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A PHASED DESIGN APPROACH TO A NUCLEAR WASTE REPOSITORY IN HARD ROCK

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ABSTRACT

The U. S. Department of Energy (DOE) Office of Terminal Waste Disposal and Remedial Action has taken the first step in developing a nuclear waste repository by issuing its Site Characterization Report (SCR) for the Basalt Waste Isolation Project (BWIP) in November 1982. This SCR has been prepared for the Nuclear Regulatory Commission (NRC) as required by the regulations in 10CFR60. The SCR establishes the process by which the DOE selected a site for a nuclear waste repository near Richland, Washington, describes the conceptual design for the repository, and provides DOE's plans for site characterization to refine the design. The primary function of the repository is to terminally store nuclear waste, provide for retrieval of the waste during a 50-year period following commencement of emplacement, and ultimately isolate the radionuclides from the accessible environment. This paper discusses a rock mechanics design approach which utilizes the data from the site characterization process to analyze the stability of repository openings.

Site characterization in a fractured hard rock such as the BWIP basalt has to emphasize the structural geology at the site, and the ability to predict the variability of the geology in the area of interest. This paper describes the site characterization process, and how the data obtained from boreholes can be gradually refined as the in situ test program is completed. The design approaches which can accommodate this gradual improvement in the quality of the rock mechanics data are elaborated upon. Both simple engineering mechanics approaches to design and thermomechanical computer modeling are described.

INTRODUCTION

The DOE is responsible for the National Waste Terminal Storage program under which research and development is being carried out to support design, licensing, construction, operation, and decommissioning of a nuclear waste repository. The program emphasis is presently on the disposal of nuclear waste in deep underground repositories mined in stable geologic formations. The locations of the types of rocks now under study are shown in Figure 1. The BWIP is studying basalt formations underlying the DOE's Hanford site.

The licensing procedures for the disposal of high-level radioactive waste are contained in the NRC regulations (10 Code of Federal Regulation Part 60, U.S. Government, 1981.) As part of the prelicensing procedures set forth in the final rule, the DOE is required to submit the SCR to the NRC as early as possible after commencement of planning for a particular geologic repository operations area and prior to starting site characterization. Site characterization, as defined in 10CFR60, refers to the program of exploration and research, both in the laboratory and in the field, undertaken to establish the geologic conditions and the ranges of design parameters of a particular site relevant to the procedures under Part 60. Site characterization includes borings, surface excavations, excavation of exploratory shafts, limited subsurface lateral excavations and borings, and at-depth testing needed to determine the suitability of the site for a geologic repository, but does not include preliminary borings and geophysical testing needed to decide whether site characterization should be undertaken.

In accordance with the prelicensing procedures, the DOE Office of Terminal Waste Disposal and Remedial Action submitted the SCR for the BWIP site in November 1982. The decision process by which the DOE selected a site for a nuclear waste repository near Richland, Washington, the conceptual design of the repository, and the DOE's plan for site characterization to refine the design are described in the SCR. This paper deals with a rock mechanics design approach which discusses the use of the data from the site characterization process to investigate the stability of openings within a repository.

SITE CHARACTERIZATION PROCESS

The objectives of the DOE site characterization activities are (1) to collect pertinent geological, hydrogeological and other site specific information that will ultimately be needed for a license application, and to provide reasonable assurance that there will be no unreasonable risk to public health and safety; and (2) to collect necessary data from alternative sites and media to permit the NRC to make National Environmental Policy Act (NEPA) findings with respect to consideration of alternatives. Unlike the site characterization efforts for other civil

