Stability of Underground Openings in the Yucca Mountain Repository

Thomas E. Blejwas
Sandia National Laboratories, Albuquerque, NM USA

ABSTRACT

The licensing of a repository for high-level radioactive waste will require assurances that underground openings do not experience frequent major instabilities, which are defined here as sudden movements of blocks of rock that limit the functions of the openings. Although the design of nuclear power plant structures is controlled by strict adherence to building or professional-engineering codes, this approach is not practical for the structural design of underground facilities because the design must accommodate a varied and partially defined geologic setting. However, regulations require the reduction of the potential for deleterious rock movement and the design of openings to maintain the option to retrieve waste. The present plans for meeting these requirements for a repository at Yucca Mountain, Nevada, include a program of state-of-the-art analyses and modified forms of existing empirically based design methods. An extensive experimental program is required to provide confidence in the results of the design-analysis process.

INTRODUCTION

Because of recent congressional action, Yucca Mountain in southern Nevada will be the only potential U.S. site for high-level radioactive-waste disposal to be characterized over the next several years. The design of a geologic repository has unique requirements. Because the repository will be licensed, a high degree of confidence in meeting performance criteria in the federal regulations is required. However, unlike nuclear power plant structures, which utilize specified construction materials from foundations upward, an underground repository utilizes a geologic setting that has variable properties, discontinuities, and that can be only partially characterized. Although mines are designed for such environments, empirical design methods are often used and the ground-support systems are often modified based on the actual conditions encountered. The need to predict with confidence the performance of the repository leads to the use of advanced analytical methods that have limited precedence in mining applications. Therefore, a comprehensive suite of thermal-mechanical experiments is needed to support the design and analysis of the repository.

The design of underground facilities at Yucca Mountain is influenced by a number of natural features, which are summarized in the Site Characterization Plan (DOE, 1988). The selected waste-emplacement horizon is about 1000 ft (300 m) below the surface (about 600 ft (200 m) above the water table) in a unit of densely welded, partially saturated tuff (TSw2 in Fig. 1). Although unconfined compressive strengths above 15,000 psi (100 MPa) are not unusual for intact samples from this unit, the host rock is thought to be highly fractured with

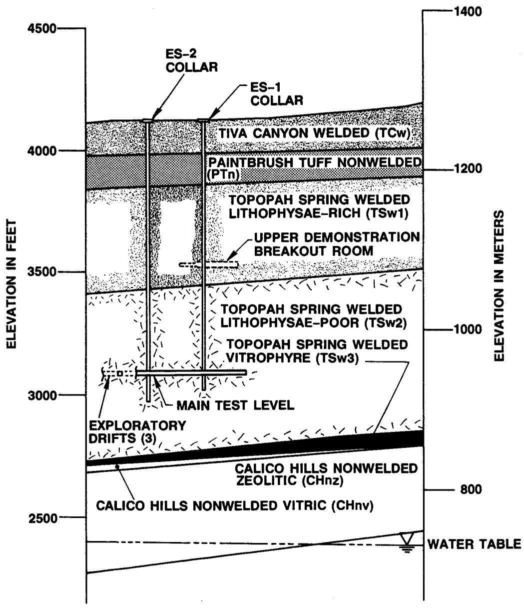

Fig. 1. Stratigraphy of Yucca Mountain with Thermal-Mechanical Units at the ESF site.

vertical joint frequencies of about four per foot (13 per meter). Also, the variability of mechanical properties is very high, including the influence, at some locations, of voids known as lithophysae.

The repository underground facility will consist of ramps and shafts from the surface (up to 24 ft (7 m) in diameter), arrays of drifts (up to 24 ft across), and vertical or horizontal boreholes for waste emplacement (SNL, 1987). The waste will heat the surrounding rock and, with time, a large volume of the underground will reach temperatures above 100° C. Constrained thermal-expansion will lead to significant changes in the stress field. Based on preliminary elastic analyses, the direction of maximum principal stress will change from nearly vertical to generally horizontal, with significant concentrations around the underground openings (St. John, 1987).

In situ geomechanical experiments, which will be conducted at Yucca Mountain as a part of site characterization (DOE, 1988), will be conducted in an exploratory shaft facility (ESF), the construction of which is scheduled to begin in 1989. The ESF includes two vertical shafts, a series of drifts and alcoves that make up a central test area at a main test level (MTL), and about a mile of exploratory drifts intended to intersect the underground extension of structural features observed on the surface. An elevation view of the ESF is presented in Fig. 1.

REPOSITORY REQUIREMENTS AND STABILITY

The need for stable underground openings in a repository can be inferred from federal regulations. In particular, the Code of Federal Regulations, 10 CFR Part 60 (NRC, 1986), specifies that the repository be designed to reduce the potential for deleterious rock movement (Part 60.133(e)(1)). The regulation also specifies that openings be designed so that operations can be carried out safely and the option to retrieve waste maintained (Part 60.133(e)(2)). Therefore, although the regulations do not specify that instabilities cannot occur, frequent major instabilities could complicate the approach to satisfying these requirements. The consideration of possible instabilities is not uncommon in mining applications, but waste-generated heat in a repository leads to thermal loads that must be taken into account (Part 60.133(i)).

