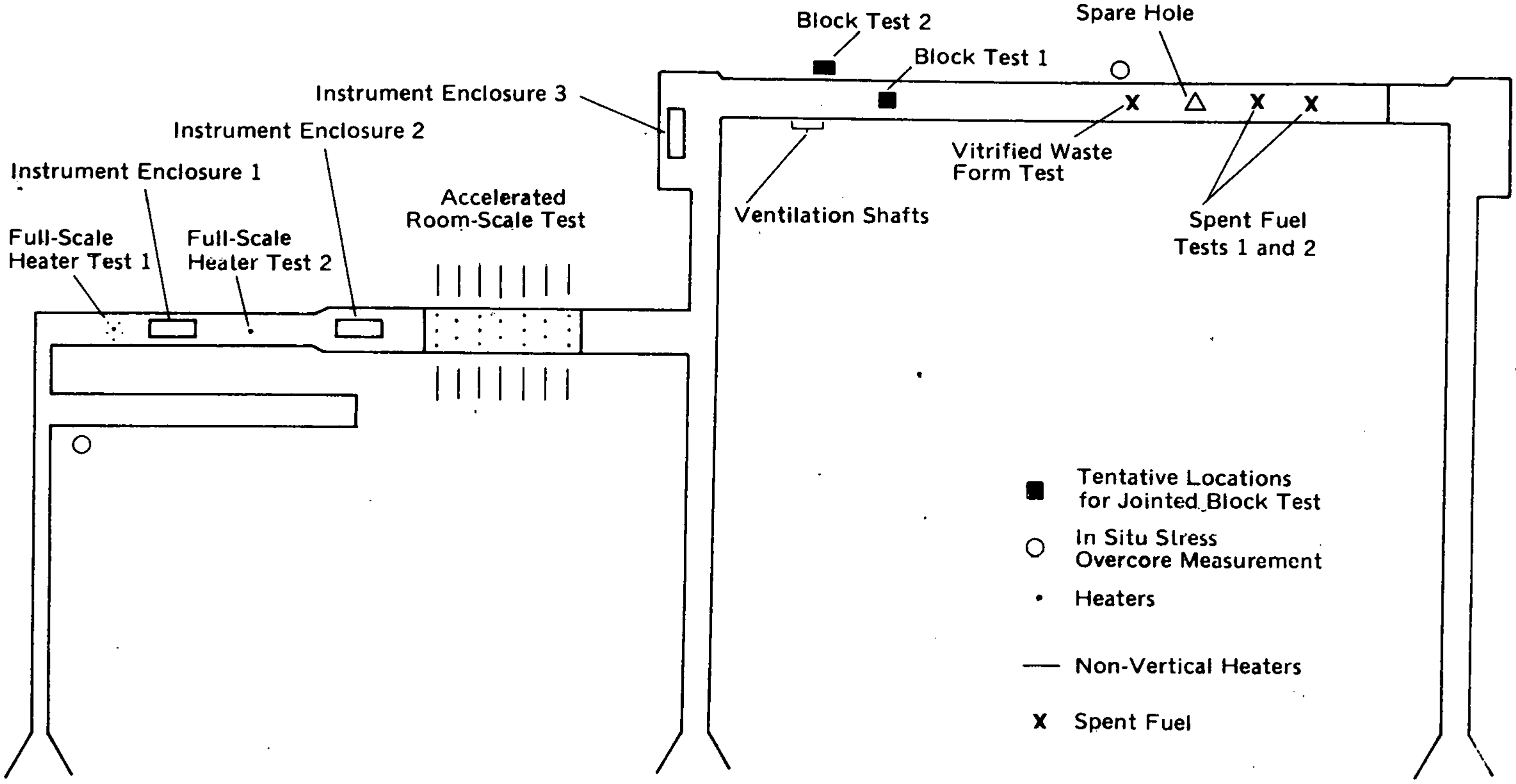


FIGURE 2. Tentative Layout of Near-Surface Test Facility Tests.