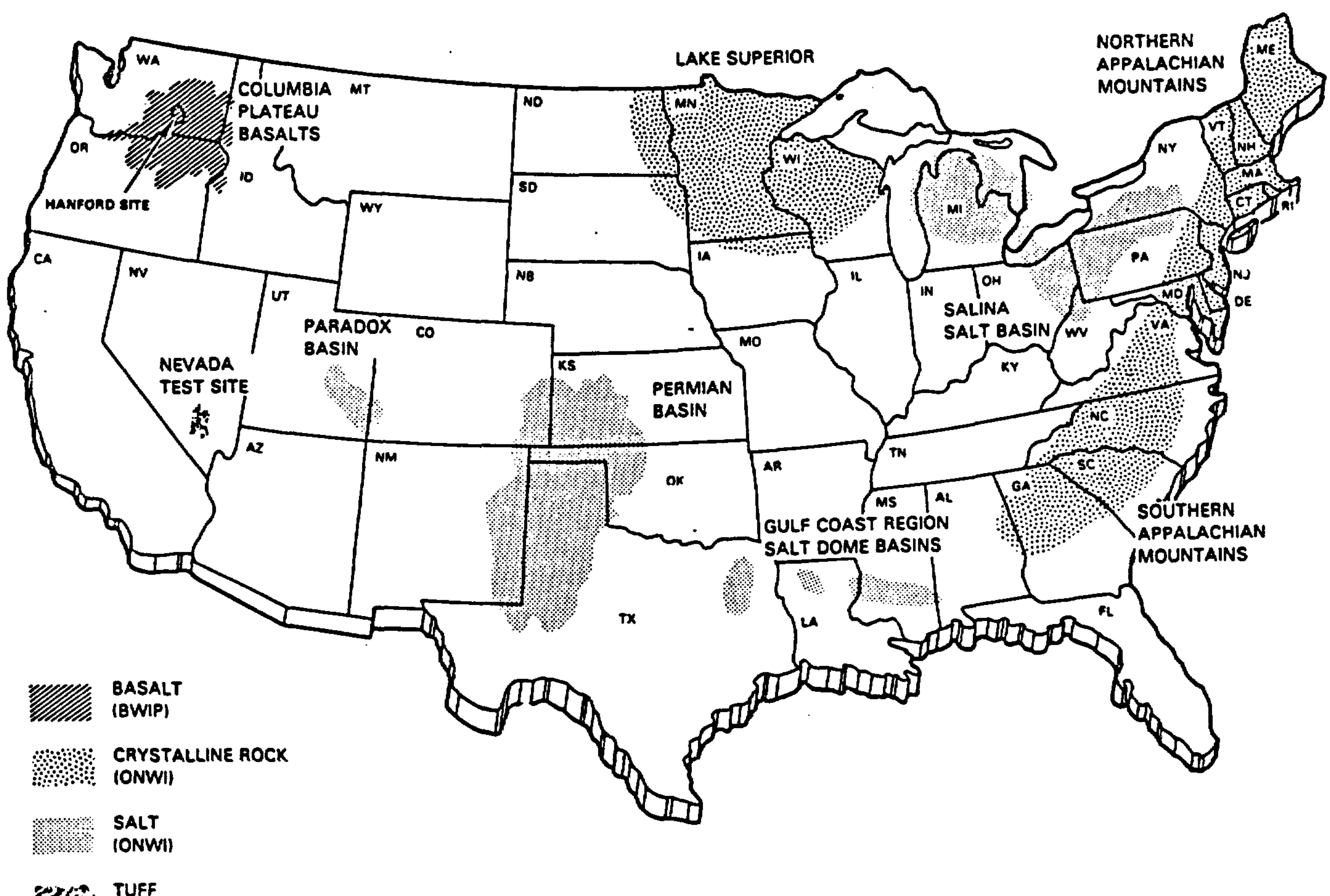

Figure 1. Regions that are Being Considered for Geological Disposal of Radioactive Waste, After U. S. DOE, 1982.

projects, a major constraint in the exploration activity for a geologic repository is the necessity to minimize subsurface penetrations into the proposed repository block, since boreholes and shafts, even if carefully sealed, could represent potential pathways for radionuclide migration to the biosphere. Hence, data collection from a few drill holes has to be maximized, and supplemented with at-depth testing at the repository horizon of interest.

The site characterization process begins with the screening work to select a candidate area and site to be characterized. The site is then explored with a few drillholes so that the geology, hydrogeology, and rock strength parameters can be obtained for conceptual design of a repository appropriate to the site, waste form, waste packages, emplacement technique and performance assessment requirements. This exploration effort permits identification of the site- and design-related issues that need further investigation. Subsequently, detailed programs for at-depth testing are formulated to resolve outstanding issues and to reduce uncertainties in the data. The site characterization process is documented by the DOE in a site characterization report, the standard format and content of which is specified by the NRC in regulatory guide 4.17 (US NRC, July 1982).

DESIGN LOGIC FOR A NUCLEAR WASTE REPOSITORY

The objectives of constructing a nuclear waste repository are to terminally store the waste and isolate the radionuclides from the biosphere. A cutaway view of the repository proposed by the BWIP is presented in Figure 2. In an effort to verify the performance of the repository and to ensure that its objectives are fulfilled, the proposed 10CFR60 rules specify a retrievability period of 50 years from the initiation of waste emplacement. There are several types of openings in a repository and the stability of these openings must be maintained, at least during the retrievability period. The stability of shafts, main access drifts, and waste emplacement rooms and holes is a major consideration in repository design.

A sound design philosophy, for any opening requiring long-term stability in rock, follows a pattern in which greater accuracy and detail are obtained as additional information becomes available. The design is complete when it fully addresses all geological conditions that may impact the stability of the opening during the period of concern.

The design of a deep geologic nuclear waste repository requires a recognition of the licensing process. Other engineered structures also require licensing or review, especially those dealing with power generation or transportation, but do not always involve totally new technologies or difficult design conditions such as the radiological and thermal loads from nuclear waste, and the long-term stability requirements. The licensing review process is primarily one of assuring that the regulatory requirements will be met and that the investigation and design processes are sound, justifiable, and traceable as to responsibility and origin. Therefore, the design of the underground openings for nuclear waste isolation must be more rigorously defined and defended at every step.

A Phased Approach to Design

The accuracy of geological assessments, and therefore the efficiency and reliability of design concepts based on them, is the lowest at early phases of exploration and increases as progress is made in exploration and construction. Modern rock engineering practice recognizes that although the accuracy of geological predictions must be improved as the exploration effort progresses, the scope of those same predictions must at all stages include the range of parameters expected to impact the performance of the opening, i.e., rock mass mechanical properties, in situ stresses, and hydrogeologic parameters.

Basic rock engineering principles and specific project requirements should be incorporated into the preliminary design concepts using methodology appropriate to the accuracy of the data at hand. Early in the project, geologic data are obtained remotely, and are regarded as somewhat speculative. Conceptual designs are therefore generalized and tend to be conservative. As further data are gained, a more accurate description of the rock mass is obtained. At the early stages, empirical design approaches are appropriate. They enable preliminary design concepts to be evaluated and compared.

Subsurface exploration by drilling, and later firsthand examination of the rock from shafts, test drifts, or rooms, afford a level of detail that justifies analytical and numerical analyses. The resulting design may still be conservative, but a better estimate of the degree of conservatism is obtained. Depending on the project, specialized, in situ tests may be required to address specific design requirements in detail.

Current methodology for a comprehensive design approach based on preliminary or generalized geologic data incorporates empirical rock classification systems. The recommendations thus generated can be modified to allow for specific concerns. For a nuclear waste repository, such concerns relate to thermal loading, the need for stability during the retrieval period, and the need for long-term isolation of radionuclides.

A comprehensive design approach based on more detailed geologic data may incorporate analytical and numerical modeling techniques. Analytical techniques commonly require some simplification and generalization of site conditions. While some detail is necessary in the data, a high level of detail is inappropriate. For the numerical modeling techniques to yield meaninful results, a well-defined data base consisting of reliable geologic data and workable underground layout concepts are required. The proper use of empirical and analytical techniques during the earlier design stages may limit the number of alternatives considered during numerical analysis, with consequent savings in time, effort, and cost.