Based on an interpretation of the regulations, a general approach for creating and maintaining underground openings in a repository at Yucca Mountain has been developed (DOE, 1988 and SNL, 1987). Consistent with mining practices, the underground openings will be reinforced with ground-support systems, such as rock bolts and shotcrete, and will be kept usable through a program of monitoring and maintenance. However, to more readily meet the regulations, openings will be designed to be stable except for infrequent rock falls that can be easily removed.

The regulations specify that, in addition to collecting data for site-characterization, data be collected for a performance-confirmation program that begins during site characterization and continues until closure of the repository (10 CFR Part 60.140). Therefore, the strategy for ensuring that openings will be stable comprises three phases. During the site-characterization phase, repository openings will be designed and analyses will be performed and interpreted with respect to usability. Experiments will be conducted to provide confidence in the analytical approaches (model validation), to better define rock-mass parameters used in models, to enhance databases for empirical analyses, and to establish specific criteria for judging opening stability. Although these same experiments may also provide a limited demonstration that repository openings will be stable, this will be more completely accomplished during the second phase. In the second phase, large-scale experiments that simulate a repository environment will be conducted and opening behavior will be observed to determine if instabilities occur. (Additional confidence in the analytical methods will also be obtained). Because these will be among the first performance-confirmation experiments, they will begin during site-characterization. The third phase will begin after the initiation of waste emplacement in the repository. As the repository responds to heat from the waste, the openings will be monitored and any instabilities will be observed.

APPROACH TO ENSURING STABILITY

The approach to ensuring that underground openings at a Yucca Mountain repository will be adequately stable includes the following: 1) design of the openings using analyses and empirical methods that have been modified to include the effects of thermally induced loads and data from experiments on tuffs; 2) specification of detailed construction methods that take advantage of experience gained from construction and monitoring of the ESF; 3) analyses of the openings using state-of-the-art models for jointed rock; 4) a suite of field and laboratory experiments to support the design-analysis process and to demonstrate the behavior of openings in simulated environments; and 5) a program of maintenance and monitoring of actual repository openings. This process will include the consideration of loads and other factors that can affect the stability of repository underground openings, including heat, seismic loads, excavation effects, in situ stress, and initial and time-dependent properties.

Design Methods

The general design approach anticipated for a repository consists of the following steps. First, the general layout for the repository and the sizes of openings are selected based primarily on operational considerations. Preliminary shapes that are expected to have desirable characteristics with respect to stress concentrations are selected for the openings. Based on a range of rock properties that are estimated from available data, rock-mass classifications are estimated and ground-support systems are selected using modifications of existing empirical approaches that include the effects of thermal loads. Rock-support interaction analyses may also be performed. The openings are analyzed for temperature and stress distributions using linear-elastic finite-element or finite-difference methods. The layout, sizes, and/or shapes are modified, if necessary. The ground-support systems are also evaluated for failure mechanisms that are hypothesized from the stress distributions and the expected joint systems. As with the existing conceptual repository design (SNL, 1987), a spectrum of ground-support options will be specified and the selection based on actual ground conditions encountered during construction. Modifications of the empirical approaches to include the effects of thermal loads, recent experience in tuff, and site-characterization results, is a part of ongoing research.

Analytical Methods

Methods for analyzing the thermal and mechanical response of the underground openings are presently being developed and evaluated as a part of ongoing research efforts. No single analytical approach is capable of evaluating the variety of underground conditions and situations that must be evaluated; therfore, multiple approaches are required. Because the repository will include on the order of one-hundred miles of drifts with a range of rock and joint properties, methods that spread out the effects of joints into a continuum representation, such as compliant- or ubiquitous-joint models, are attractive. However, although these methods may provide estimates for locations and magnitudes of joint slip, the interpretation of the results with respect to predicting actual rock falls is not straightforward. Also, the methods tend to overestimate joint slip because they approximate joint sets as parallel and infinite in persistence. The response of individual joints/blocks around the surface of an opening may be predicted using discrete-joint or distinct-element models, but detailed geometries must be specified. These methods may be better suited to analyzing openings after they are excavated.

Many analytical methods are limited in practical application to two-dimensional approximations. Even when the methods are extended to three dimensions, complexities of the models often limit their application. Thus, the treatment of discontinuous ground-support systems, such as rock bolts is severely limited. Finally, criteria are required for interpreting the results of these advanced analytical methods to predict the acceptability or failure of an opening and can only be developed with a large database of experience in suitable rock. However, as long as the limitations of various analytical methods are recognized and confidence in the methods is improved with experimental data, the application of these methods will become an important part of demonstrating compliance with the regulations.

EXPERIMENTAL PROGRAM

Data Needs and Data Users

The site characterization of Yucca Mountain will include an extensive program of thermal-mechanical experiments. The program is designed to satisfy several data needs: 1) information to expand the database for empirical design methods; 2) data for the validation of advanced analytical methods; 3) observations of drift performance for the development of criteria for acceptability or failure; 4) demonstrations of opening behavior for confirmation that openings behave as predicted; and 5) data for the selection of parameter values for the design and analysis of the repository.

