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Experiments, Conceptual Design, Preliminary Cost Estimates and Schedules for an Underground Research Facility

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September 1981

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High Level Waste Technical Development Branch
Division of Waste Management
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EXPERIMENTS, CONCEPTUAL DESIGN, PRELIMINARY COST ESTIMATES AND SCHEDULES FOR AN UNDERGROUND RESEARCH FACILITY

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ABSTRACT

Plans for an underground research facility are presented, incorporating techniques to assess the hydrological and thermomechanical response of a rock mass to the introduction and long-term isolation of radioactive waste, and to assess the effects of excavation on the hydrologic integrity of a repository and its subsequent backfill, plugging, and sealing. The project is designed to utilize existing mines or civil works for access to experimental areas and is estimated to last 8 years at a total cost for construction and operation of $39.0 million (1981 dollars). Performing the same experiments in an existing underground research facility would reduce the duration to 7-1/2 years and cost $27.7 million as a lower-bound estimate. These preliminary plans and estimates should be revised after specific sites are identified which would accommodate the facility.

1. INTRODUCTION

In the course of developing its regulatory program, and to aid in making licensing decisions, the Nuclear Regulatory Commission (NRC) will sponsor geotechnical research. The research program will form the basis for review of Department of Energy (DOE) repository site investigations, will help determine whether the techniques used by the DOE to assess the hydrological, geomechanical, and geochemical settings of candidate repository sites are realistic and sufficient in their scope, and will investigate new methods to accomplish this assessment. To do this research, one or more experimental facilities may be utilized, taking advantage of access afforded by existing underground openings. In this respect, Task 1 of the Lawrence Berkeley Laboratory's Geotechnical Measurement Verification Support Program identified four primary candidate sites in mines and civil works in granitic rocks within which openings for an experimental facility may be excavated (Wollenberg et al., 1981). Concurrently, Task 2 has developed a recommended experimental research program (Section 3 of this report) and the conceptual design of an underground research facility to accommodate such a program (Section 4).

It is emphasized that this report presents conceptual designs of experiments, preliminary cost estimates, and schedules generally applicable to sites in granitic as well as basaltic and tuffaceous rock. After selection of a final candidate site, these estimates and concepts will be refined for that specific site.

2. BACKGROUND

In situ tests and experiments in underground openings have been conducted since the early 1960s as part of the program for geologic disposal of radioactive wastes. Initial efforts concentrated mainly on salt as the disposal medium; experiments done more recently have emphasized such rocks as granite, basalt, tuff, and shale. A detailed summary of this activity, including test description, objectives, and results presented by Gnirk (1980), has been updated to include recent experiments and is given in Appendix A. The in situ tests include a wide variety of heater experiments with single and multiple arrays at full and reduced scale, block tests, heated room-and-pillar tests, brine-and-water migration experiments, permeability tests, fracture hydrology and groundwater chemistry tests, instrumentation development and testing, and others.

The need for in situ testing can be generalized by one or more of the following objectives:

1. Predictive model validation and/or development.
2. Phenomenological and/or mechanistic investigations.
3. Evaluation and mitigation of the effect of sample size.
4. Determination of material physical properties.
5. Instrumentation development and/or field testing.

It should be emphasized that, in general, in situ tests are not a substitute for careful laboratory investigations, nor are laboratory investigations a substitute for in situ tests. Each test or investigation has specific contributions and specific limitations. Well-designed field experiments are most often a balance of laboratory investigations, predictive modeling, and in situ tests. Typically, for predictive model validation physical

properties determined from laboratory tests are employed in the model, the results of which are then compared with those from the in situ experiment.

Although the list of tests given in Appendix A appears to be extensive, there are major gaps in our knowledge related to the response of the repository environment for which in situ tests are required. These technical concerns have been delineated in Holzer and Ramspott (1979), LBL (1979, 1980), DOE/USGS (1980), and National Academy of Sciences (1980). Wigley et al. (1980) summarized many of the technical questions. Given below are those questions for which in situ tests should provide definitive answers.

1. How do the physical properties of the rock mass change as a function of temperature and stress?
2. How does the rock behave over time as a function of temperature and stress?

To address both these questions requires an extensive program of laboratory investigations and constitutive model development. Large-scale in situ tests, however, will also be required for constitutive model validation and further development. It is not reasonable to assume that laboratory investigation alone will provide the necessary relationships needed for predictive modeling of rock mass response on the scale of the repository or room-and-pillar dimensions. Significant rock mass defects or discontinuities, which cannot be studied in typical laboratory-scale investigations, must be studied in the field. In situ testing for the evaluation of material physical properties and model validation experiments must encompass a large enough volume of rock to include an appropriate number of defects and discontinuities.

3. How does the repository-induced stress field affect the behavior of discontinuities in the rock mass?

4. How does the stress field affect the groundwater flow through the rock mass system?

Again, rock mass systems, including significant discontinuties, must be studied in the field. The experiments should be designed with simple, well-controlled initial/boundary conditions to minimize uncertainty and maximize the information obtained.

5. How does the physical size of the tested sample affect the results of the test?

Material size effects are known to exist. They are partly related to the heterogeneity of the rock mass and other factors that are not fully understood. Sample size has been shown to influence material strength (Pratt et al., 1972) and hydraulic conductivity (Witherspoon et al., 1979). Ultimately, the evaluation and/or mitigation of size effect and its incorporation in predictive models will require large-scale in situ tests.

6. Can a discontinuous rock mass be adequately modeled by a continuum representation?

7. Can numerical models be verified on a generic basis?

Both questions assume some type of model verification. To be convincing, the models must be compared with results from field tests of the appropriate scale and rock type.

In addition to the general questions posed above, the participants in the two workshops on thermomechanical-hydrochemical modeling have provided specific conclusions and recommendations concerning the need for in situ testing (Holzer and Ramspott, 1979; LBL, 1980). A major theme of the 1979 workshop was the importance of size in all aspects of in situ testing and model validation: "Validation experiments must be large enough to include all types of the significant rock mass defects" (p. 3). "The relevant

fractures may range from grain to repository size and are site specific. Because rock samples in question could be several meters, the experiments will be large" (p. 19). The importance of in situ tests for predictive model validation was also clearly stated: "We have the responsibility of carrying out the most convincing short-term validation experiments we can devise" (p. 32).

Conclusions and recommendations from the 1980 workshop reconfirmed the importance of in situ testing: "In situ experiments and tests are required to understand the phenomena and mechanisms acting in rock masses under thermal loading, provide thermomechanical and hydrologic data for code verification, aid in repository design, and assist in instrumentation development and evaluation" (p. 2). Furthermore, the specific types of in situ tests needed for model validation and to aid in repository design were delineated: "Combined hydrologic/thermomechanical tests are the next logical sequence in the evolution of in situ testing. These need to be (of) a meaningful scale. The design of new and different tests of this type are a high priority task" (p. 111).

Combined or coupled hydro/thermomechanical field tests, of the type suggested above and representative of the repository environment, have not yet been carried out. Several preliminary studies, however, have been made. Two tests were performed in hard rock at the Climax Stock and G-Tunnel, Nevada Test Site (NTS). The experiments were located above the groundwater table in the partially saturated regime, influenced a relatively small volume of rock, and were affected by relatively complex initial/boundary conditions. The complex boundary conditions, which limit the usefulness of the results for predictive model validation and development, were caused largely by the proximity of the underground openings to the test area.

Future in situ tests designed to investigate the hydro/thermomechanical response of a rock mass should:

1. be located near repository depth so that the stress field is similar to the repository environment;
2. be positioned well below the groundwater table;
3. influence a relatively large volume of rock, including significant discontinuities and defects;
4. employ simple initial/boundary conditions;
5. be located within an undisturbed region away from extraneous openings or undesirable perturbations.

The objectives of the experiments should include:

1. model validation and development to confirm and improve predictive capabilities;
2. assessment of large-scale rock mass physical properties and comparison with laboratory results to aid in repository design;
3. investigation of the response of the rock to controlled excavation and thermally induced perturbations, both to improve our understanding of the rock mass behavior and to aid in confirming the rock mass integrity.

Another important area of investigation which requires field tests but which has received little attention is excavation damage and repository sealing, plugging, and backfill. At present, the only field test that has been performed to assess excavation damage is the one done at the Colorado School of Mines' Experimental Mine (see Appendix A). This test was limited in scope and performed above the groundwater table in a relatively low in situ stress field. Furthermore, the initial or baseline conditions were not well established.

A buffer mass test is underway at the Stripa Mine to evaluate the thermomechanical/hydrological response of a sand/bentonite backfill material; it is the first field test of its kind (see Appendix A). Tests to evaluate full-scale seals for shafts or connecting tunnels have not as yet been carried out, but are planned for the underground research laboratory proposed by the Canadian Atomic Energy Commission.

3. EXPERIMENTAL PROGRAM

The purpose of the experimental program presented here is to gain an adequate understanding of the response of a rock mass to the construction of a repository and to the introduction and long-term storage of radioactive waste. It is necessary that NRC have this understanding to assess information provided by the DOE in the course of repository site investigations and to evaluate the reliability of methods employed in the investigations. This includes verification of predictive models and of methods for monitoring the repository response.

As previously described, there are two major geotechnical areas requiring investigation:

1. Hydro/thermomechanical rock mass response.
2. Excavation damage, plugging, sealing and backfill.

The first topic includes investigations to measure, predict, and monitor the coupled effects of the mechanical, hydrological, and geochemical response of the rock mass. The second involves investigations to (1) measure the hydrologic integrity of the rock immediately surrounding the underground openings, (2) minimize excavation damage, and (3) provide an adequate seal and backfill for all excavated openings within the repository.

Experiments described here are preliminary, designed to meet the purpose of an experimental program as well as to address important areas in which our knowledge is limited. Thus it is also the purpose of the experiments to provide substantial new information, beyond that already obtained from similar experimental facilities or in situ tests. The remainder of this section discusses specific objectives, approach, program and test procedure, advantages and limitations, and schedule and cost estimates.

The two experiments described in this section, although broad in scope, do not specifically address all the questions and objectives of in situ experiments discussed in Section 2. These experiments were designed to consider as many aspects as practicable, and the objectives are clearly stated. For example, the hydro/thermomechanical experiment is not a specific investigation of material size effect; however, the effect of size is taken into account by the relatively large scale of the test. A comparison of physical properties determined from laboratory tests and those calculated from the measured response of the rock mass in situ will provide useful information on material size effect.

In a fundamental investigation of the type described here, it is important to make every effort to separate the influence of inadequate material properties identification, predictive model deficiencies, and measurement or other experimental errors when comparing predicted and measured response. Accordingly, a well-designed experimental program should be of sufficient scope to address these concerns adequately, and must, of necessity, be a multidisciplinary effort.

It is likely that as the project progresses, additions to these experiments and/or new experiments will be proposed by groups conducting research in radioactive waste isolation. An example is the application of the hydro/thermomechanical and backfill experiments (described in Sections 3.1 and 3.2) to the development of underground hydrological tracer techniques. Another example is the use of the facility for investigation of electrical and acoustical geophysical techniques to characterize a site, incorporating surface, borehole, and underground sources and receivers. With these considerations in mind, the layout of the research facility (described in Section 4) is designed to accommodate additional experiments.

3.1 HYDRO/THERMOMECHANICAL EXPERIMENT

3.1.1 Objectives

Listed below are the primary objectives and design considerations of the hydro/thermomechanical experiment:

1. Perform a carefully controlled series of in situ tests simulating the thermal loading of a nuclear waste repository environment.
2. Influence a relatively large volume of rock to mitigate the effect of scale or size.
3. Monitor the extent and magnitude of the heat- and excavation-induced perturbations on the hydrological, mechanical, and geochemical properties of a rock mass.
4. Compare measured response with theoretical predictions of coupled hydro/thermomechanical models.
5. Employ the experimental results for needed model development.
6. Determine rock mass physical properties for repository design.
7. Develop and test required instrumentation and installation procedures for monitoring the rock mass response.

It is the purpose of the experiment to provide a comprehensive data base for predictive model verification and model development as well as to provide fundamental information on the response of a rock mass to excavation, heating, and cooling, including the evaluation of physical properties. The experiment is designed to consider the geologic environment -- that is, the hydrologic setting, geochemistry, and thermomechanical behavior of the rock as a coupled system. The ability to model accurately the measured response of the rock to perturbations caused by this experiment would be a significant

contribution to the ability to model an operational repository. The experiment provides for the necessary synthesis of rock mass physical property data, constitutive models, and numerical codes required for use in repository design.

3.1.2 Approach

The initial activities will consist of a detailed assessment of the geologic and hydrologic settings of the experimental facility site and its environs. Prior to the excavation of a 3 to 6 ft (1 to 2 m) diameter cylindrical test chamber, a large number of horizontal and inclined holes will be core drilled in the rock surrounding the future excavation (Figure 1). Instruments will be installed in the holes to monitor temperature, water pressure, changes in rock stress and strain from measurements of deformation, and to conduct tracer tests, fluid injection/withdrawal tests, and geophysical experiments. All drill holes will be sealed with packers to prevent drainage from the system.

The initial stage of monitoring and testing will provide background data on the initial conditions of the rock mass or baseline information. These data are most important for the accurate interpretation of measured changes caused by excavation- and heat-induced perturbations. After the baseline is established, the 100 to 150 ft (30 to 45 m) long cylindrical test chamber will be carefully excavated, the response of the surrounding rock mass to excavation recorded, and the system allowed to equilibrate prior to the next phase of experiments.