Critical Design Input Parameters

Design input parameters that govern or constrain repository planning must include geological/hydrogeological considerations and parameters relating to repository layout and use. Geological/hydrogeological considerations relate to the basic fact that a geological repository is an underground structure excavated in rock the behavior of which is governed by rock mass characteristics. Design considerations also depend on repository layout and use, and extend to thermal loading, the retrievability criteria, repository life, isolation of radionuclides, operational factors such as rate of emplacement of and capacity for nuclear waste storage, and safety requirements. These factors dictate the repository layout and support facilities, and hence, govern the selection of design criteria and specifications.

Basic geologic factors that should be addressed at all stages of the design process include, as a minimum, rock strength, rock fracturing, in situ stresses, elastic properties, thermal response, and the hydrogeologic regime.

A definition of instability is necessary so that conformance of the rock behavior with stability criteria can be verified. This definition would provide a framework for design, by establishing the extent of deformation or localized failure that can be tolerated in the repository. The expected performance of rock support systems needs to be established prior to their inclusion in the repository design. Principal concerns relate to temperature effects and creep.

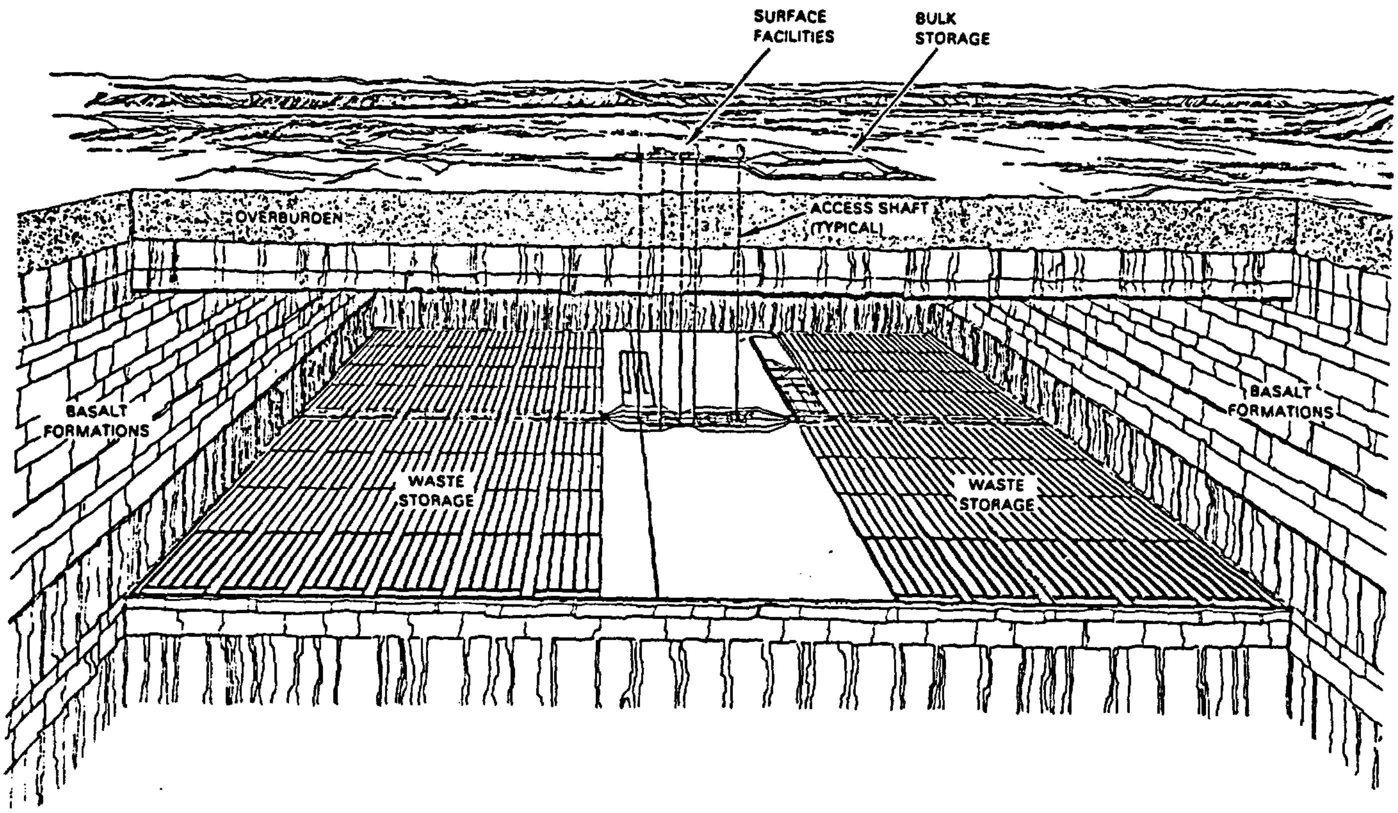

Figure 2. Cutaway of a Repository Proposed by the Basalt Waste Isolation Project, After U. S. DOE, 1982.

Design Approaches

The design of repository openings, as discussed earlier, is a phased process in which the conceptual design is refined as more data become available from in situ testing. The sequence begins with empirical, general concepts, which allow selection of several suitable options for further study. Information needs are identified, data are collected accordingly, and designs based on principles of engineering mechanics are carried out (analytical techniques). A comparison of the designs is then possible, perhaps based on cost and technical criteria. A few alternatives are then selected for detailed consideration, in which the interaction of all critical design factors is evaluated through numerical modeling; this design phase should be supported by in situ testing for specific input parameters. From this effort, design specifications and performance criteria are formulated. Finally, the conformance of the rock mass behavior with performance criteria is verified by monitoring.