Jointed block tests (2.0 meters by 2.0 meters by 2.5 meters deep) will be performed at several different locations within the NSTF. Fifteen small, 1-kilowatt heaters will be used to create the desired heat distribution and large flatjacks will provide the confining stress.

One full-scale heater test will simulate the conditions closely resembling those in the actual repository. The expected temperatures the waste will undergo in a repository in basalt will be reproduced in a controlled fashion utilizing electric heaters to model the waste canister. This test will be run at a power level of approximately 1 to 2 kilowatts. A second full-scale heater test will be used to determine the ultimate power capacity of the boreholes and the effects of decrepitation of the borehole, fracturing in the near field, and the subsequent effects on the in situ thermal conductivity. The test will be operated at power levels up to 5 kilowatts.

An accelerated room test, which has 60 1-kilowatt heaters, will simulate repository conditions at time periods of 25 to 50 years after only 1.5 to 2.0 years of testing. This test will provide data on stress and deformation on a room scale (larger volume of basalt) close to the strength limits of the basalt and the shotcrete roof support system. The accelerated room test will serve for verification of selection of constitutive relations at room scale from the smaller scale tests.

Numerical modeling and analysis scoping calculations have been performed for purposes of selection of instrumentation layout and test procedures for the larger scale in situ tests. As in situ test data become available, the numerical models will be refined to incorporate nonlinear and post-peak constitutive relations for the rock mass and discrete discontinuities.

Design application has progressed to a stage of formulating preliminary or preconceptual design criteria for repository temperatures as well as selection of load factors to provide design margin for a repository in basalt. This design effort has identified a number of critical design areas such as ventilation and access dimensions, canister retrievability, and roof support. The design will utilize in situ test results obtained from the NSTF.

3.3.3 Tuff Investigations at G-Tunnel, Nevada Test Site

Tuffaceous rocks are being investigated at the NTS as part of the Nevada Nuclear Waste Storage Investigations. In situ testing is under way at the G-Tunnel to observe the response of welded tuff to an imposed thermal load. The test zone is located in a perched water zone of saturation and the migration and chemistry of water near the emplaced heater will be monitored. The jointed structure of the tuff media in G-Tunnel will be carefully mapped and sampled for mineralogical characterization to help site the planned expanded test facility. Laser interferometry is being used to augment extensometer measurements of strain induced by thermal expansion and/or dehydration reactions. A thermocouple array will monitor heat dissipation in the tuff mass surrounding the heater.

Results from laboratory measurements and in situ tests will be used to refine computer codes that simulate time-dependent responses of tuff to anticipated repository conditions. Theoretical studies of the relationships of fluid pressure, confining pressure, and temperature to thermal properties of jointed rock mass will also be conducted to yield more realistic models for code development.

As data from all tuff study activities become available, they will be integrated by a planning activity for future in situ tests to determine the effects of joints and contained water on the response of tuff to a repository environment.

3.4 SWEDISH-AMERICAN COOPERATIVE PROGRAM

A cooperative program between the Swedish Nuclear Fuel Supply Company and the former U.S. Energy Research and Development Administration was organized in July 1977. The principal objectives of the program to date (Witherspoon and Degerman, 1978) have been to investigate the effects of elevated temperatures on the geomechanical response and fracture hydrology of Stripa granite.

The program is principally scientific in nature and emphasizes international cooperation in technical areas of hydrological and chemical transport phenomena, rock mechanics, and engineered barriers. The Swedish participants provided technical support in smooth-wall blasting of the underground experimental facilities of the Stripa Mine (Figure 3) as well as performing important baseline studies. The Swedish Geological Survey has been involved in assembling geological information and performing geophysical surveys and mechanical borehole measurements for purposes of rock mass characterization. Laboratory testing to assess intact thermomechanical properties of Stripa granite have been performed at the University of Lulea in Sweden.

Full-scale and time-scale heater tests have been conducted and analyzed in the Stripa Mine to assess the geomechanical response of the Stripa granite. Numerical modeling incorporating linear thermoelastic analyses from both laboratory and in situ test properties has been performed.