After installing a liner and placing bulkhead and monitoring devices in radial drill holes, the test chamber will be completely filled with formation water at ambient temperature and low pressure. Use of formation water--i.e.,

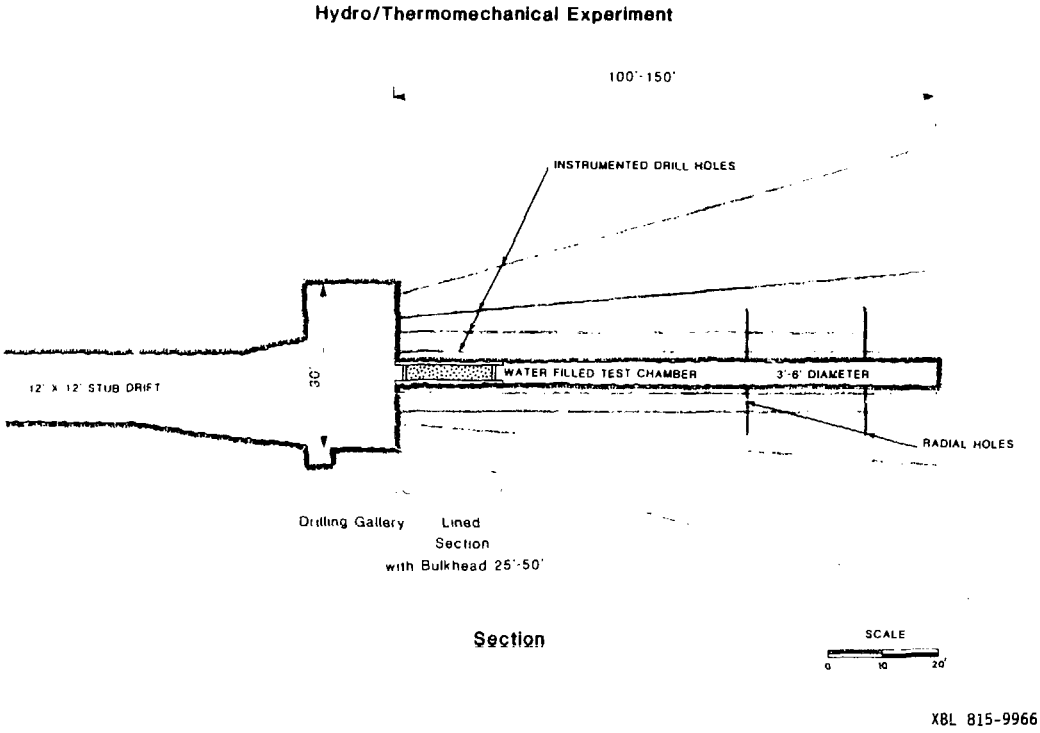


Figure 1. Longitudinal section of the excavation and drill holes for the hydro/thermomechanical experiment.

water with chemistry similar to that of the natural groundwater--eliminates the geochemical and hydrological complications associated with an air-water interface at the chamber wall. Monitoring the water flow from the test chamber at constant pressure and monitoring the pressure field within the surrounding rock will provide a measure of the rock mass permeability. (Because the water pressure within the test chamber is less than the hydrostatic pressure of the surrounding rock mass, groundwater will flow into the chamber.)

On establishing the permeability of the rock mass surrounding the test chamber, the influence of heating a relatively large volume of rock will be investigated by increasing the temperature of the water within the chamber. Water is an excellent medium for transferring heat uniformly to the wall rock, and provides a well-defined boundary condition. The chamber temperature will be limited to less than 100°C to prevent flashing at ambient pressure. The changes in the rock mass permeability, the pressure field, the temperature field, as well as other mechanical and geochemical parameters will be monitored over a period of approximately one year. At the end of the period, the water flow from the test chamber will be shut off and the pressure allowed to increase. The re-establishment of pressure equilibrium within the hydrologic system of the rock mass and the possible development of convection currents in that hydrologic system will be studied under these conditions.

The final phase of the experiment includes cooling the test chamber water to the initial ambient temperature and reducing the chamber pressure. Again, the permeability of the rock mass will be assessed to determine if the cycle of heating and cooling has permanently altered the hydraulic properties of the surrounding rock. The influence on the geochemical and mechanical properties will also be examined.

3.1.3 Program and Test Procedure

The various stages of the hydro/thermomechanical experimental program are:

A. Design and fabrication.

B. Baseline studies.

C. Chamber excavation.

D. Test chamber experiments.

E. Data analysis and modeling.

A. Design and fabrication. This stage of the program includes a detailed analysis of the experimental design by personnel from all disciplines concerned. The entire experiment will be modeled in sufficient detail to predict the hydro/thermomechanical response of the rock mass, to optimize the number and position of the monitoring instruments, to determine the final geometry of the test chamber, and to evaluate the appropriate duration for each phase of the experiment. The specific types of tests to be carried out, the test procedure, and the priority of each test will then be ascertained.

Selection of proven instrumentation and development of instrumentation will require a concentrated effort. It is anticipated that extensometers, stress meters, and other transducers will require considerable development in order to perform adequately under water pressures of 400 to 800 psi for several years. The experimental design should include, whenever possible, the capability of replacing or repairing all instrumentation without perturbing the experiment. Furthermore, a degree of redundancy should be designed into the monitoring system.

Preliminary activities will include construction of the drilling gallery and drill platform; fabrication of the test chamber liner and bulkhead, the

mechanical plant for controlling the chamber water temperature, and the holding tank for the water; procurement of a data-acquisition system, the required tracer-detection instruments, and other necessary supplies and equipment. Preliminary geologic investigations, including fracture mapping of the drilling gallery, drilling and logging test holes, hydrologic tests, and material property tests, will be initiated to assist in the design of the experiment.

For use in preparing this report, preliminary modeling of the experiment has been carried out. Results are given in Appendix B; the major findings are summarized, where appropriate, in the discussion of stage D (test chamber experiments).

B. Baseline studies. This stage involves identification of the ambient conditions within the experimental area prior to excavation of the test chamber. It includes drilling and logging the horizontal and inclined monitoring holes, installing and testing the downhole instruments, sealing the instrument holes, and re-establishing steady-state conditions prior to chamber excavation. Preliminary calculations (Appendix B) indicate that the drill holes farthest from the test chamber should be inclined to reach at least 65 ft (20 m) beyond the chamber wall at mid-plane (Figure 1).

Specific tests and techniques used to evaluate the hydrological, geochemical, and mechanical baseline conditions include: overcoring for absolute stress measurement, stress meters and extensometers for detecting relative changes in the stress-strain field, fluid injection/withdrawal tests for measuring hydraulic conductivity, fracture mapping, borehole television and geophysical logging, acoustic emission for fracturing, cross-borehole pressure pulsing and tracer testing for porosity and velocity

assessment, tracer testing for radionuclide retardation, groundwater chemistry analyses, determining mineralogy of rock and joint-filling material, identifying thermal and water-pressure fields, and laboratory testing for thermomechanical rock properties.

C. Chamber excavation. Excavation of the test chamber is to begin after the baseline has been satisfactorily established. Changes from the base conditions will be continuously monitored during and after excavation, until steady state is re-established. Of particular interest during this phase of the experiment are changes in the pressure field, stress-strain field, and hydraulic conductivity within the rock nearest the opening; such changes could indicate the formation of a damage zone. To minimize the thickness of this zone, controlled blasting techniques will be utilized in the excavation of the test chamber or, if economically reasonable, the opening will be excavated by machine.

In preparation for the main series of experiments and filling of the chamber with water, a number of holes are to be drilled radially from within the chamber for multiple-position extensometers and stress meters. Additional extensometers are to be employed to monitor changes in the diameter of the opening. The section of the chamber nearest the drilling gallery will be lined with steel and firmly grouted in place. The bulkhead, feedthroughs, and heating/cooling system will then be installed and the chamber filled with formation water at ambient temperature.

During phase (c) of the experiment, when the pressure within the test chamber is allowed to increase, the groundwater will flow toward the drilling gallery. To minimize this flow, the liner in the section between the chamber and gallery will be pressure grouted in place after its installation.

The designed length of the lined section should be based on hydraulic calculations, adjusted for site-specific conditions. Furthermore, the excavations for the experiment should be properly oriented with respect to the rock mass discontinuities to minimize fracture continuity between the test chamber and drilling gallery. Grouting of unfavorably oriented joints may be required. The redirection of some flow toward the drilling gallery on chamber pressurization is of minor consequence, provided that the region between the chamber and the gallery is adequately instrumented to monitor the changes in the hydro/thermomechanical regime. A simple system for collecting and monitoring the water flow into the drilling gallery will be necessary.

If the drilling of radial holes and the installation of instrumentation from within the test chamber are found to be impractical, it would be possible to install a second drilling gallery to the side of the chamber. From this location instrument holes would be drilled in the plane perpendicular to the chamber axis. Besides the added expense, the second gallery would inevitably result in disturbance and is therefore considered less desirable than the scheme employing radial holes.

D. Test chamber experiments. The test chamber experiments consist of the following four experimental phases:

Phase (a) P = several atmos., T = ambient, Q = measured;

(b) P = several atmos., T ≈ 100°C, Q = measured;

(c) P = measured, T ≈ 100°C, Q = 0;

(d) P = reduced, T = ambient, Q = measured;

where P = test chamber pressure, T = temperature, and Q = flow. The first phase identifies the new baseline conditions after excavating the test

chamber and filling it with water. The remaining three phases include heating and the concurrent measurement of water flow from the chamber, continued heating without flow, and cooldown. Major parameters to be monitored throughout the experiment include temperature, hydraulic conductivity, porosity, groundwater chemistry, rock stress-strain, and sonic/EM wave attenuation. The type of test will determine whether monitoring will be continuous or periodic.

Instrumentation and heating/cooling equipment installed within the test chamber--that which is not readily repaired or replaced--should be designed to survive at least through the first three experimental phases, or about two years. Prior to the cooldown phase, it should be possible to renew some of the instrumentation if required.

Preliminary modeling of the thermal field (Appendix B, Section B.1) shows that on employing a reasonable power input of 2 kW per linear meter of chamber for a 2 m diameter opening, the chamber water and wall rock are raised from 10°C to the maximum design temperature of 100°C in 19 days. Beyond this time, the power input is reduced to maintain the 100°C chamber temperature. Radial distributions of temperature at various times reveal after 500 days of testing that a large volume of rock will have been influenced and that the rate at which additional rock is influenced by continued heating significantly decreases from that indicated for the first 500 days. Consequently, it is believed that 1-1/2 years of heating--experimental phases (b) and (c)--will meet the objectives of the test.

The duration of the cooldown test, phase (d), should be at least as long as the period of heating to return the rock surrounding the chamber to as close to the initial ambient temperature as possible. Since it may be possible to speed the cooling process, the effects of refrigeration were

compared with the results of heater turn-off and natural cooling by convection (Appendix B, Section B.2). After heater turn-off, the temperature returns to within 16°C of ambient after 500 days of cooling. Refrigeration returns the chamber water to within 7°C of ambient temperature after 500 days at a power output equivalent to the heat power input, 2 kW per linear meter of chamber.

There is, however, a disadvantage to refrigeration. As illustrated by the radial stress distribution expected on heating (Figures B.11 to B.13, Appendix B) and cooling with and without refrigeration (Figures B.22 to B.27, Appendix B), the loading and unloading paths are not the same when refrigeration is used. This is generally undesirable and complicates any assessment of permanent changes in physical properties associated with one cycle of rock mass heating and cooling. It may, however, be possible to use some refrigeration to speed cooldown, but with less power output. This needs further investigation and should be carried out as a part of the experiment design.

On completion of the cooldown phase, the chamber will be emptied of water. Samples of the rock wall and rock joints will be obtained and analyzed for chemical and mineralogical changes. When possible, the instrumentation will be removed, recalibrated, and evaluated for performance.

One of the major advantages of the hydro/thermomechanical experiment is the relatively large volume of rock influenced by heating and cooling, but these processes require considerable amounts of time to be effective. One method by which to decrease the time needed, yet still influence a significant volume of rock, is by increasing the surface area of the test chamber wall or diameter of the opening. However, this also has the disadvantage of increasing the complexity and expense of the test chamber. At this point in

the investigation, a 3 to 6 ft (1 to 2 m) diameter chamber appears to be appropriate. The site-specific character of the rock mass, in particular the joint spacing, will influence the diameter selected (and hence, the representative volume of rock to be tested) as well as other factors, such as the orientation of the chamber.

The test chamber should be oriented with respect to the rock mass discontinuities to investigate specific features. As an example, joints oriented perpendicular to the axis will be largely affected by the heat-induced perturbations and to a lesser extent the influence of excavation (assuming a plane strain condition). At the end of the heating period, the normal stress across these joints will range between 60 MPa at the chamber wall and 30 MPa at a depth of more than 3 m (Figure B.12, Appendix B). Although the stress field is not uniform, the measured thermomechanical response of the rock mass will provide needed information on the physical properties of these joints for a large-scale sample.

E. Data analysis and modeling. This stage of the program involves a concentrated effort both in the initial verification of predictive models and in the subsequent development of the required model. At the early stage of the program, before experimental results are available, appropriate models will be selected and employed to predict the theoretical response of the rock mass to the induced perturbations resulting from excavation and from each experimental phase. State-of-the-art models will be used to predict the hydrological, thermomechanical, and geochemical responses. Models will include some that are similar to the one employed for the preliminary calculations presented in Appendix B, coupled hydromechanical and hydro/thermomechanical models such as those summarized by Tsang (1980), and more

sophisticated three-dimensional models developed specifically for analysis of the experiment.