Engineering Mechanics Approach

Design approaches based on engineering mechanics considerations are the rock classification schemes, and analytical solutions to analyze stability. Rock classification systems address most of the factors governing the stability of repository openings in rock, i.e., basic rock strength, fracturing, water conditions, and overall geologic setting. The method proposed by Kendorski (1980) is basically a discounting method, in which the intact rock strength is discounted according to the nature and degree of fracturing, to obtain the rock mass strength. This value can be used for analytical computations as well as an indicator of overall rock mass competence. The Geomechanics System of Bieniawski (1979) develops a relationship of span versus stand-up time. The Q-System of Barton, Lien, and Lunde (1974) is a detailed system with the chief advantages of considering span and in situ stress. The RSR Concept of Wickham and Tiedemann (1974) is fairly simple but is not recommended for the design of shotcrete and rock reinforcement, since the data base for these types of support did not contain sufficient examples of their use to permit definitive criteria to be developed (Wickham and Tiedemann, 1974, p. 5-24). The RSR system is far more reliable for selecting steel arch support. The system proposed by Terzaghi (1946) computes a dead rock load due to loosening, and is also widely used for the design of steel arch support in tunnels.

These systems either enable or directly yield generalized support recommendations. Application of these systems to circumstances outside the classification data base requires discretion. Thus, the particular requirements of nuclear waste repositories, especially thermomechanical effects, will require some modification of the direct results obtained from classification systems before an adequate preliminary design is obtained for any single repository concept. However, various repository concepts can be readily compared for long-term stability and constructibility using classification approaches. Typically, recommendations from the various classification systems are compared, to obtain preliminary rock mechanics design concepts.

Classical engineering mechanics approaches are based on arriving at a balance of forces acting on an opening. Driving forces are the rock loads, and resisting forces come from the rock mass competence and the support system. The in situ material properties of the rock and support must be known for such an approach to be meaningful.

Simple elastic theory (Obert and Duvall, 1967) gives a first approximation of the distribution and magnitude of stresses and destressed zones surrounding an opening. However, the assumptions of homogeneity, isotropy, and linear elasticity implicit in the theory are seldom met in rock masses. Elastic theory also does not allow for the effects of rock reinforcement. However, even with these limitations, simple elastic analyses yield useful information for conceptual design of openings in rock.

Elastic-plastic ground reaction curve methods seek to match the support to the rock mass such that the amount of deformation allowed for corresponds both to the peak rock mass shear strength and the peak deformation resistance of the support (Egger, 1980). For the optimum use of the method, proper timing of support installation is essential. While the deformation of the support can be fairly readily evaluated, the rock deformation (ground characteristic) is commonly nonlinear and ordinarily cannot be predicted accurately from basic geomechanics data. To estimate the general magnitude of the initial deformations, an analytical solution for the development of a plastic zone can be used, based on estimates of rock mass frictional properties. For design, preliminary estimates of rock mass behavior can be obtained from underground test facilities within the horizon of interest, by monitoring the deformation with respect to time, face position, and distance from the opening, either in a single drift or (preferably) in mine-by tests. Mine-by tests permit the deformation monitoring of an opening during the excavation of an adjacent opening. During construction, detailed geologic studies coupled with further field measurements can result in enhanced capability for predicting rock mass behavior.

Numerical Modeling Approach

There is a variety of numerical modeling approaches available for use in the design of repository openings (St. John and Hardy, 1982). For a geologic repository, modeling appears at present to be the best way to address the following specific design issues:

- Rock mass deformation around openings
- Time-dependent behavior
- Nonlinear stress-strain characteristics
- Anistropic properties
- Inhomogeneities
- Rock-support interaction
- Effect of hydrologic regime
- Rock mass behavior under thermal loads
- Repository layout
- Geologic variations: stress field, rock mass competence, and water conditions.

For the use of numerical modeling schemes to yield meaningful results a considerable base of reliable in situ as well as remotely-gained data are required. Hence, these methods are most useful when such data are available from underground test excavations. Also, some numerical codes are quite complex and costly to use, and therefore should be used with caution. The biggest advantage of numerical modeling however, is the facility with which a number of scenarios can be studied using a range of expected input parameters.

Differential methods (finite element and finite difference) permit the introduction of interfaces (slide lines or element boundaries) within a continuum. The finite element method (FEM) (Zienkiewicz, 1971) has the advantages of handling complex geometries, inhomogeneities, nonlinearity, and support-rock interaction. In problems involving repository excavations, several nonlinear phenomena may need to be considered. These involve plasticity, creep, behavior of joints, and the coupled thermal-mechanical response of the rock mass.

Elastic-plastic methods hold significant potential in their ability to model the complexities of repository design concepts, and the ability to handle inhomogeneities. One important aspect of the elastic-plastic model is the definition of a damaged zone in the rock where yielding has propagated, away from the opening and into the rock mass, according to the selected yield criterion (Goodman, 1980). Certain associated aspects of the conceptual elastic-plastic model, which need to be considered in applications to design of repository openings are: the change in both stiffness and strength of the damaged rock, the influence of time (and distance from the face) before installation of supports, and the support-rock interaction.

Integral or boundary-element methods are based on the solution of integral equations that connect the boundary tractions to boundary displacements (Crouch, 1976; Cruse and Rizzo, 1975). The boundary of the opening is discretized and defines the solution for the interior. Thus these methods are most applicable when conditions at the boundary are of chief concern.

Thermomechanical behavior can be modeled by assuming the validity of the principle of superposition, in which stresses due to thermal and excavation effects are algebraically added. Thermomechanical modeling develops thermal stress values for this purpose; an example is ADINA/ADINAT (Bathe, 1978) which has been used to model the repository environment. Two-dimensional models can be useful for preliminary design. Coupled models assess the interaction of thermomechanical and hydrological conditions. Three-dimensional models avoid the simplifying assumptions inherent in a two-dimensional approach, but are more complex and costly.

Observations During Construction Approach

During the construction of any underground facility, in situ monitoring of the rock mass is essential for verifying that the design objectives are being achieved.