Ongoing applied research activities presently include directional permeability testing, in situ state of stress determinations by hydraulic fracturing, and macroscopic permeability of Stripa granite in a large-scale room test.

Once the geohydrological subsurface properties and conditions of the fractured granite are determined and verified against the gross seepage rate in the large-scale room test, a multi-national effort in the areas of borehole plugging and shaft sealing is planned.

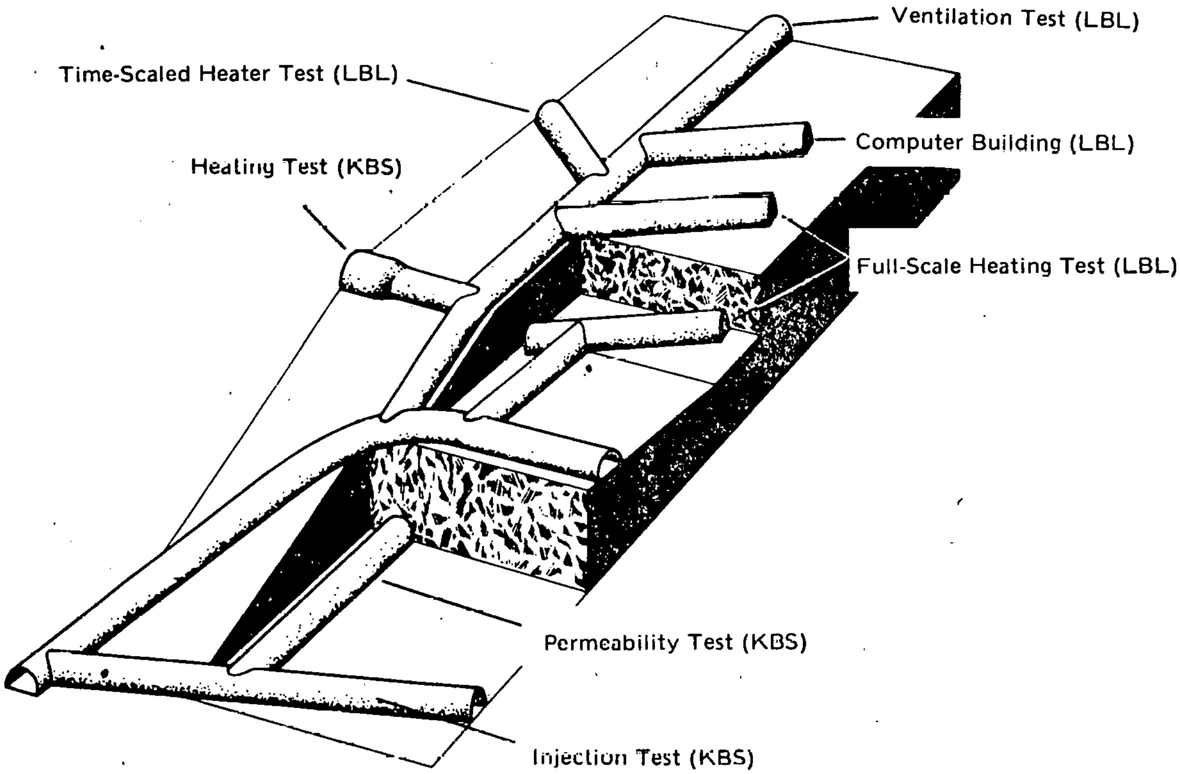


FIGURE 3. Stripa Mine Experimental Layout.

4.0 STATUS OF RESOLUTION OF ROCK MECHANICS ISSUES

Summarized in this section are the status to date of generic studies and site-specific investigations in granite, basalt, and tuff aimed at resolution of the rock mechanics issues identified in Section 2.2.

4.1 THERMOMECHANICAL EFFECTS

To date, the largest amount of in situ thermomechanical data has been generated for granite from the Stripa international cooperative effort. In the United States, laboratory and modeling programs support that effort. In situ tests in granite at the Colorado School of Mines and at the NTS are just starting.