After the experimental results are obtained and analyzed, the predicted and measured responses will be carefully compared. Identification and evaluation of the discrepancies, which will inevitably occur, will provide guidance for model development and improved identification of material properties. As a major emphasis of this experimental program, it is most important that deficiencies in our understanding of the mechanical and hydrological phenomena be recognized and that appropriate steps be taken to rectify any problems.

3.1.4 Advantages and Limitations

The proposed hydro/thermomechanical experiment is not designed to model the perturbations of one heater, an array or room of heaters, or the repository proper. It is intended to be a very carefully controlled test in which the initial/boundary conditions are selected to provide the maximum information on the response of a rock mass to repository construction, operation, and decommission. The test simulates the thermal loading of a nuclear waste repository environment and its influence on a relatively large volume of rock. Test chamber experiments, phases (a) and (b), are related to the excavation- and heat-induced perturbations anticipated during construction and operation. Phases (c) and (d) are related to changes anticipated on decommission.

This experiment is not a substitute for full-scale single- or multiple-array heater tests, which are important for evaluation of the very-near-field response and specific details such as the behavior of the canister overpack. Simple heater tests, however, are not the most appropriate method by which

to evaluate heat and excavation-induced perturbations on the hydrological, mechanical, and geochemical properties of a rock mass, particularly for regions beyond the very near field (e.g., room-and-pillar or repository scale).

For the general investigation of rock mass response, typical heater tests, in which one or more heaters are placed in the floor of an open drift, have several limitations which the hydro/thermomechanical experiment is designed to minimize. For example, in conventional heater tests, the drift in which the heaters are installed has a large influence on the test results. Basically, it acts as a large sink or drain for groundwater. This makes it difficult to study accurately the effect of heat on the hydrology when the largest perturbation to the groundwater regime is the open drift itself. For the same reason, it is also difficult to study aspects related to decommission of the repository after backfill and sealing, such as the re-establishment of the natural groundwater flow paths with continued heating of the rock mass and eventual cooling.

Boundary conditions at the heater/borehole interface are not always well defined or easy to control. The borehole may be allowed to fill with water at ambient pressure, it may be sealed, or it may be filled with an overpack material. Convection can occur within the borehole if left open. Geochemical changes, such as mineral solution or dissolution along fracture surfaces, are difficult to observe and monitor, as is the degree of saturation of the rock mass (particularly if evaporation is occurring within the heater drift).

Use of multiple heaters in an array often results in a complex three-dimensional temperature field which complicates the analysis of coupled phenomena. By employing a large test chamber, a large volume of rock is

influenced by the heated water in a relatively uniform manner. The volume of rock significantly influenced after 500 days of testing (i.e., temperature change in excess of 40°C and stress change in excess of 28 MPa) is approximately 1670 m^3 for a 2 m diameter chamber 30 m long. This is at least 50 times the volume of rock influenced by the Stripa heater experiment (see Table B.3, Appendix B). A temperature rise of 2°C, which is the lower limit of practical measurement with reasonable accuracy, influences a volume of 43,500 m^3.

Besides the importance of influencing a large volume of rock to mitigate size effects, the relatively large scale of the hydro/thermomechanical experiment improves the ability to monitor the rock mass response in detail. Because of the large scale, the temperature, stress, and pressure gradients extend over a greater distance, making them easier to monitor. Complicated tests, carried out on a small scale, can be adversely influenced by the instrumentation if the density is excessive and precautions are not taken to minimize disturbance. In general, the smaller the test region, the greater are these problems.

The experiment is basically limited to a maximum 100°C temperature, unless the risks and design complications associated with flashing at high temperatures and pressure are accepted. It appears, however, that the capabilities of this test system would not be severely restricted by the 100°C temperature limit, especially in view of the lower power levels and maximum rock temperatures under consideration for repository design. The lower temperature does have an adverse effect on the ability to study convection as opposed to conduction. If convection is believed to be of major importance, the test chamber could be located within a rock mass of higher permeability, thus accentuating the response.

The usefulness of this experiment in evaluation and determination of material physical properties is most important. Despite the inhomogeneous stress and displacement fields induced within the rock surrounding the test chamber, the well-controlled boundary conditions and detailed monitoring system allow for the investigation of physical properties. Naturally, the range of variables, such as temperature, stress, and displacement, are restricted and controlled by the various phases of the test. Within the context of these limitations and assuming possible dependence of certain material properties, it is still possible to obtain significant, basic material property information, especially related to size effect.

The difficulties outlined above are not unique to the hydro/thermomechanical experiment. Large-scale block tests, designed mainly for physical property determination, also have significant limitations. In particular, the unconfined free surface complicates hydrologic testing and limits the evaluation of material properties to the case in which the minor principal stress is always zero. Furthermore, it is difficult to uniformly heat and cool the rock block, and the range of applied stresses and measured displacements is relatively small.

In summary, it is emphasized that the hydro/thermomechanical experiment is intended to provide fundamental information on coupled phenomena and mechanisms basic to the overall response of the repository. This information will be employed for predictive model validation, required model development, and evaluation of material physical properties. After validation, the models will be used for repository design. This experiment is not a substitute for more specific tests, such as the full-scale heater test, needed to evaluate the very-near-field response.

3.1.5 Site-Specific Considerations

Results of the thermoelasticity calculations given in Appendix B are based on material physical properties typical for granitic and other crystalline rocks. A rough comparison between these properties and those for Columbia Plateau Basalts and welded tuff from the Nevada Test Site is presented in Table B.4, Appendix B.

Because of the lower thermal conductivity of basalt and tuff and the higher specific heat of basalt as compared with the properties of granitic rock employed for the thermoelasticity calculations, the temperature at a specific point and time within the rock surrounding the test chamber will be less than that indicated by the results given in Figures B.3 and B.4 (Appendix B). Consequently, the absolute volume of rock influenced by heating for a fixed period of time will be less than that indicated in Section 3.1.4. This, however, does not change the conclusions with respect to the relative volume of rock affected by a single or multiple array of heaters as compared with the water-filled test chamber. After a specific site has been selected, it is a simple matter to recalculate the temperature, stress, and displacement fields for the appropriate material properties, rather than attempt to scale the results given in Appendix B.

More influential than the intact rock properties, the character of the rock mass discontinuities will have a significant effect on the diameter, length, and orientation of the test chamber. As previously described, the chamber axis should, if possible, be oriented perpendicular to one major joint set. A granitic rock mass typically has an orthogonal system of joints with a spacing on the order of meters. The joints can be tight, rough and clean, coated with chlorite, or healed with quartz, feldspar, epidote, calcite, etc. The entablature zone of a basalt flow has a highly variable

pattern of jointing. Spacing is on the order of decimeters to meters, and coatings of clay minerals and zeolite are common. Welded tuffs are generally laminar, with one major joint set parallel to the depositional surface (sub-horizontal unless folded or faulted) and two or more sets normal to this surface. Average spacing is on the order of meters. Coatings can include clay and zeolite, although clean, tight, or slightly open joints are common.

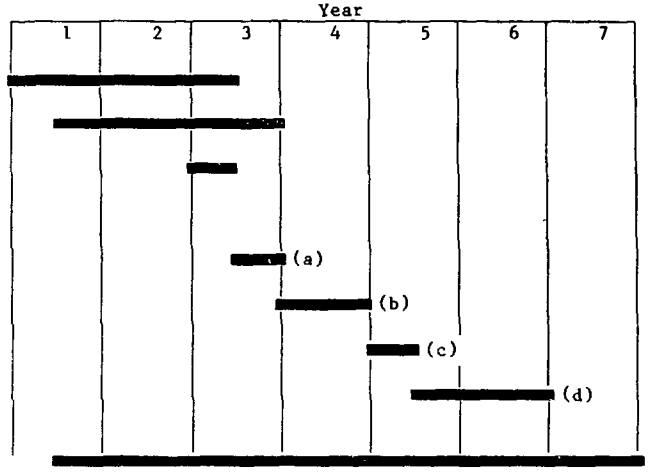
At this preliminary phase of the investigation, no specific property of the intact granite, basalt, or tuff or specific character of their discontinuities has been identified which would preclude implementation or significantly modify the conceptual design of the hydro/thermomechanical experiment as presented.

3.1.6 Schedule and Cost Estimates

As previously described, the experiment is necessarily time consuming because of the relatively large volume of rock influenced. As illustrated in Table 1, the time required for the various phases of the test chamber experiments is estimated to range from 6 months to 1-1/2 years. Design and fabrication and baseline studies will require up to 2 years before test chamber excavation can proceed. This time is mainly needed for detailed experiment design and instrumentation development, testing, and installation. Data analysis and modeling is a nearly continuous process extending approximately one year beyond the end of the last experimental phase. Reports covering the results of each phase of the experiment will be written as the experiment progresses.

An estimate of the technical and scientific personnel required for this program is also given in Table 1. Instrumentation is emphasized in the early

Table 1. Schedule and personnel for the hydro/thermomechanical experiment.



Stage	Year 1	2	3	4	5	6	7
1. Design and Fabrication							
2. Baseline Studies							
3. Chamber Excavation							
4. Test Chamber Experiment							
Phase (a)							
Phase (b)							
Phase (c)							
Phase (d)							
5. Data Analysis and Modeling							
Personnel							
PI, Manager	2	2	2	2	2	2	2
Instrumentation	4	4	4	2	1	1	1
Rock Mechanics	2	2	2	1	1	1	1
Hydrology/Geology	2	2	2	1	1	1	1
Geochemistry	1	1	1	1	1	1	1
Modeling	2	4	4	4	4	4	4
Totals (FTE)	13	15	15	11	10	10	10

part of the program, and modeling is emphasized throughout the course of the program.

An estimate of the total cost of the hydro/thermomechanical experiment is provided in Table 2, the details of which are given in Appendix C, Section C.1. The major cost items are divided among construction and fabrication, operating equipment and services, and personnel. The distribution of these costs on a yearly basis is given in Table 3. It should be emphasized that the costs presented in this preliminary appraisal are only rough estimates.

Table 2. Total cost estimate for the hydro/thermomechanical experiment (thousands of 1981 dollars).[a]

1.	Construction and Fabrication		$ 1,713
	(a) drilling gallery	($390)	
	(b) monitoring drill holes	($447)	
	(c) test chamber	($319)	
	(d) liner and bulkhead	($557)	
2.	Operating Equipment and Services		$ 6,743
	(a) instrumentation	($1179)	
	(b) data acquisition system	($360)	
	(c) mechanical plant (heating/cooling)	($75)	
	(d) travel and per diem	($1649)	
	(e) computer costs	($1800)	
	(f) consultants	($735)	
	(g) miscellaneous	($945)	
3.	Personnel		$ 6,741
		Total	$15,197

[a]Details in Appendix C, Section C.1.

Table 3. Distributed cost estimate for the hydro/thermomechanical experiment (thousands of 1981 dollars).

Category	Year 1	2	3	4	5	6	7
1. Construction and Fabrication	837	876	0	0	0	0	0
2. Operating Equipment and Services	1133	1530	1020	840	840	690	690
3. Personnel	1034	1198	1198	884	809	809	809
Totals	3004	3604	2218	1724	1649	1499	1499

3.2 EXCAVATION DAMAGE/SEALING EXPERIMENT

3.2.1 Objectives

Listed below are the primary objectives of the excavation damage/sealing experiment:

1. Assess the extent of excavation-induced damage to the virgin rock mass for various methods of tunnel excavation.
2. Determine the effectiveness of sealing and grouting materials and the influence of method of placement and excavation on the ability to seal tunnels and/or shafts for long-term containment of radioactive waste.
3. Develop monitoring systems for assessing the performance of the tunnel seal.

As in the proposed hydro/thermomechanical experiment, the excavation damage/sealing experiment is designed to consider the hydrology, geochemistry, and mechanical response of the rock as coupled phenomena. Although the purpose of this experiment is not specifically for predictive model verification or development, models will be used for experiment design and to aid in the interpretation of the results. Because of the influence of several factors which are difficult to quantify, such as method of excavation and placement of sealing materials, it is not possible to model accurately the complete sealing/backfill/grouting system. The evaluation of the effectiveness of these systems can be achieved with the aid of carefully performed field and laboratory experiments in conjunction with a detailed monitoring program.

The detail provided on the design of this experiment is less than that provided for the hydro/thermomechanical experiment, particularly with

respect to preliminary predictive modeling of results and site-specific considerations. This is due largely to the lack of general and site-specific information on this important topic. Considerable research is presently underway, the results of which may have a significant influence on the final design of an excavation damage/sealing experiment. The general concepts presented here, however, should be applicable to any underground openings or repository sites in rock currently under investigation.

3.2.2 Approach

Tests and excavations for the excavation damage experiment are essentially separate from those of the sealing experiment, as indicated in Figure 2. The drift excavated for the damage experiment is, however, required for access in the sealing tests. Consequently, the damage experiment must be carried out first.

Prior to excavation, a number of horizontal monitoring holes, on the order of 100 ft long, will be drilled from the main access drift parallel to the future excavation for the damage experiment and perpendicular to the seal test area. These monitoring holes will be used to establish baseline conditions, as in the case of the hydro/thermomechanical experiment. Instruments for monitoring water pressure, acoustic emissions, changes in rock stress and strain from measurements of deformation, and for conducting tracer tests, fluid injection/withdrawal tests, and geophysical experiments are to be installed in the holes.