In conformance with the provisions of 10CFR60, a detailed monitoring program should be implemented. This should include measurements of relative and absolute ground movements, support load response, visual performance of support, geologic mapping, hydrologic monitoring, and records maintenance. Specific plans will depend on the design of the repository, but should be complete and at a level of accuracy that affords a reasonable prediction of rock mass behavior.

Analysis of these data may lead to redesign of some construction elements. Since prediction of geologic conditions is not an exact science, some redesign is anticipated in even the most thoroughly investigated underground construction projects.

CONCLUSIONS

The phased design approach described in this paper lends itself to the site characterization process for a nuclear waste repository. The degree of conservatism in the design can be reduced as data from at-depth testing becomes available. The details of the at-depth testing should be developed on the basis of input data requirements for design optimization. Data from the at-depth tests should be collected under a rigorously implemented quality assurance program. The manner in which the data will resolve the design issues should be identified at an early stage.

Acknowledgments

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MEASUREMENT OF ROCK PROPERTIES AT ELEVATED PRESSURES AND TEMPERATURES

Abstracts

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ASTM

DETERMINATION OF A CONSTITUTIVE LAW FOR SALT AT ELEVATED TEMPERATURE AND PRESSURE

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A constitutive law form has been selected for use in the commercial high-level nuclear waste disposal program. The law contains eight parameters; two describe elastic behavior and six describe inelastic behavior. The elastic parameters are determined from the unload-reload portion of constant-stress-rate triaxial compression tests while the inelastic parameters are determined from constant-stress (creep) triaxial compression tests.

Ten computer-controlled triaxial machines are used to determine the constitutive parameters for natural rock salts. These machines test specimens that are 100 mm in diameter and 200 mm long at temperatures between 20°C and 200°C. Confining pressures and axial loads up to 70 MPa and 1.5 MN, respectively, can be imposed. Axial load is measured by a load cell in the load train outside the pressure vessel. Confining pressure is measured by a pressure transducer in the line between the pressure vessel and intensifier, while temperature is measured by a thermocouple in the pressure vessel wall. Axial deformation is measured by two LVDT's mounted outside the pressure vessel and lateral deformation is determined using a dilatometer.

Specimens are prepared from 100-mm-diameter core. The core is cut to approximate length in a band saw using a high-speed steel blade. The specimen ends are finished flat and parallel within 0.015 mm in a lathe using carbide tooling. For testing, the specimens are jacketed with 1.6-mm-thick, molded Viton tubing.

A matrix of constant-stress tests is performed on salt specimens from the Permian Basin in Texas to determine estimates of the six inelastic parameter values in the constitutive law. The matrix comprises twelve tests that span the ranges of stress and temperature expected in a nuclear waste repository and represents the minimum number of tests required to obtain adequate estimates of the parameter values.

Determination of Steady State Creep Rates and Activation Parameters for Rock Salt

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New problems in geotechnical design require constitutive models for rock salt that can be extrapolated to low stresses and long times. On one hand, the long duration of the problem offers the possibility that the response of salt masses is governed by its steady state creep behavior and that transients can be neglected. While this assumption facilitates calculations, it also necessitates that true steady state creep rates be determined. This is difficult at strain rates less than about 10^{-8} s^{-1}.

The need for model extrapolations considerably beyond the realm of laboratory conditions creates another, new characteristic of modeling in geotechnical engineering. To justify extrapolations it is desirable that the models also describe the physical processes governing the constitutive behavior of salt. The correlation between constitutive models and deformation mechanisms is commonly achieved by means of characteristic creep activation parameters.

This paper will discuss approaches and results concerning both of the foregoing topics. Following a brief review of methods to conduct triaxial creep experiments to 200°C on relatively large samples (10 cm diameter by 22 cm long), several techniques will be described to estimate steady state creep rates. Most reliable, it appeared, was the use of temperature change tests. Because of characteristic transients, such experiments generated upper and lower bound estimates of the steady state creep rates. This method is particularly suitable at temperatures below 120°C when transients are most pronounced.

Activation analyses entail the measurement of activation enthalpies, activation areas and back stresses that determine the nature and rates of salt creep caused by thermally activated rate processes. Activation enthalpies and activation areas were evaluated in multistage tests where either the temperature or the stress was changed from time to time. Back stresses were measured in so-called stress dip experiments.

Although the paper emphasizes methodologies, a brief discussion will be included concerning the implications of low activation enthalpies, relatively large activation areas and transients following changes in temperature. All of these features, together with substructure observations, indicate that the creep of rock salt below 200°C is controlled by a combination of glide and recovery.

MEASUREMENT OF PERMEABILITY AT ELEVATED PRESSURES AND TEMPERATURES

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Laboratory measurements of the permeability coefficients of various rock types suggest that the permeability coefficient is sensitive to the temperature and the pressure at which it is measured; the effects become more pronounced as the temperature or pressure is increased. This paper presents a summary of data in the literature to support this statement and describes in some detail laboratory techniques utilized to obtain the data base.

Laboratory observations indicate that the permeability coefficient is temperature sensitive and that it is affected in many different ways as the temperature is increased. Temperature might be expected to affect the permeability coefficient through purely physical effects such as thermal expansion or thermal cracking. However, a variety of water-rock interactions apparently play a role, evidently through pore geometry alteration, which can have profound effects on the value of the permeability coefficient. The change in permeability coefficients due to temperature reviewed in the paper were large but not quantitatively predictable.

The permeability of porous media is known to depend upon pore dimensions whereas the permebility of fractured media is known to depend upon fracture aperture. Pore dimensions, particularly the aperture or width, change with stress so that it is not suprising to find that the permeability coefficient of various rock types can be quite stress dependent. The paper discusses general trends in stress related behavior changes for both low and high porosity unjointed rocks as well as for some jointed rocks.

The paper describes recent advances in interpretive technique as well as summarizing efforts to quantify temperature and pressure effects on the permeability coefficient. Temperature and pressure effects in radial permeability tests designed to simulate field test conditions are also presented.