In addition to satisfying varied data needs, the results of site characterization will have many different users. The data will directly support repository designers and DOE-sponsored analytical groups. The staff of the NRC will require access to the data for independent calculations. Because the publications from site characterization will be available to the public, representatives of the State of Nevada or special-interest groups may choose to use the data for their own analyses. It is impractical to predict all of the particular types of analyses and evaluations that may use data from the thermal-mechanical characterizations. Therefore, an attempt will be made to collect data of sufficient breadth to support a wide range of analytical methods.

Program Development

The geomechanical site-characterization program was developed based on specific data needs known at the time of development (Blejwas, 1986 and US DOE, 1988). The resulting program includes many different types of experiments to meet the varied data requirements. In addition, the plans for the experiments have undergone modifications so that they may better satisfy multiple purposes and needs that will develop and change. For example, some experiments were originally designed to provide data for validating analytical methods but, by including geometries and other conditions that closely simulate expected repository environments, the experiments will also provide data for evaluating empirical approaches.

Brief descriptions of the experiments are provided in section 8.3.1.15 of the Site Characterization Plan (DOE, 1988). Additional detail is being provided in study plans, which are in varying stages of development. A summary of the present plans is provided in Blejwas, 1989. A general overview of the program is provided here.

Program Overview

The geomechanical experimental program includes eight studies that are described in the following paragraphs. Each study includes a number of experiments that will be conducted in the ESF or laboratories.

The excavation-investigations study includes three experiments in the ESF in which the response of the shafts and drifts due to the excavation process will be measured. The primary use of the data will be the validation of models of the mechanical response of the rock mass around underground openings. As a part of shaft-convergence tests the cross-shaft convergence and displacements in the surrounding rock mass will be measured. Upper and lower demonstration-breakout rooms will be constructed off shaft ES-1 in the lithophysae-rich unit, TSw1, and on the MTL (Fig. 1). As mining proceeds, instruments will be installed to measure post-excavation displacements. A mine-by experiment will start with the excavation of two instrument drifts followed by the mining of a third parallel drift between the two instrument drifts. The total mechanical response of the rock mass due to the excavation process will be measured.

The in situ thermomechanical-properties study consists of four experiments that will provide data for the validation of thermomechanical models of the rock mass. Borehole heater tests in units TSw1 and TSw2 will simulate the environment around individual waste packages. All other experiments in this study will be conducted on the MTL. A heated block experiment will require the cutting of a large block, approximately 6 ft (2 m) on a side, using a chain saw with diamond-tipped cutters. Flatjacks in the slots around the block and heaters outside the block will provide mechanical and thermal loadings. The temperatures, stresses, and displacements of the block will be monitored. A thermal-stress experiment will consist of the heating of the back and rib of a large drift and monitoring the thermal-mechanical response, including the observation of any instabilities. A heated room experiment, which will be started during site characterization and continue past the license application, will include the heating of the rock mass around one or more drifts. Again, the response will be monitored and any instabilities observed.

Two types of tests will be conducted as part of the in situ mechanical-properties study to obtain direct measurements of rock-mass properties. Plate-load tests will be conducted using standard procedures to obtain measurements of the rock-mass modulus of deformation. Other tests to determine measures of the rock-mass strength are presently under investigation. These tests will be conducted at several locations on the MTL, but may also be conducted in the upper demonstration-breakout room.

The in situ design-verification study will include four monitoring activities that will provide data to support design and construction methods and to establish criteria for judging the acceptability of opening performance. Mining activities will be monitored in the shafts and drifts of the ESF. The installation and performance of ground-support systems will be monitored in the drifts on the MTL, particularly in the long exploratory drifts. The stability of all drifts in the ESF will be observed and drift response will be measured at specific locations. Finally, measurements that will be used in the design of the ventilation system for the repository will be made.

Four studies of thermal and mechanical properties are planned to be conducted in laboratories. Sufficient samples from several surface coreholes and the ESF will be tested to obtain statistical representations of properties for each of the penetrated units for which data are required. The data will be used to obtain parameter values for design and analyses of the repository.

Because underground facilities do not exist at Yucca Mountain, preliminary experiments have been conducted in G-Tunnel on the Nevada Test Site (Zimmerman and Finley, 1987). The experiments are providing insight into the behavior of tuffs, evaluations of in situ experimental methods, and experience and procedures for the conduct of future experiments in the ESF. A mine-by experiment in G-Tunnel has demonstrated that large openings can be constructed in highly jointed, welded tuff and remain stable when reinforced with only rock bolts and wire mesh. Data from this experiment and various heater experiments have been compared with data from analyses already performed; the results of the comparisons are promising with respect to validating the analytical models.

CONCLUSIONS

Providing adequate assurance that underground openings in a repository at Yucca Mountain will remain usable requires a complex program of design, analyses, and experiments. The program will evolve as plans are reviewed, new analyses are completed, and early data are obtained. Results obtained to date indicate that stable openings at Yucca Mountain are feasible with existing technology.

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