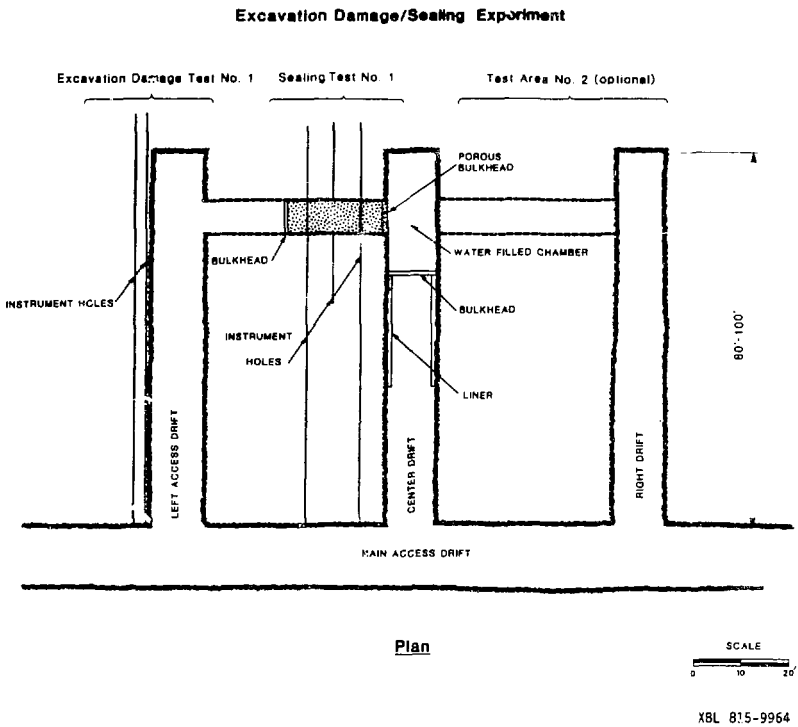


Figure 2. Plan of the openings and drill holes for the excavation damage/sealing experiments.

After the baseline conditions are established, the left access drift will be excavated. One or more methods of excavation can be employed to evaluate the influence of various mining techniques on the formation of a damage zone around the opening. Drill hole instrumentation will record the response of the surrounding rock to excavation. Particular attention should be given to changes in hydraulic conductivity and porosity resulting from the opening and closing of discontinuities and the formation of new fractures. Changes in rock stress are also important to the interpretation of the resulting hydrological conditions.

At the same time the excavation damage experiment is being carried out, the center drift for the sealing test can be excavated. Once completed, a 25 to 50 ft length of the drift is to be lined and grouted and a bulkhead installed as shown in Figure 2. The resulting chamber will be filled with formation water at ambient temperature, pressurized, and the flow measured to determine, from pore pressure measurements, the hydraulic conductivity of the rock mass within the test area.

After the geomechanical and hydrologic conditions are established, the crosscut between the left and center drifts will be excavated. As in the excavation damage experiment, the influence of the excavation on the baseline conditions will be recorded. A porous bulkhead is to be installed at the intersection of the crosscut and center drift, the seal material placed possibly in conjunction with other grouting techniques, and a second bulkhead installed to confine the plug material. During these operations, additional instruments will be placed within the seal material, at the seal/rock interface, and installed in radial drill holes from the crosscut. The instruments will monitor changes in stress and pore pressures due to swelling of the material as it resaturates. It may also be necessary to

install a water-injection and/or vacuum system within the plug to speed the rate of saturation in order to perform the experiment within a reasonable time.

During and after placement of the seal, the monitoring systems will record the readjustment of the natural flow paths in the rock mass and the restoration of the pressure field observed before excavation of the crosscut. After steady-state conditions are established, the chamber will again be filled with water and pressurized, following the same procedure as in the first test to obtain the baseline. The chamber pressure should be greater than hydrostatic pressure to establish a gradient parallel to the crosscut, coincident with possible fractures parallel to the opening wall and the plug/wall-rock interface. Differences between the first and second pressurization or injection tests will be used to evaluate the effectiveness of the sealing/grouting system.

Two optional tests can be performed, depending on the need to carry out additional tests of excavation techniques or backfill/sealing materials and the influence of heat on the sealing system. Test Area No. 2 (Figure 2) is available for additional excavation damage/sealing experiments; however, the second test must be carried out after the completion of the first sealing experiment, by which time the same chamber can be used for water injection. If the sealant materials or damage zone are believed to be adversely affected by heat-induced perturbations, this can be tested by heating the water within the pressurized chamber using the same procedures and equipment employed for the hydro/thermomechanical experiment.

3.2.3 Program and Test Procedure

The various stages of the excavation damage/sealing experiment program are given below:

A. Design and fabrication.

B. Baseline studies.

C. Excavation damage experiment.

D. Chamber excavation.

E. Sealing experiment.

F. Data analysis and modeling

A. Design and fabrication. Design of the experiment is intended to proceed in a manner similar to that described for the hydro/thermomechanical experiment. Prior to the experiment, it will be necessary to construct some models to define the range of the measured parameters and to refine the geometry of the experiment. It will also be necessary to develop the appropriate instrumentation. Many of the predictive modeling and instrumentation requirements are common to both experiments. Consequently, the level of effort required at the design stage is somewhat reduced if the hydro/thermomechanical experiment precedes this experiment, or vice versa. If both experiments are performed concurrently, the effort is shared.

The methods of excavation to be studied have yet to be selected, as is the case for backfill/sealing/grouting materials. Before these materials are selected for testing, their performance should be documented by extensive laboratory studies. Although laboratory testing will be carried out as required in the program, it is assumed that most of the background information will have been acquired in other investigations. The same applies for the development of techniques for installation of the seal.

Other activities include fabrication of the liner for the center drift pressurization chamber, the bulkheads, and the holding tank for the chamber water; and acquisition of the mechanical plant for controlling the chamber water pressure and the needed instruments and backup systems. The liner and bulkheads should be of the same design as used for the test chamber in the hydro/thermomechanical experiment.

B. Baseline studies. Prior to excavation, the baseline conditions within the test area will be established with the aid of several instrumented horizontal drill holes. Tests will be made to evaluate the hydrological, geochemical, and mechanical conditions of the rock mass. For the excavation damage experiment, the undisturbed hydraulic conductivity and porosity are essential. In general, the specific tests to be carrried out are much the same as those for the baseline studies of the hydro/thermomechanical experiment. Again, some of this information is applicable to both experiments and need not be repeated.

C. Excavation damage experiment. Employing one or more excavation methods or techniques, the left access drift (Figure 2) will be driven parallel to the previously installed monitoring holes. The response of the rock mass surrounding the opening is recorded simultaneously with excavation. After completion of excavation, additional testing and sampling of the wall rock can be carried out from within the drift. The end of the access drift will also be used as a gallery from which horizontal holes will be drilled parallel to the future seal-test crosscut to establish baseline conditions for this experiment.

With a slight change in schedule, it would be possible to use the center drift for additional baseline instrumentation. Holes oriented perpendicular to the axis of the access drift would be particularly useful for monitoring deformations resulting from excavation.

D. Chamber excavation. Excavation of the center drift for the construction of the pressurization chamber can proceed as soon as the baseline conditions within the plug test area are obtained. The procedures for excavation and installation of the liner and bulkhead are essentially the same as those for the test chamber of the hydro/thermomechanical experiment. When completed, the chamber will be filled with formation water at ambient temperature in preparation for testing.

E. Sealing experiment. This consists of the following phases:

Phase (a) chamber pressurization; P > hydrostatic, T = ambient, Q = measured;

(b) crosscut excavation and seal emplacement;

(c) resaturation; P = measured, T = ambient, Q = 0;

(d) repressurization; P > hydrostatic, T = ambient, Q = measured;

(e) heating (optional); P > hydrostatic, T > ambient, Q = measured;

where P = chamber pressure, T = temperature, and Q = flow. The first of these involves pressurization of the water-filled chamber to establish the hydraulic regime of the rock mass within the test area. The direction of the pressure gradient produced by water injection is ideally suited for evaluating the hydraulic conductivity parallel to the axis of the future crosscut, along the rock-seal interface and possible damage zone.

After characterization of the rock mass, the water will be drained from the chamber and stored for later use. The crosscut is to be excavated by a suitable method and, as in the case of the excavation damage tests, the influence on the wall rock will be recorded. The size and shape of the crosscut, the sealing materials, and the method of placement should be similar to proposed repository sealing systems under investigation. Several different sealing materials and methods of placement can be investigated by installing various material/placement test sections in series with separate instrumentation for each section.

The plug or seal and additional instruments will be installed before testing for resaturation, repressurization, and optional repressurization with heat. Major parameters to be monitored throughout the experiment include hydraulic conductivity, porosity, groundwater chemistry, rock and seal material stress-strain, and, depending on the heating option, temperature. In addition, tracers will be used to identify the flow paths and possibly to investigate radionuclide retardation. At the end of the tests the plug material will be removed for a more detailed examination of the rock-seal interface and damage zone.

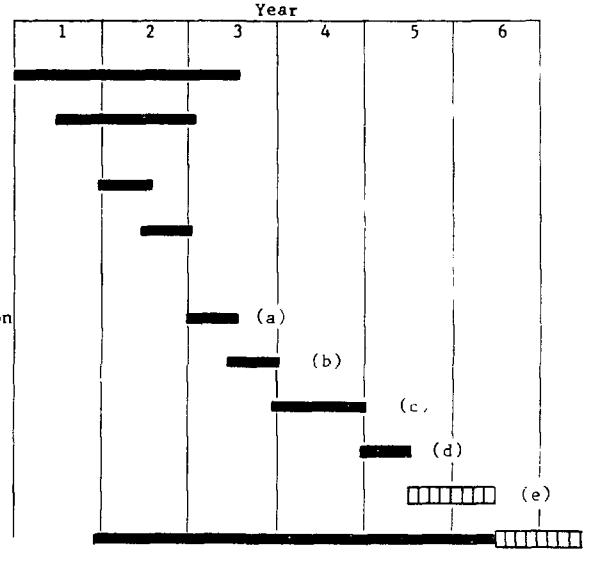
F. Data analysis and modeling. Data analysis will proceed with the field investigations, starting about the same time as the baseline studies and finishing approximately one year after the field tests. Predictive models will be used primarily to aid in the interpretation of the results, although a certain amount of model development is expected. It is anticipated that major efforts of model development, such as those proposed in the hydro/thermomechanical experiment, will provide a significant background of information for this study.

3.2.4 Schedule and Cost Estimates

Table 4 gives an estimate of the schedule and personnel requirements. In the formulation of this estimate, it is assumed that a significant portion of the required instrumentation development, and to a lesser degree the model development, has been or will be performed for the hydro/thermomechanical experimental program. For an optimum transfer of this information and technology, the excavation damage/sealing experiment should start 1 to 2 years after the hydro/thermomechanical experiment begins. The total duration of the experiment is approximately 5-1/2 to 6-1/2 years, depending on the heating option. Personnel requirements assume an average 6-year project duration.

An estimate of the total cost of the excavation damage/sealing experiment is provided in Table 5, the details of which are given in Appendix C, Section C.2. Major cost items are divided among construction and fabrication, operating equipment and services, and personnel. The distribution of these costs on a yearly basis is given in Table 6. As for the hydro/thermomechanical experiment, it should be emphasized that the costs presented are only rough estimates.

Table 4. Schedule and personnel for the excavation damage/sealing experiment.



Stage						
1. Design and Fabrication						
2. Baseline Studies						
3. Excavation Damage Experiment						
4. Chamber Excavation						
5. Sealing Experiment						
(a) chamber pressurization						
(b) crosscut excavation						
(c) resaturation						
(d) repressurization						
(e) heating (optional)						
6. Data analysis, modeling						
Personnel						
PI, Manager	1	1	1	1	1	1
Instrumentation	2	2	2	1	1	0
Rock Mechanics	1	1	1	1	1	1
Hydrology/Geology	1	2	2	2	2	1
Geochemistry	1	1	1	1	1	1
Modeling	1	1	1	1	1	1
Totals (FTE)	7	8	8	7	7	5

Table 5. Total cost estimate for the excavation damage/sealing experiment (thousands of 1981 dollars).[a]

1.	Construction and Fabrication		$1,724
	(a) monitoring drill holes	($219)	
	(b) excavation damage drift	($359)	
	(c) center drift, liner and bulkhead	($815)	
	(d) crosscut and bulkheads	($331)	
2.	Operating Equipment and Services		$4,095
	(a) instrumentation	($784)	
	(b) mechanical plant	($83)	
	(c) travel and per diem	($918)	
	(d) computer costs	($600)	
	(e) consultant	($450)	
	(f) miscellaneous	($810)	
	(g) plug materials and placement equipment	($450)	
3.	Personnel		$3,371
		Total	$9,190

[a]Details in Appendix C, Section C.2.

Table 6. Distributed cost estimate for the excavation damage/sealing experiment (thousands of 1981 dollars).

Category	Year 1	2	3	4	5	6
1. Construction and Fabrication	434	959	331	0	0	0
2. Operating Equipment and Services	678	1106	907	498	498	408
3. Personnel	562	642	642	562	562	401
Totals	1674	2707	1880	1060	1060	809

4. CONCEPTUAL DESIGN AND OPERATION OF THE FACILITY

4.1 FACILITY DESIGN

Design of the experimental facility must provide for:

1. safe, economical underground access for in situ field experiments within the appropriate environment;
2. separation of the various experiments to minimize possible interaction;
3. isolation of the experiments from existing underground workings and related disturbances;
4. sufficient working space.