Improved Acoustic Emission Locations

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Crack propagation is the principal mechanism of deformation in brittle rocks. It provides a source of acoustic emissions (A.E.) useful in determining the changes in rock properties which occur during deformation. We report here solutions to two problems which typically occur in laboratory studies of A.E. locations in rock samples, those arising from transducer size and from velocity anisotropy.

Sample size is usually restricted to dimensions of tens of millimeters, particularly if the samples are to be tested inside pressure vessels under confining pressure. Piezoelectric transducers however, which are of adequate sensitivity to detect A.E. in these samples, have dimensions which are a significant fraction of the least sample dimension, e.g. 6 mm diameter transducer on a 17 mm width face. Treating these transducers as point receivers introduces scatter in A.E. locations. An experimental determination has been made of the effective transducer dimension and location as a function of the direction from which the acoustic energy arrives. To determine A.E. locations, the center of each receiving transducer is used as its preliminary location. A correction to this position is then made based on the direction to the A.E. source. The A.E. is then relocated with substantially improved precision.

The velocity field in a highly deformed brittle rock tends to become extremely anisotropic. Variations in velocity of a factor of two are typical for velocities parallel and normal to the maximum principal stress direction. Inversion of arrival time and transducer position data based on an isotropic constant velocity model results in large uncertainty and errors in A.E. locations. The velocity field however can be reasonably determined throughout a deformation experiment by repeatedly transmitting from various sending transducers on the sample to the same receiver array used for A.E. locations. Again, appropriate size corrections for both transmitting and receiving transducers are made. The observed velocity field is then used in the inversion for locations. As a check on the final accuracy of the entire process, the transmission data may be inverted to locate the sending transducers.

Data is reported for such a uniaxial compression experiment on a rectangular prism of Westerly granite, 55 x 53 x 179 mm. Final accuracy for A.E. locations appears typically to approach the limit set by the arrival time resolution of ± 50 nsec.

Crack Development in Geologic Materials

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The influence of environment on the crack growth and interactions which lead to failure of geologic materials is examined. Results from experimental studies of rock deformation are compared with a theoretical formulation of the fracture process. The dependence of deformation and fracture on moisture, temperature and strain rate is shown to be reasonably well described by the model.

Suites of igneous and sedimentary rocks are tested to failure under triaxial ($\sigma_1 > \sigma_2 = \sigma_3$) compression at various moisture contents, strain rates and temperatures. The procedure includes a preliminary excursion of all samples to a temperature above that used during testing. This reduces the scatter in results by providing all samples with an identical recent history.

The compression tests are conducted in an internally heated, liquid pressure medium apparatus capable of confining pressures to 300 MPa and temperatures to 300° C. Temperature is controlled with a 3 zone servo controlled furnace permitting good control of the temperature distribution and rates of change. Samples are sealed in thin extruded copper tube jackets with metal to metal pre-stressed seals. Strains are observed directly with high temperature strain gages bonded to the copper jackets. Data are recorded on a computer based automatic data acquisition system.

A model of brittle failure has been developed in which subcritical crack growth due to stress corrosion decreases the load bearing capacity of the rock until failure results. Constant stress rate, constant strain rate, and creep loading are considered. A normal density distribution curve describes the stresses at the crack tips until crack growth becomes significant. Then, areas within the sample are allowed to respond to stress independently. Interaction of cracked areas in the form of stress redistribution occurs upon the complete failure of a local area.

Stress-strain curves compare well with experimental data. Discrepancies show changes in crack number and morphology which occur during real rock deformation but are not yet accounted for in the model.

MEASUREMENTS OF DYNAMIC PROPERTIES OF ROCK AT ELEVATED TEMPERATURES AND PRESSURES

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A major goal of seismology is to provide information on the nature of materials beneath the earth's surface. Velocities have been measured as a function of depth for many regions underlying both the oceans and continents. For some areas shear wave velocities have been determined as well as compressional wave velocities and in several seismological investigations the azimuthal dependence of velocity has been investigated in some detail. The major purpose of laboratory studies of rock velocities is to provide data for the interpretation of the seismological velocities in terms of chemistry, mineralogy and porosity. To accomplish this it is often necessary to perform the velocity measurements under carefully controlled confining pressures, temperatures and pore pressures. Velocity measurements in rocks are usually obtained from cylindrical samples using the pulse transmission technique. Transducers with natural resonant frequencies of 1 to 2 MHz generate and receive the seismic waves. Barium titanate, lead zirconate and lithium niobate transducers have been successfully used to measure compressional wave velocities, whereas AC cut quartz and shear mode lead zirconate transducers are usually employed for shear velocity measurements. Both velocities have been routinely measured in a wide variety of rocks to confining pressures of 10 kbar (1000 MPa) and compressional wave velocities have been measured in several rocks to confining pressures of 30 kbar (3000 MPa) using a modified Birch-Bridgman hydrostatic press. Velocities measured as a function of temperature and pressure have been reported to confining pressures of 10 kbar and temperatures of 500°C using solid pressure media and to 2 kbar, 500°C with gas pressure media and a three zone furnace. Recently, compressional and shear velocity data have been obtained for a wide variety of rocks using sample holders and pressure generating systems which allow accurate control of pore pressures as well as confining pressures. Comparisons of the laboratory measured velocities of rock cores obtained from drill sites with logging velocities of lower frequencies suggest little dispersion in the frequency range of 2 MHz to 10 KHz.

THE EFFECTS OF PORE PRESSURE, CONFINING PRESSURE AND TEMPERATURE ON PORE AND BULK VOLUME COMPRESSIBILITIES OF CONSOLIDATED SANDSTONES

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An experimental apparatus has been developed to measure pore volume and bulk volume changes for consolidated sandstones subjected to pore pressure, confining pressure and elevated temperatures. A 128 byte random-access computer is used to monitor and record the pressures, pore volume, specimen temperature and bulk strain. The pore pressure and temperature are computer controlled using feedback.