The most recent analysis (Chan and Others, 1980) of the Stripa heater test data indicates the importance of accounting for temperature dependence in thermoelastic properties. The prediction of displacement induced by thermal load is improved when considering the temperature dependence of:

- Thermal conductivity, k;
- Young's modulus, E;
- Poisson's ratio, μ;
- Thermal expansion coefficient, α.

While the prediction of displacement is improved by considering temperature dependence, particularly as it relates to the thermal expansion coefficient, the radial stress predictions based upon linear thermoelasticity using laboratory values are still higher. However, if account is taken for the in situ rock modulus, the predicted radial stress is scaled down. The development of thermal stress is sensitive to the increased compliance at the larger scale. This points to the need to assess the effects of sample size on fundamental rock mechanics properties.

For basalt, laboratory tests are being conducted. The NSTF (Figure 2) has been excavated for and is presently being instrumented for the full range of in situ tests. The NSTF in situ tests are taking on added importance in view of the closer joint spacing in granite as compared to basalt. These tests will provide engineering and scientific data to assess the site-specific influence of scale on geomechanical properties of a highly jointed basalt.

In tuff, a reduced effort is under way with limited laboratory and in situ tests. In many respects, the thermomechanical problems associated with tuff are more complex than for the other two hard rocks. For low levels of thermal loading, however, the technical issues are essentially the same as for harder crystalline rock.

4.2 COUPLED THERMOMECHANICAL AND HYDROLOGICAL PHENOMENA

Programs are currently in progress in granite, basalt, and tuff to resolve the issues associated with coupled thermomechanical and hydrological phenomena. Primary emphasis has been on the field work at Stripa, with supportive laboratory testing and modeling in the United States. Modeling with fully coupled thermal, mechanical, and hydrological codes is under way under sponsorship of ONWI and BWIP. Full-scale verification testing of these models is presently restricted to back analysis of the ventilated room test at Stripa. Laboratory and bench-scale testing is under way or planned at several locations which should be of general application to all jointed crystalline rocks.

4.3 MINE-INDUCED FRACTURING

Activities are in progress to resolve issues related to mine-induced fracturing in granite and basalt. A block test is under way at the Colorado School of Mines' test mine. The accelerated room test in the NSTF will provide engineering and scientific data for both thermal and blast-induced fracturing. No activities in this area are currently under way in tuff.

4.4 RELATIONSHIP BETWEEN SEISMIC EVENTS AND STRUCTURAL INTEGRITY OF A REPOSITORY

Activities are progressing to resolve the rock mechanics issues associated with seismicity. Most studies are centered on the effect of a seismic event on a repository. Historical data bases are being developed for BWIP and NTS from which to predict the maximum likely event in these areas. Generic studies are currently being conducted to assess the effect of depth on ground motion, and also to determine severity of damage at repository depth with respect to surface damage. The effect of a design basis earthquake on the underground repository is being assessed using numerical models.

4.5 MINE STABILTITY

Activities to resolve mine stability issues are under way as part of the BWIP. Rock mechanics design criteria were included in the preconceptual design of a repository in basalt. Considerations regarding operational safety, waste retrieval, and repository integrity are incorporated into the programs for conceptual design of a repository in basalt.

The accelerated room test within the NSTF of the BWIP will provide engineering and scientific data for the basalt/shotcrete support interaction and the post-peak behavior of basalt at room scale.

Evaluation of the regional impact of a repository is being conducted for hard rock media through modeling and predictive analysis.

5.0 CONCLUSIONS

The rock mechanics issues that have been identified in preceding sections are the most complex issues that have ever been encountered in the analysis, design, and construction of an underground facility. To qualify a waste repository in crystalline rock, scientific and engineering data from laboratory testing, in situ testing, monitoring, and numerical analysis will have to be compiled and evaluated in a short period of time. The advancement of the state of the art in rock mechanics on multiple fronts in a short period of time is essential for final risk assessment, and formulation of a design basis for a repository. This is a fundamental goal of the United States' program in rock mechanics for the NWTS Program.

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