The choice of appropriate environment for the facility involves consideration of the rock mass characteristics, in situ stress field, hydrologic regime, and logistical criteria. These factors have been discussed in detail in Wollenberg et al. (1981). In general, the openings will be situated within a massive to blocky rock mass, at depths representative for a repository (300 to 1000 m), well below the water table. The facility from which access to the underground will be obtained should be readily accessible via surface roads, and the operation of the test facility should not significantly conflict with mining or other operations.

Separation of the various experiments within the facility depends on the purpose of the experiment and its sensitivity to external influence. The hydro/thermomechanical experiment, which involves heating a relatively large volume of rock and requires stable, undisturbed baseline conditions, should be well separated from all other experiments or possible sources of disturbance. The excavation damage/sealing experiment, although not as sensitive, also requires adequate isolation. At present, an estimate of the

distance between these experiments and additional test areas is 150 to 300 ft (Figure 3).

Isolation of the experiments from the influence of the existing underground workings is most important. Ideally, the experimental chamber should be located well beyond the influence of the existing excavations on the stress field and hydrogeologic regime. The amount of excavation or drifting needed to achieve these conditions depends on the location of the proposed test facility with respect to the existing workings, the extent of the workings, and the character of the rock mass. Without site-specific information, a maximum distance of 1000 ft is believed to be appropriate. Under ideal conditions this could be reduced to as little as 500 ft, but the space for the various experiments and support facilities then becomes rather restricted. For the purpose of these preliminary schedules and cost estimates, a 1000 ft drift has been assumed.

Design of the facility should provide not only adequate access to the experimental areas, but also space for support activities. In addition to the surface facilities, space is required for underground shops, garage, office, instrumentation, mechanical plant, and refuge.

As an alternative to conducting the experiments in an inactive mine, they could be performed at existing underground research facilities, such as the candidate repository sites in rock currently under investigation. Many of the details outlined in the following sections would require modification: the layout and facility development costs could be reduced; surface and underground facilities as well as operation and maintenance costs could be shared. These factors are considered, and lower-bound estimates of

Underground Test Facility Plan

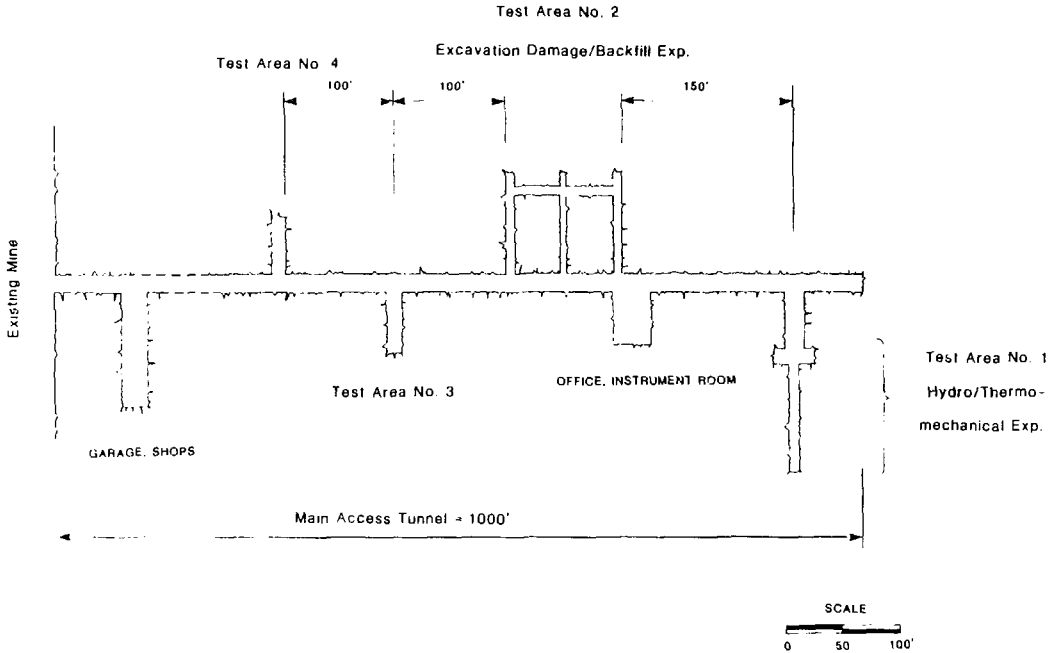


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Figure 3. Plan of the general layout of the underground experimental facility, showing locations of test areas.

development and facility operation costs are presented for comparison with a complete facility in an existing or inactive underground mine or civil work.

4.2 LAYOUT

Given the design considerations discussed above, a general layout of the underground experimental facility is presented in Figure 3. Four test areas are included, two of which are dedicated to the hydro/thermomechanical and excavation damage/sealing experiments. Test areas No. 3 and No. 4 are reserved for future experiments. The four test areas are staggered along 500 ft of drift with the hydro/thermomechanical test area positioned farthest from the existing workings. Initially, each test area will be serviced by a 50 ft long stub drift driven perpendicular to the main access tunnel.

The main access tunnel is designed as a modified horseshoe section, 12 ft high by 12 ft wide (Figure 4). This size opening will provide adequate space for a permanent rail transportation system, walkways, and utilities. The invert should be paved with concrete for safety and convenience, although this may not be necessary if careful excavation is employed.

A combination office/instrumentation/refuge room is located opposite test area No. 2. It should be about 20 ft wide by 15 ft high and at least 30 ft long. The garage and shops can be placed near the facility portal. This area should incorporate a floor space of about 2000 ft^2 and also have a height of 15 ft.

Assuming that the experiments are to be carried out from an existing underground research facility and that test areas No. 3 and No. 4, the

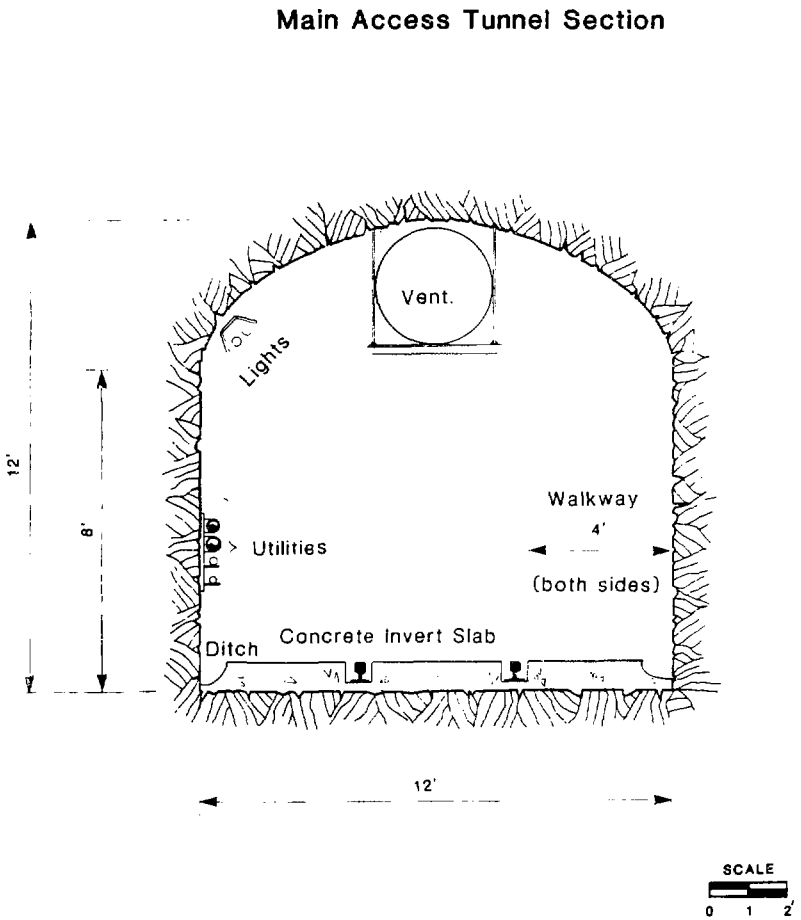

Figure 4. Cross section of the main access tunnel.

garage, and the office are not required, the layout shown in Figure 3 between test area No. 3 and the end of the access tunnel could remain largely unaltered. This reduces the length of the main access tunnel from 1000 ft to a minimum of 350 ft.

4.3 FACILITY CONSTRUCTION

The construction contract for the experimental facility should include the main access tunnel with paved invert, four stub drifts, the garage and office excavations, as well as the permanent installation of ground support, utilities, ventilation, lighting, dewatering system, and track for the transportation system. Furthermore, it should be assumed that the site is readily accessible, the tunnels will be driven from an existing opening at a depth in excess of 1000 ft, all debris will be hoisted from the mine or transported from an adit, controlled blasting will be employed, the rock is basically competent requiring only light support, and only minor groundwater inflows will be encountered (less than 200 gpm total).

Temporary and permanent ground support should include fully grouted No. 7 rock bolts on a 4 by 4 ft pattern (Figure 5). Wire mesh should also be used for safety to control minor raveling of loosened rock. The system should be employed along the entire length of the main access tunnel.

To keep construction costs to a minimum, no major experiments or tests are planned during the construction of the underground facility. However, because the construction is scheduled as a two-shift-per-day operation, it will be possible to carry out a limited amount of testing and/or geotechnical investigation during the third shift. In addition, up to 40 hours of standby time is included in the [illegible] which would interfere with the contractors' operations. It is assumed that

Main Access Tunnel Support

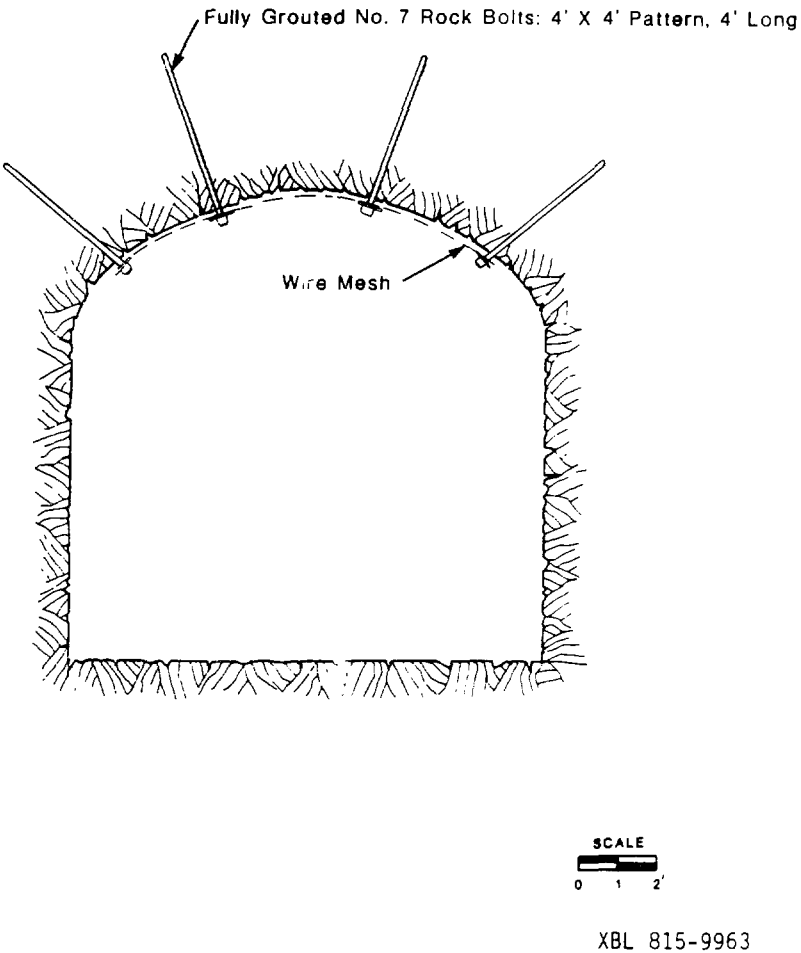

Figure 5. Roof support system, main access tunnel.

geologic mapping of the tunnel line can proceed without significant delay to the contractor.

In preparation for construction and award of the construction contract, it will be necessary to retain an architect/engineer firm for facility design, contract specifications, and contract supervision. The cost of this service is approximately 16% of the construction cost. A good portion of the required site investigation for the test facility will be performed as a part of the site-selection process currently underway.

4.4 SURFACE FACILITIES

Surface facilities should include an office/shop/change-room complex, the ventilation and shaft plant, yard storage area, water and electric supply, debris-disposal area, waste treatment or disposal, and security fencing with gate house. It would also be desirable to have limited living quarters and food service at or near the site. Most of the existing mines or civil projects under consideration have these facilities available for use, although they may be in need of some repair or modification.

4.5 EXISTING UNDERGROUND ACCESS

The mines under consideration for a test facility either have operating hoists or access by adit. The shafts and level access tunnels are generally in good condition. At most, it may be necessary to replace or install a minor amount of rock support and enlarge narrow sections of tunnel. A contingency is included for this in the cost estimate of facility development; however, it is excluded in the cost for operation from an existing underground research facility.

4.6 OPERATION AND MAINTENANCE

To operate the test facility for two 8-hour shifts per day will require an on-site staff of approximately 12 people, exclusive of the staff performing the experiments. This would include an administrator/public relations officer, secretary/clerk, maintenance superintendent, mechanic/electrician, electronic technician, two hoistmen, two cage tenders, store keeper, and two general laborers/miners. (In a facility where access is by adit, the hoistmen and cage tenders would not be required.) Other required services, such as security staff, janitorial services, and vehicle maintenance, should be performed on a contract basis.