Hydrostatic confining pressure is applied to the rock specimen inside a chrome-steel alloy pressure vessel filled with silicone oil. The cylindrical rock cores, of 5.1 cm. length and diameter, are sheathed with teflon shrink-fit tubing to separate the pore and confining fluids. Bulk strain is measured with longitudinal and transverse strain gauges mounted on the rock, with dummy strain gauges placed inside the vessel to provide temperature compensation. Confining pressure and pore pressure are measured with strain-gauge pressure transducers.

Changes in pore fluid volume are measured by means of a precision-bore cylinder containing a movable piston connected to a linear variable differential transformer (LVDT). The other end of the piston is connected to a larger piston, with an area ratio of 20:1, upon which nitrogen acts to control the pore fluid pressure. The computer compares the measured pore pressure to the desired pore pressure, and instructs a stepping motor to either increase or decrease the nitrogen pressure. This system allows the pore pressure to be maintained constant within $\pm$.07 MPa (10 psi) during periods where either the temperature or confining pressure is changed.

The vessel is heated by external segmented cylindrical electric heaters which are controlled by the computer to allow for either uniform-rate temperature rise, or constant temperature maintenance to within $\pm 3^{o}$C. The temperature of the specimen is measured with thermocouples, whose outputs are used for the feedback control of the heater.

Tests are being run on Berea, Boise and Bandera sandstones. Confining pressures are varied from 6.9 to 41.4 MPa (1000-6000 psi), and pore pressures from 0 to 27.6 MPa (0 to 4000 psi). Temperatures renge from 20^{o}C to 180^{o}C (68^{o}F to 356^{o}F). The tests are being carried out to provide data to test a theoretical model being developed to predict pore and bulk volume compressibilities as a function of mineral composition, clay content, pore geometry, crack lengths and crack density.

DEVELOPMENT OF A TEST SERIES TO DETERMINE IN SITU THERMOMECHANICAL AND TRANSPORT PROPERTIES

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In order to ascertain the environmental effects due to the storage of nuclear waste products in underground repositories, predictive numerical models will be required to assess the thermal, mechanical and hydrological response of the host material to the heat generated by the emplaced nuclear waste. Scale effect problems suggest that input data to the predictive models should be obtained from relatively large scale in situ tests. Large scale in situ tests have the further advantage that they can be utilized for verification of model calculations. This paper describes the conceptualization and evolution of a large scale heated block test to quantify the mechanical, thermal and hydrologic behavior of a jointed rock mass in situ.

The specific tests comprising the test series were designed to individually address mechanical, thermal and hydrological response as well as any coupling which might exist. The specific test types include:

- measurement of the stress-strain behavior of the test block at ambient and elevated temperatures to determine the elastic constants for the rock mass and their variations with stress and temperature;
- measurement of the normal and shear deformations of selected individual joints under applied mechanical stresses and imposed thermal strains;
- measurement of the thermal fields and the resulting thermal strains and stresses to determine the thermal conductivity, diffusivity, and coefficient of expansion and their variation with confining stress and temperature;
- measurement of the ultrasonic compressive and shear wave velocities and their variation with applied stress and imposed thermal strains; and
- measurement of the permeability of a selected joint and its variation with applied stress, imposed thermal strains, and test injection pressure.

The heated block test is a logical test for providing information on repository design and licensing. It provides a standard means of characterizing the rock mass properties of a repository at the access level provided by an exploratory shaft. Data provided by such a test would be of considerable practical value in supporting the repository design and modeling effort.

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Task Order 003

Meeting Report

Place: College Station, Texas

Dates: June 20 - 22, 1983

Purpose: To present a paper related to Task Order 003 at the 24th U. S. Symposium on Rock Mechanics.

Attendees: V. Rajaram, Engineers International, Inc.

Meeting Summary

This annual meeting summarized the progress in rock mechanics in the U. S. and abroad. On June 20th, the American Society of Testing Materials (ASTM) sponsored a symposium on Measurement of Rock Properties at Elevated Pressures and Temperatures. There were 9 papers presented at the ASTM symposium and about 90 papers presented at the Rock Mechanics Symposium. The papers at these symposia that relate to high level waste disposal are discussed below, and are grouped into basalt, salt and tuff.

ASTM Symposium

There were three papers of direct interest to site characterization of geologic repository sites.

Hardin, E. L., and others presented a paper entitled "Development of A Test Series to Determine In Situ Thermomechanical and Transport Properties." This paper describes the conceptualization and evolution of a large scale heated block test to quantify the mechanical, thermal and hydrological response as well as any coupling effect which might exist. The objective of this test series is to minimize the scale effect of input data for predictive models. The parameters determined, for example, are normal and shear deformations under applied mechanical stresses and imposed thermal strains; the permeability of a selected joint and its variation with applied stress, imposed thermal strains and test injection pressure. The tests appear logical and can provide information for repository design and licensing. It provides a standard means of characterizing the rock mass properties of a repository using an exploratory shaft.

Voegele, M. D., and W. F. Brace presented a paper entitled, "Measurement of Premeability at Elevated Pressures and Temperatures." This paper suggested that the permeability coefficient is sensitive to temperature and pressure, and the effect becomes more pronounced as temperature or pressure is increased. Laboratory studies indicate that the permeability is affected by temperature in many ways. Physical effects, such as thermal expansion or cracking may affect the permeability. Water-rock interaction produces pore geometry alteration. Permeability is also stress-dependent since pore dimensions and fracture apertures are affected by stress. Recent advances in interpretive techniques as well as efforts to quantify temperature and pressure effects on the permeability coefficient are presented.