Annual operating costs in addition to staff include, power, insurance, surface vehicles, underground transportation system, shop tools and equipment, various spare parts, and general supplies.

Many of the required personnel and other operating costs could be shared if the experiments are carried out in an existing underground research facility. As a minimum, the required site staff could be reduced from 12 to roughly 3-1/2. This includes an administrator, electronic technician, general laborer, and half-time mechanic/electrician.

4.7 SCHEDULE AND COST ESTIMATES

Design and construction of the underground test facility are estimated to require about one year and to cost $3.15 million (architect/engineer, $435 thousand; construction, $2.72 million).* Construction of the facility

*Construction cost estimates were provided by T. McCusker, tunnel consultant, San Francisco.

will require approximately 7 months and could proceed within 5 months after the design contract is awarded to the architect/engineer, assuming no delays due to unusual permit procedures or environmental impact statement.

In addition to the development costs for the test facility, an initial expense for surface facility development and/or repair and maintenance or improvement of the existing underground openings should be considered. This should amount to less than $500 thousand for a total facility development cost of $3.65 million.

Annual expenses for operating equipment, services, and personnel, totalling $1.56 million, are itemized in Table 7 (details given in Appendix C, Section C.3). The total cost for development and operation of the underground test facility over a period of 8 years is $14.57 million. As with the cost estimates for the proposed experiments, it should be emphasized that this is a rough estimate. Furthermore, the costs are site specific and are likely to be lower at sites located away from major metropolitan centers.

Annual operating expenses at an existing underground research facility are given in Table 8 (details in Appendix C, Section C.4). Using this lower-bound estimate, $349 thousand per year, and a development cost of $826 thousand, the total cost for development and operation over a period of 7-1/2 years is $3.27 million.

Table 7. Annual operating expenses for an underground experimental facility (thousands of 1981 dollars).[a]

1.	Operating Equipment and Services		$ 750
	(a) contracted services	($45)	
	(b) inventories	($450)	
	(c) utilities	($255)	
2.	Personnel (12)		$ 810
		Total	$1,560

[a]Details in Appendix C, Section C.4.

Table 8. Annual operating expenses for an existing underground research facility (thousands of 1981 dollars).[a]

1.	Operating Equipment and Services		$113
	(a) contract services	($0)	
	(b) inventories	($113)	
	(c) utilities	($0)	
2.	Personnel (3-1/2)		$236
		Total	$349

[a]Details in Appendix C, Section C.4.

5. SUMMARY

5.1 SCHEDULE AND COSTS

A summary of the schedule and costs for development at an existing mine or civil work, for operating the facility, and for conducting the two proposed experiments is presented in Table 9. As indicated, the hydro/thermomechanical experiment is scheduled to begin 6 months after the start of facility development. This should permit the tunneling contractor to excavate the drilling gallery concurrently with construction of the facility, resulting in significant savings of time and cost. Preliminary drilling for the excavation damage/sealing experiment can begin 1-1/2 years after the start of facility development. Design and fabrication will begin 1/2 year later, allowing time to develop materials and related methodologies for backfill, sealing, and grouting.

Total cost of the facility, including experiments, [illegible] $39.0 million distributed over 8 years. This is comparable with other major test facilities designed for waste isolation investigations. The Stripa Project (Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock) in Sweden, largely active between 1977 and 1980, resulted in average expenditures of $4 to $5 million per year. The Pinawa Project, a 20-year study already underway by the Canadian Atomic Energy Commission, is projected to cost $40 million (personal communication, Pavel Kurfurst, AECL). This, however, includes a new shaft and surface facilities at a virgin site on the Canadian Shield.

A summary of the schedule and costs for development at an existing underground research facility, for operating the facility, and for conducting the two proposed experiments is presented in Table 10. The only difference

Table 9. Schedule and costs of facility and experiments developed at an existing mine or civil work (millions of 1981 dollars).

Stage	Year 1	2	3	4	5	6	7	8
1. Facility Development	(3.65)							
2. Facility Operation		(1.56)	(1.56)	(1.56)	(1.56)	(1.56)	(1.56)	(1.56)
3. Hydro/Thermomechanical Experiment[a]	(3.00)		(3.60)	(2.22)	(1.72)	(1.65)	(1.50)	(1.50)
4. Excavation Damage/ Sealing Experiment			(1.67)	(2.71)	(1.88)	(1.06)	(1.06)	(0.81)
Annual cost	$5.15	$4.86	$6.14	$6.24	$5.12	$4.20	$4.12	$3.12

Total cost $39.0

[a]Annual costs distributed equally to the year in which they occur.

Table 10. Schedule and costs of facility and experiments developed at an underground research facility (millions of 1981 dollars).

Stage	Year 1	2	3	4	5	6	7	8
1. Facility Development	(0.83)							
2. Facility Operation	(0.17)	(0.35)	(0.35)	(0.35)	(0.35)	(0.35)	(0.35)	(0.17)
3. Hydro/Thermomechanical Experiment	(3.00)	(3.60)	(2.22)	(1.72)	(1.65)	(1.50)	(1.50)	
4. Excavation Damage/ Sealing Experiment[a]			(1.67)	(2.71)	(1.88)	(1.06)	(1.06)	(0.81)
Annual Cost	$4.00	$4.79	$4.76	$4.37	$3.47	$2.91	$2.78	$0.58

Total cost $27.7

[a]Annual costs distributed equally to the year in which they occur.

in schedule between development from a research facility and from a mine or civil work is a reduction of roughly six months due to the shorter length of the main access tunnel and deleted underground garage and office space. Total cost for the facility, including experiments, is $27.7 million distributed over 7-1/2 years. It is emphasized that this is a lower-bound number and should be used for comparison with the cost for complete facility development, i.e., $39.0 million.

Besides the utilization of an existing underground research facility, additional economies could conceivably be achieved by combining the hydro/thermomechanical and excavation damage/sealing experiments. Although careful design and scheduling would be necessary to avoid interaction of the two experiments, it should be possible to save $1 to $2 million by employing the same test/pressure chamber and general baseline studies. Further investigation is warranted to determine whether this saving is practical in view of the additional complications imposed.

5.2 CONTINUING WORK

This report provides the preliminary conceptual designs, schedules, and cost estimates for the underground test facility and proposed experiments. These results are necessarily general and are not site specific. After selection of a candidate site, or sites, the design, schedule, and costs of the facility should be modified to reflect the specific conditions at these locations. Similarly, the proposed experiments should be refined to provide additional details and anticipated test results with the aid of simple predictive models, as employed for the results given in Appendix B, but using site-specific material physical properties. This study should include the results of coupled hydro/thermomechanical models, considering the possible influence of convection as well as conduction on the predicted response.

ACKNOWLEDGMENTS

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APPENDIX A. SYNOPSIS OF IN SITU TESTS FOR MINED GEOLOGIC DISPOSAL OF RADIOACTIVE WASTES (partly after Gnirk, 1980)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
BASALT: NSTF, Hanford Site, Richland, WA (Rockwell Hanford Operations) et al., 1980	Full-Scale Heater Test No. 1: Single electrical heater emplaced in central borehole and surrounded by 8 peripheral heaters; heater array capable of simulating a thermal loading of 25 to 50 W/m^2.	1980-83	Assess thermomechanical response of basalt to thermal loading from a unit cell configuration of emplaced electrical heaters, for thermal loadings up to twice expected repository levels.	Test initiated in July, 1980.	BWIP-NSTF Test Program, 1979; Baca et al., 1980
	Full-Scale Heater Test No. 2: Single electrical heater emplaced in borehole; power output levels range from 1 to 5 kW.	1980-83	Determine maximum acceptable thermal power input to basalt from emplaced electrical heater.	Test initiated in July 1980.	
	Jointed Block Tests: Cube of basalt, approx 2 m on each side and excavated on vertical sides by line drilling, loaded with flat-jacks and rows of electrical heaters emplaced in boreholes.	1981	Measure elastic, thermoelastic, and thermal properties of basalt as function of temperature, stress, rock mass quality, and direction.	Test scheduled for initiation and completion in 1981.	
BEDDED SALT: Carey Salt Mine, Hutchison, KS (ORNL)	Heated Model Room Test: 2.4 x 2.9 x 0.6 m high room, with 10 heaters inside room; 11 kW power level reduced to 9 kW after 40 days.	1962-63 (214 days at ambient temp, 297 days of heating	Evaluate influence of elevated temperature on structural deformation of scale-model room.	At end of heating period, closure rate approx one order of magnitude greater at 140°C than at ambient temp of 20°C, but decreasing.	Bradshaw, 1971
	In Situ Block Test: 1.5 m cube excavated on vertical sides and loaded biaxially by flatjacks.	1963-64	Evaluate instruments for in situ stress measurements	Borehole pressure cells and deformation gauges adequate for elastic salt response; determined in situ deformation modulus and onset of plastic deformation.	
	Prototype Hole Liner Test: 3.9 m deep borehole with 40.6 cm diam upper portion and 30.5 cm diam lower portion, lined with 35.6 cm OD carbon steel well casing and 15.2 cm OD 304L stainless steel tubing; Calrod heaters in annulus between tubing and salt induced wall temps of approx 200°C.	1964-65 (4 separate heating phases of 48, 100, 50, and 47 days)	Evaluate in situ response of canister-emplacement hole liner to elevated temperature.	Approx. 1.2 cm of floor uplift near borehole collar and 2 cm of borehole closure during heating; small amounts of water inflow observed during heating phases; some indications of refluxing of water.	

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
BEDDED SALT: Project Salt Vault, Carey Salt Mine, Lyons, KS (ORNL)	Radioactive Waste Handling Demonstration.	1965-67	Demonstrate radioactive waste handling equipment and techniques, incl lowering into mine, emplacement, storage, and retrieval from lined boreholes, and removal from mine of canisterized spent fuel assemblies.	Demonstration accomplished successfully with 3 sets of 7 canisters each containing 2 irradiated ETR fuel assemblies.	Bradshaw and McClain, 1971; McClain and Bradshaw, 1971
	Irradiated-Fuel Canister Array Test: 6 canisters emplaced in peripheral lined boreholes on 1.5 m centers and one canister in central lined borehole; 1.2 to 1.6 kW heat generation per canister at emplacement, with two complete exchanges for canisters of freshly irradiated assemblies; nominal 10.5 kW power output for array, with nominal 15 kW during final 5 mo of test.	1965-67 (19 mo of heating)	Determine possible gross effects of radiation on hole closure, floor uplift, salt shattering temp, etc., in salt regions experiencing temp. of 100 to 200°C; determine possible radiolytic production of chlorine; compare temperature fields and structural deformations for salt heating by irradiated-fuel canisters and electrical heaters; collect technical information, especially on creep and plastic flow of salt, which could be used in the design of an actual radioactive waste disposal facility.	No apparent gross effects of intense radiation field on structural response of salt during heating; essentially no difference in temperature fields induced in salt by canisters of irradiated fuel and electrical heaters; no free chlorine was released from salt; qualitative correlation between salt deformations, bedded salt structure, and heating cycles; reasonably good agreement between measured room convergence and model calculations with use of constitutive law of creep derived from model pillar tests in the laboratory; collection and documentation of considerable bulk of salt temp and deformation data, in situ heater test design and installation information, and operational procedures for future use in test design and model development and verification.	
	Heater Array Test: Electrical heater array basically identical to geometries and conditions of Irradiated-Fuel Canister Array Test.	1965-67 (19 mo of heating)			
	Heated Pillar Test: 3 electrical heaters emplaced in boreholes on each side of a pillar, with nominal power input of 1.5 kW per heater, or 33 kW total.	1965-67 (11 mo of heating)			

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
PARADOX BASIN: Woodward-Clyde Consultants	In situ testing at Gibson Dome.	1980	1) Subhydrostatic drill stem tests. 2) Superhydrostatic drill stem tests.	1) Measured initial unloading behavior of salt, creep rate at maximum deviatoric loading in salt, and rebound behavior of salt. Negligible amounts of creep in salt at depths less than 2700 ft. Borehole diameter changes caused by initial loading of salt varied from 0.02 to 0.4 in. 2) Measured susceptibility of salt to hydrofracturing, stress conditions in salt, and estimated salt behavior under loading conditions to compare with unloading data obtained in 1) above. Breakdown pressures on the order of 1500 psi above overburden pressure; varying liquid injection rates do not affect the maximum stable (post-breakdown) pressures significantly.	Conwell, 1980
	Microearthquake monitoring.			Microearthquake events appear to originate from the top of the Precambrian basement at approximately 7 km with a slight clustering at the shallower depths.	

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
DOME SALT: Avery Island (Sandia--RE/SPEC)	Instrumentation Development and Field Testing.	1979-80	Develop instrumentation applicable to in situ testing in salt in a mine environment, incl borehole closure measurement device, borehole stress gauge, thermal conductivity probe, quartz lamp heater, moisture collection apparatus, and radar scanner for intact salt.	In situ testing of instruments with data analysis and requisite modifications in progress through FY 1980.	Cook, 1980; Sattler, 1980
DOME SALT: Avery Island Mine, LA (ONWI--RE/SPEC)	Full-Scale Heater Test--Site A: Single electrical heater emplaced in borehole (44 cm diam and 6 m depth) which is lined with carbon steel sleeve, operated at 6 kW power level. Full-Scale Heater Test--Site B: Same as Site A, except 41 cm diam borehole and 3 kW power level.	1978-present (26 mo of heating) 800 days of heating (1980) Now steady-state	Evaluate near-field short-term thermomechanical response of dome salt to simulated waste-canister heating at two different power levels; Assess borehole closure and corrosion by-product gas generation during heating.	Tests continuing with data analysis in progress; nearly steady-state temperature fields after 300 days of heating. Plans to continue data collection through cool down period. Retrieve instruments for post-test calibration. Sample collection by overcoring salt. Metallurgical analyses (ORNL) of sleeves and heaters.	Van Sambeek, 1979, 1980a Van Sambeek, 1980b
	Full-Scale Heater Test--Site C: Single electrical heater emplaced in borehole (41 cm diam and 6 m depth) which is lined with carbon steel sleeve (sleeve-salt annulus backfilled with crushed salt) and surrounded by 8 peripheral heaters of 1 kW power capacity on 1 m radius; central heater operated at 4 kW with peripheral heaters operated at increasing power level to produce unit cell configuration for 37 W/m^2 thermal loading.	1978-present (26 mo of heating) 800 days of heating (1980) Now steady-state	Evaluate near-field long-term thermomechanical response of dome salt to simulated waste-canister heating, representative of a unit cell configuration in a repository; Evaluate buildup of salt pressure on borehole liner and liner corrosion.	Tests continuing with data analysis in progress. Power in peripheral heaters increased for 600 days to 700 W per heater, then power held constant. Floor heave resulting from salt expansion increased for 600 day period and then stabilized. Tangential stress near heater borehole increased rapidly to 1000-2500 psi, stress then relaxed to about 700 psi after 200 days of heating. Largest stress change occurs about 3 ft into solid salt; at 22 ft, change is very small	Van Sambeek, 1980b

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
	Brine Movement Tests: Three separate test installations, involving a single 1 kW electrical heater emplaced in a borehole situated within an array of peripheral instrumentation and synthetic brine container holes.	1979-present Heating completed (1980)	Examine movements of natural and synthetic brines in dome salt in ambient and elevated temperature fields, incl influence of in situ salt permeability and thermally-induced microfracturing, instrumentation development. Cracking of salt occurred during cool down.	Tests continuing with data analysis in progress; good agreement between predicted and measured inflow rates of brine. Significant amount of brine migrated from brine borehole to heater borehole within 3 mo, mechanism of migration still not known. Both permeability and rate of moisture collection increased when power level of heaters was reduced.	Krause and Quirk, 1979; Chou and Clynne, 1980; Van Sambeek, 1980a,b
	Accelerated Borehole Closure Test: 20 cm diam borehole centrally located within a 1 m diam in-place core, loading provided by flatjacks with contained electrical heaters around outer periphery of core, five separate test installations.	1980-present	Evaluate closure of open and crushed-salt backfilled bore holes in dome salt under controlled stress and temperature conditions.	Installation of test in progress. Flatjacks grouted in place because of greater deformation of salt than expected.	Van Sambeek, 1980a,b
DOME SALT Gulf Coast salt domes	Studies at Vacherie Dome and Rayburn's Dome.	1980	Determine tectonic and hydrologic stability of North Louisiana salt domes. Study petrology and geochemistry of salt stock. Study hydrologic isolation of mined openings in salt domes. Determine sizes and shapes of two North Louisiana salt domes. Determine erosional effects on domes for next 250,000 years.	Monitoring movement over domes. Observation wells east and southeast of Vacherie Dome have been used to detect saline plume; no plume was observed at Rayburn's Dome. Chemical and isotopic analyses of water from leaks at Belle [illegible], Weeks Island, and Jefferson Island salt mines strongly indicate that mine brines are formation waters. Geologic studies indicate [illegible] evidence of tectonic uplift over Vacherie Dome during quaternary. Possible dissolution over Vacherie and signif. int. dissolution over Rayburn's Dome during quaternary. Maximum erosion of 120 ft at both sites during next 250,000 years.	Martinez, 1980

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
				Boreholes in Vacherie and Rayburn's domes relogged to determine the in situ response of salt. Most trace water is found along grain boundaries in salt. Compared with modern sea water, mine leaks and groundwater at Avery Island are enriched in Ca, Rb, Li, Ba, NO_3^{-2}, and I^- and are generally low in K, Mg, Sr, Br, and SO_4.	
DOME SALT: East Texas salt domes	Potential of East Texas salt domes.	1978-present	Evaluate salt domes as waste repositories. Determine tectonic and hydrologic stability over long time periods.	Geomorphic studies indicate that Oakwood Dome is less mature than Keechi or Palestine domes. Palestine Dome eliminated because of extensive brining that has occurred there. Preferred orientation of lineaments shows that shallow domes have affected regional lineament trends to a greater extent than deeper domes. Chemical analyses of waters from wells near Oakwood Dome helped verify hypothesis that area over the dome is recharge area.	Kreitler, 1980

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
				Subsurface geology and geometry of 15 salt domes were studied in detail (these included Oakwood and Keechi domes). Well data and petroleum resource data on producing formations have been tabulated. Lithology of salt core from Oakwood Dome has been logged, photographed, and studied. Analysis of layering and folding revealed in the core suggest that the mushroom-shaped crown of the Oakwood Dome has been truncated to levels below the original diapiric crest, probably by groundwat solution. Caprock on Oakwood Dome is the result of multiple stages of diagenesis.	
DOME SALT: Asse Mine, Braunschweig, Lower Saxony, FRG (IFT-GSF)	Temperature Test Field 1A and 1B: Electrical heaters emplaced in boreholes.	Late 1960s	Develop experience in heater design and temperature measurement.	Test objectives satisfied.	Kuhn, 1979
	Temperature Test Field 2 Electrical heaters emplaced in boreholes arranged in triangular pattern, decreasing power level with time.	1968-71	Simulate decaying heat generation from radioactive waste, measure temperatures, strains, and convergences, compare temperature measurements with model calculations.	Test objectives satisfied, measured temperatures compared to within 10% with those calculated from modeling.	

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
	Temperature Test Field 3 Five electrical heaters, 23 cm diam and 1 m length, emplaced in borehole of 32 cm diam and 50 m depth; 9 kW power level, second borehole without heaters located 7.5 m from heated borehole.	1976 (90 days of heating)	Measure thermally induced convergence of boreholes.	Heated borehole experienced 11% closure during 90 days of heating, unheated borehole was not influenced by temperature field around heated borehole.	
	Temperature Test Field 4: Excavation of 6 by 6 m drift in two lifts, with borehole extensometers installed after first lift; five 2 kW electrical heaters, each 1 m in length, installed at the bottom of 15 m deep borehole in floor of drift.	1978-80	Measure deformations in salt due to excavation and thermal loading, measure convergence of heated borehole, evaluate brine migration as function of temperature field.	Heating phase of test completed, data and post-test analyses in progress.	Durr, 1979, Rothfuchs, 1979
	Ellipsoidal Cavern Convergence Test: Excavation of 10,000 m^3 ellipsoidal cavern in 1976-77 and instrumentation with borehole extensometers.	1976-present	Evaluate stability of large underground cavern under isothermal conditions.	Test continuing with measurements in progress, convergence rate decreasing with time.	Kuhn, 1979, Staupendahl, 1979

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
DOME SALT: Asse Mine, Braunschweig, Lower Saxony, FRG (BGR)	Time-Scaled Brine Migration Test TMV-1: Electrical heater emplaced in central borehole, with surrounding boreholes containing brine, thermocouples, and resistance electrodes; initial 5 kW power level reduced to 3 kW over 50 day heating period.	1978-79 (50 days of heating)	Assess influence of thermally-induced fracturing in salt on brine migration during heating over a time-scaled period equivalent to approx 14 years of full-scale performance.	No evidence of thermally induced fracturing during heating phase; 2 to 4 days after power shutdown; brine movement initiated due to generation of large horizontal fissure in salt below upper end of heater as indicated by post-test coring.	Kopietz, 1979
BEDDED SALT: Bell Canyon (Sandia)	Borehole Plugging Program	1978-80 (continuing)	Develop, test, evaluate cement grouts and other materials for laboratory and field testing. Develop geochemical program to check long-term stability and suitability of cement grouts and other materials as well-bore plugging materials. Develop instruments to test plug performance. Evaluate plug designs in situ.	Cement groups should be adequate. Bond strength not adequate indicator of plug adequacy; may not result in low interface permeability. Brine water mix poorer than fresh water mixes in salt; other test mixes being used.	Christensen, 1980
"POTASH SALT": Mississippi Chemical Co. Mine, Carlsbad, NM (Sandia)	Full-Scale Pillar Test-to-Failure: Installation of stress and deformation instrumentation in roof, rib, and floor of mining face area prior to subsequent room-and-pillar excavation by continuous miner in operating panel of mine, 90% extraction ratio, with total collapse of pillars after several months.	1979	Measure stresses and deformations in and around pillar during regular mining operations, leading to eventual total loss of load-bearing capacity of pillar due to high-extraction-rate mining.	Test objectives satisfied, with stress and deformation data documented; modeling of field test and supporting laboratory testing currently in progress.	Sattler and Christensen, 1980

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
GRANITE: Climax, NTS, Nevada (LLNL)	Small-Scale Heater Test: Electrical heaters, 16 mm diam and 3 m length, emplaced in boreholes at two separate locations, with thermocouples in boreholes parallel and perpendicular to principal fracture direction; 3.7 kW power level. (Heater T ~ 600°C at steady state.)	1977-78 (68 and 62 days of heating)	Determine in situ thermal conductivity and thermal diffusivity.	Test objectives satisfied; thermal conductivity approx. 15% greater than laboratory measurements on intact core specimens without confining pressure; thermal diffusivity agreed with laboratory measurements. Final report 1980.	Ramspott, 1979a, 1979b
	In Situ Permeability Test: Use of Small-Scale Heater Test site with single electrical heater in central borehole and inflatable rubber borehole packers in thermocouple holes.	1978 (83 days)	Determine in situ permeability as function of temperature with air as fluid medium.	Test objectives satisfied; decrease of permeability with increasing temperature; results consistent with laboratory measurements on other granitic rocks.	
	Mine-By Test: Excavation of parallel drifts, followed by installation of stress and displacement instrumentation in pillar; subsequent excavation of drift in two lifts through pillar. System of drifts intended for use in Spent-Fuel Storage Test.	1979	Obtain data for mechanical response of granite to mining for continuum model evaluation, for qualitative examination of structural stability of excavations, and for comparison with measurement during long-term heating phase during Spent-Fuel Storage Test.	Data obtained as planned; evaluation of applicability of continuum model for predicting mechanical response and model development for mechanical behavior of fractured rock in progress. Uses overcore stress values different from calculated values.	Ramspott, 1979b; Ramspott et al., 1979

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
	Spent-Fuel Storage Test: 11 canisters of spent-fuel assemblies and 6 electrical heaters emplaced in boreholes on 3 m spacing in central storage drift, 10 electrical heaters emplaced in boreholes on 6 m spacing in each parallel drift on either side of central storage drift; simulated gross thermal loading of 44 W/m^2.	1979-85 (1-5 years; 1981 first full year of operation)	Simulate disposal room configuration in repository by use of spent-fuel canisters and electrical heaters; evaluate difference between radioactive waste source and electrical simulators on test environment; comparison of excavation-induced and thermally induced stresses, deformations. Heat removal by mine ventilation. Provide thermomechanical response data for design of repository.	Canisters emplaced during Spring of 1980, with test currently in progress. Fuel loaded 5-28-80. 1.65 kW at 2.5 years out of reactor. Thermal peak approx. 6 mo at rock face, approx 85°C calc. Peripheral heaters turned on 6-27-80 at 925 W, to be increased twice 1300 W at 0.6 years, 1400 W at 0.8 years, peak canister temp. 145°C reached and passed 12-80, peak temp at edge of 15 X 15 m repository calculated to be 2 years into test.	Ramspott et al., 1979 Ballou, 1980; Ramspott, 1980
	Acoustic monitoring	1980		Events in concrete floor above one of the canisters (associated with cracking of the concrete). Events in the rock mass near the canister are associated with redistribution of stress as rock expands during the thermal pulse of the spent fuel test. Repository rock has average P- and S-wave velocities of 5.5 and 3.2 km/sec, giving a Poisson's ratio of 0.25, value typical for granite.	Majer, 1980

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
GRANITE: Climax	In situ migration test.	1980 preliminary tests	Compare field-measured with laboratory-measured retardation factors.		Ballou, 1980; Ramspott, 1980
		1981 experimental plan	Develop and evaluate equipment and experimental techniques to be used for in situ tests at potential repository sites.		
		1982 field tests	Collect field test data on radionuclide migration.		
GRANITE: Cornwall, UK (UKAEA Harwell)	Heater Test 1: 18 kW capacity electrical heater, 15 cm diam. and 5 m length, emplaced at depth of 10 m in 20 cm. diam. surface borehole; 11 kW operating power level.	1977-78 (120 days of heating)	Evaluate influence of thermally induced fracturing on rock permeability and convective water movement in rock mass in vicinity of heater emplacement.	Borehole wall temp reached 300°C after 100 hr, followed by sudden increase in temp and heater failure at 120 hr; borehole diam increased by 25% due to rock degradation; increased water influx into borehole.	Bourke, et al., 1978
	Heater Test 2: Heater Test 1 borehole reamed to 30 cm diam and cased with 25 cm diam pipe; electrical heater emplaced in cased borehole; initial power level of 10 kW, reduced to 3 kW (required to achieve and maintain 100°C borehole wall temp), with intent to increase to 6 kW and finally 18 kW.	1978	Same test objectives as for Heater Test 1.	Test in progress at time of publication of reference.	
GRANITE: Stripa Mine, Sweden (KBS-Univ. Luleå)	Pilot Heater Test: 6 kW electrical heater emplaced in 30 cm diam borehole, with 1 kW electrical heaters in 3 peripheral boreholes; all boreholes were inclined to floor of room so as to be situated perpendicular to plane of in situ stresses.	1977-78 (2 mo of heating)	Evaluate thermomechanical response of granite for maximum rock temperature of 100°C near emplaced heaters.	Peripheral heaters shut down after 19 days of operation because of excessive water inflow; obtained measurements of temp, stress changes, and water inflow in rock mass and of surface fracture displacement.	Carlsson and Stephansson, 1978