P. E. Senseny presented a paper entitled "Determination of a Constitutive Law for Salt at Elevated Temperature. A constitutive law was suggested for use in the design of high-level nuclear waste repositories. The law contains eight parameters: two describe elastic behavior and six relate to inelastic behavior, which were determined from triaxial compression tests. Twelve (12) tests were reported and spanned the ranges of stress and temperature anticipated in a nuclear waste repository. The test specimens were obtained from the Permian Basin in Texas. The test results are very scattered and inconsistent within each batch. The applicability of this constitutive law and associated constants needs to be better defined.

Basalt

There were four (4) papers related to the work being done at the Basalt Waste Isolation Project (BWIP). Cramer and Black presented a paper on "The Design and construction of a Block Test in Closely Jointed Rock." The large scale block test is being conducted at the Near Surface Test Facility (NSTF). The drilling of the cable anchor (275-ton capacity) and instrumentation boreholes, the drilling of the slots, installation of the cable anchor tendons and jacks, installation of grout boxes and flatjacks, and installation of the borehole instrumentation and optical deformation measurement system were described.

The paper by Cramer and others reported on the rock mass deformational properties from a large scale block test. Deformation moduli, Poisson's ratio, the coefficient of thermal expansion, and the thermal conductivity of a jointed and fractured basalt block at ambient temperature were determined from this test. The deformation modulus at a confining stress of 1.5 MPa was 13 GPa and 23 GPa, for principal loading in the horizontal and vertical directions, respectively. The increase in confining stress from 1.5 to 5.0 MPa produced a 60% increase in the deformation modulus. The authors conclude that the deformational response is strongly anisotropic with a significant level of directionally dependent inelasticity.

Gregory and others presented a paper entitled "Applicability of Borehole Stress Measurement Instrumentation to Closely Jointed Rock." This paper summarizes the development efforts that have been made at BWIP to improve the reliability of the borehole deformation gage (BDG) and the vibrating wire stressmeter (VWS) when used under conditions of elevated temperature and humidity. Hermetic sealing improved VWS reliability significantly. Stress results from the VWS were generally in closer agreement with the applied stresses in the Block Test than were those from the BDG.

Rajaram and others presented a paper on the design approach for a nuclear waste repository in hard rock. The site characterization process has to emphasize the structural geology and hydrology in the area of interest, and permit the estimation of variability of these parameters within and around the repository. Design approaches which accommodate the gradual improvement in the quality of rock mechanics data obtained during this process are elaborated upon. Engineering mechanics approaches and thermomechanical computer modeling are described.

Salt

There were five papers related to rock salt. The papers ranged from laboratory and in situ rock mechanics tests to the thermomechanical analysis of nuclear waste emplacement in bedded salt. A brief summary of the papers is given below.

Thoms and Gehle described a technique successfully utilized by them to monitor room closure in 100-foot-high rooms in a salt mine. A commercially available electronic distance measuring (EDM) instrument modified by the addition of a detachable mirror-adaptor for vertical sighting of roof mounted retroreflectors was used. This instrument can be used in a repository without obstructing traffic or other operations.

Blankenship and others described a core jacking test which has been successfully used in salt for measuring the rock mass deformability. This is suggested as an alternative to the plate bearing test, flatjack or borehole jack test and dilatometer test for measuring the rock mass deformability in anisotropic rock. The ability to measure in situ stresses by this method is also discussed.

Branstetter and Preece reported on detailed analysis of laboratory uniaxial and triaxial creep experiments on rock salt specimens. The purpose of the analysis was to estimate the effect which the friction between the ends of the salt sample and the platens of the testing machine produce in the interpretation of creep data.

Berest and others described the principle of a method which can be used to measure the volume of any large natural or artificial caverns when access is available only through drilling. Results of field tests using this method were comparable with the sonar method. During the characterization of salt sites, this method may be used to determine the volumes of any brine pockets encountered during drilling.

In the very-near-field (canister-scale), the thermal and thermomechanical response was evaluated by Svalstad for two potential nuclear waste repository sites in bedded salt formations located in the Permian and Paradox basins. The finite element method was used in conjunction with site-specific conceptual repository designs for underground vertical borehole emplacement of commercial high-level waste (CHLW) and Spent Fuel (SF). Based on the results of the study, the author concludes that the very-near-field performance constraints will be satisfied with the proposed conceptual design except the radial pressure on the CHLW package at the Davis Canyon site (Paradox basin). Consequently, the areal thermal loading may have to be reduced by as much as 33 percent to limit the resulting salt pressure on CHLW packages at the Davis Canyon site. The conclusion is qualitative and considerable validation work is required, especially due to the deficiency of field test results which were used as input data for numerical analysis.

<u>Tuff</u>

Two papers were presented on the investigations being conducted at the Nevada Test Site (NTS) in support of high level waste storage. Morrow and others presented a paper entitled "Permeability and Pore Fluid Chemistry of the Bullfrog Tuff in a Temperature Gradient." Samples of the Bullfrog tuff from NTS were studied under simulated nuclear waste repository conditions to determine the ease with which radionuclides could be carried in the environment. The permeability of the Bullfrog tuff cylinders did not reduce significantly during heating runs because mineral deposition or growth caused only a small decrease in the large initial pore and vug spaces. The authors hypothesize that the lack of permeability decrease is beneficial since downward percolating ground waters would not accumulate around the canisters in the repository horizon.

Zimmerman presented a paper on the first phase of small diameter heater experiments in tuff. Two heater experiments conducted in vertical boreholes drilled into welded and nonwelded tuffs at the G-tunnel are described by the author. Small amounts of liquid water migrated into the welded tuff borehole early in the heating period. Once the rock-wall temperatures exceeded 94°C, there was mass transport of water vapor in both the tuffs and this condensed in the cooler regions of the borehole.

Closure

In closing, the symposia provided a forum for the exchange of rock mechanics information among researchers and practitioners in the field. The importance of in situ testing in understanding the rock mass response under stress and elevated temperature was the theme that emerged from many of the papers. Design incorporating the results of in situ tests provides a cost-effective approach to the excavation of safe structures in rock.