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
GRANITE: Stripa Mine, Sweden (KBS-Hagconsult)	In Situ Permeability Test: Central "Withdrawal" borehole surrounded by 16 peripheral "injection" boreholes; constant water pressure test; rock heated to 35°C by circulating hot water in boreholes.	1977	Measure in situ permeability of granite as function of temperature.	"Intrinsic" permeability of granite decreased by factor of approx 4 for temp rise of 25°C.	Lindblom et al., 1978
GRANITE: Stripa Mine, Sweden (LBL)	Full-Scale Heater Array Test: Electrical heater, 30 cm diam and 2.5 m length, emplaced in 40 cm diam borehole of 5.5 m depth and surrounded by 8 peripheral heaters of 1.1 kW capacity in boreholes; 4 kW power level for central heater; array provides thermal loading of 5 kW.	1978-79	Assess long-term near-field heating effects in rock mass around a simulated canister of reprocessed high-level waste 3.5 years out of reactor.	Heating phase of test terminated in June 1979, but preceded by deliberate increase in power levels of peripheral heaters to induce decrepitation of borehole wall rock; data and post-test analyses and model refinement in progress.	Cook and Hood, 1978; Witherspoon and Cook, 1979
	Full-Scale Heater Test: Electrical heater, 30 cm diam and 2.5 m length, emplaced in 40 cm diam borehole of 5.5 m depth; 3.6 kW power level.	1978-79	Assess short-term near-field heating effects in rock mass around a simulated canister of reprocessed high-level waste 5 years out of reactor.	Heating phase of test terminated in June 1979; data and post-test analyses and model refinement in progress.	Cook and Hood, 1978; Witherspoon and Cook, 1979
	Time-Scaled Heater Array Test: Eight electrical heaters, each 0.8 m in length, emplaced in vertical boreholes of 11 m depth and situated on 7 m by 3 m centers; initial power output of 1.1 kW per heater, reduced to 0.4 kW over period of 2 years.	1978-79	Simulate interaction between adjacent canisters of reprocessed high-level waste 5 years out of reactor, over a time period equivalent to two decades.	Heating phase of test terminated in June 1979; data and post-test analyses in progress.	

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
GRANITE: Stripa Mine, Sweden (LBL)	Fracture Hydrology and Groundwater Chemistry Tests: Vertical and inclined boreholes drilled from surface and from 330 m and 410 m levels of mine; boreholes in vicinities of heater tests.	1977-80	Assess directional permeabilities of fractured rock mass; determine groundwater flow velocities; evaluate role of fractures on groundwater movement; evaluate instrumentation.	Testing completed at end of FY 1980; data analysis in progress.	Gale et al., 1979
	Borehole Geophysical Measurements: Use of neutron, gamma-gamma, resistivity, gamma-ray, sonic, caliper, and temperature techniques.	1977-80	Define fracture geometries; locate permeable zones; determine chemical and physical inhomogeneities; qualitatively assess water content and porosity.	Testing completed at end of FY 1980; data analysis in progress.	Gale et al., 1979
	Ventilated Room Test: 30 m end section of drift sealed with bulkhead; water pressure instruments installed in boreholes around periphery and at end of drift; humidity of inlet and return ventilation air monitored, with provisions for heating inlet air.	1979-80	Determine groundwater inflow into mine and rock mass macropermeability, including influence of low-level elevated temperature of ventilation air through drift. Flow rate increased during final cooldown at 20°C after decreasing during phases at 30°C and 45°C.	Testing completed at end of FY 1980; data analysis in progress. Hydraulic conductivities 1.1×10^{-10} at 20°C 9.4×10^{-11} at 30°C 1.0×10^{-10} at 45°C	Gale et al., 1979 Cook, 1980
GRANITE: Stripa Mine, Sweden (JTC/SKBF-KBS--Univ. Lulea)	Buffer Mass Test: Placement of 10% bentonite/90% sand mixture in 12 m segment of ventilation room, with two 600 W electrical heaters emplaced in boreholes in floor; 600 W electrical heaters emplaced in boreholes in floor of open drift; all borehole heaters backfilled with bentonite.	1980-84	Evaluate thermal, mechanical, and hydrological responses of sodium bentonite and sodium bentonite/quartz sand mixtures to simulated waste-canister heating and rock mass groundwater flow conditions.	Final test design in progress; test installation initiated in October 1980. Test being conducted in ventilation drift; revised general test program.	Pusch, 1980a Pusch, 1980b

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
GRANITE: Stripa Mine, SKBF/KBS	Hydrogeologic investigations in boreholes.	1980	Develop methods for hydrogeological and hydrogeochemical investigations in nearly horizontal and vertical subsurface boreholes	One 1000-m vertical borehole and two 300-m horizontal boreholes to be drilled on 360 m level.	Carlsson and Olsson, 1980
	Hydraulic, chemical, and isotopic characterization of Stripa granite and groundwater.		Instrument and equipment development for boreholes.		
GRANITE: Stripa Mine, Royal Institute of Technology, Sweden	Migration in a single fissure.	1980	Develop a reliable tracer method for single fissures. Test injection and sampling equipment to be used in method.	9 meter hole drilled to fracture, fracture at 8.5 m. Cores being studied. Groundwater being collected under anoxic conditions by purging equipment with nitrogen. Lab tests to measure stability and sorption of tracers on granite and materials used in equipment.	Neretnieks, 1980
GRANITE: Stripa Mine, LBL	In situ stress measurements.	1980	Provide in situ stress measurements. Assess and compare two methods of in situ stress measurements: overcoring, hydrofracturing.	Overcoring at four depths: 100, 200, 300, and 380 m. 19 stress measurements made: σH Max = 25.3 MPa, σH Min = 11.7 MPa, σV = 12.0 MPa. 17 hydraulic fractures made: σH Max = 22.3 MPa, σH Min = 11.2 MPa, σV = 8.1 MPa.	Doe, 1980

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
GRANITE: Stripa Mine, LBL	Post-heater drillback.	1980	Investigate effects of heating/cooling cycle on H-10 borehole at Stripa and the adjacent granite rock mass.	Degree of damage to walls of H-9 and H-10 heater holes was documented by stereophotographic surveys. Boreholes were drilled through H-10 hole, cored, photographed, TV logged. Core went to Berkeley for study.	Wollenberg, 1980
GRANITIC GNEISS: CSM Experimental Mine, Idaho Springs, CO (ONWI--CSM)	Crystalline Rock Mining Technology Development.	1979-1981	Design and monitor blast patterns for room excavation to minimize damage in surrounding rock mass; evaluate rock mass behavior during excavation process, including blast zone damage and rock mass/fracture permeability.	Constructing 3-D geologic model. Room 5 m wide, 3 m high, and 30 m long completed. Holes drilled and cored to determine degree of damage due to excavation. Borehole tests to be used to assess damage.	Hustrulid, 1979; Hustrulid, 1980; Hustrulid et al.,1980
GRANITIC GNEISS: CSM Experimental Mine, Idaho Springs, CO (ONWI--Terra Tek)	Jointed Block Test: Cubic block, approx 2 m on each side, excavated on vertical sides by line drilling; loaded biaxially with flatjacks and electrical heaters emplaced in row of boreholes.	1979-present	Determine in situ thermal, mechanical, and hydrologic properties of jointed crystalline rock under controlled conditions of stress and temperature. Excavation of flatjack slots in distressed block of rock.	Flatjack grouted in place. Instruments acquired and calibrated to measure stress, strain, displacement, temperature, and velocity within the rock mass. Manufacturing and testing of flatjacks, pressure/permeability and ultrasonic equipment completed.	Board et al. 1979; Voegele, 1980
SHALE: Conasauga Formation, Oak Ridge, TN (Sandia)	Near-Surface Heater Tests: Single [illegible]tical heaters emplaced in surf[illegible] holes at two loca[illegible]tions; b[illegible] power level, as required for 38[illegible]rnal surface of heater at [illegible]me.	1977-78	Identify phenomenological aspects of thermal, mechanical, and hydrological responses of shale to heating; development of data base for design of future vault-type tests in other localities.	Final analysis of test and post-test data in progress. Good agreement between thermal modeling results and temperature measurements.	Krumhansl, 1979, Tyler, 1979a

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
SHALE: Eleana Formation, NTS, Nevada (Sandia)	Near-Surface Heater Test: Single electrical heater, 30 cm diam and 3 m length, emplaced in surface borehole with depth of 24.4 m; 2.5 kW power level for 21 days, followed by 3.8 kW until termination of heating phase.	1978-79 (250 days of heating)	Obtain phenomenological data for preliminary evaluation of waste storage potential of argillaceous rocks; assess predictive capabilities of thermomechanical models; evaluate applicability and reliability of laboratory-measured shale properties; assess experimental techniques.	Thermal and mechanical response of argillite dominated by effects of clay concentration near boiling point of water; thermal and thermomechanical modeling results agree fairly well with measurements and post-test observations; no "failure" mechanism identified to disqualify argillaceous rocks from further consideration as emplacement media for nuclear wastes.	McVey et al., 1979; Tyler, 1979a
SHALE: Conasauga Formation	Heater experiment.			Samples subjected to highest temperatures did not disperse, had minor changes in x-ray peaks of chlorite, and lost some argon from the fine fraction. Heating caused a decrease in $\delta^{18}O$, indicating a mineralogic change occurred.	Weaver, 1980
TUFF: G-Tunnel, NTS, Nevada (Sandia)	Water Migration/Heater Test: Single 1.9 kW electrical heater emplaced in borehole inclined 20° upward from horizontal, surrounded by boreholes for thermocouples and water migration sensors.	1979-80	Assess water generation/migration behavior of welded tuff under thermal loading conditions; measure in situ thermal conductivity and provide support for model and in conservation development.	Testing and data analysis in progress. Drying of rock due to processes other than simple boiling.	Tyler, 1979b; Johnstone, 1980

Appendix A (cont.)

TEST SITE (CONTRACTOR)	TEST DESCRIPTION	OPERATIONAL PERIOD	TEST OBJECTIVES	TEST RESULTS/STATUS	REFERENCE
TUFF: G-Tunnel, NTS, Rainier Mesa	Field experiment program in tuff, G-tunnel.	1980	Nuclide migration in nonwelded tuff.		Lincoln, 1980
		1982	Rock mechanics experiments in welded tuff.		
		1980	Extensive geological characterization of welded tuff in G-Tunnel.		
		1981	Preliminary rock mass property measurements, in situ stress, modulus of deformation, permeability.		
				1980 generalized geologic map completed for Yucca Mountian area.	Byers and Dixon, 1980
				On the basis of available data, moderately to fully welded tuff is a potential medium for a repository for heat-generating wastes. At a depth of 425 m, above the water table, but rock 95% saturated, 25% pore water by volume.	Lincoln, 1980
GRANITE: Lac du Bonnet batholith (massive pluton), Canada (AECL)	Underground research laboratory of several small rooms, depth of 300 m, access by ramp or shaft. "First test facility in the world which will be built below the water table and in an undisturbed rock formation."	1980-2000	1) "Correlation of surface features observed by geologist, geophysical and drilling methods with the nature of the rock mass at depth." 2) "Hydrogeology in a large intact rock volume by careful monitoring of water input/output, ventilation and water table changes during facility construction and, in the long term, during operation." 3) "The thermomechanical behavior of the rock mass due to in-situ stresses and the effect of heat generated by electrical heaters, for comparison with laboratory and mathematical analyses." 4) "The testing of engineered barriers such as backfill, sealing and grouting materials under realistic conditions."	1) Drilling from surface in progress.. 2) Modeling of surface hydrology in progress.	Boulton, 1980

APPENDIX B. PRELIMINARY MODELING FOR CONCEPTUAL DESIGN OF THE HYDRO/THERMOMECHANICAL EXPERIMENT

T. Chan and D. E. Wedge

B.1 HEATING PHASE

B.1.1. Introduction

Preliminary thermal and thermomechanical calculations have been undertaken for the hydro/thermomechanical experiment (Figure 1). The purpose of these calculations is to provide approximate numerical estimates of the power requirement and distribution of rock temperature, deformation, and stress as a function of time to guide the conceptual design of the experiment. Specifically, the following questions are addressed:

1. Is the reasonable power input of 2 kW per meter of chamber adequate?
2. What volume of rock will be heated?
3. Is the proposed time schedule for the field experiment adequate?
4. What are the optimal locations for (a) thermocouples, (b) extensometers, and (c) stress meters?
5. What are the effects of different rock properties?

Since this represents only the initial phase of modeling, a simple linear heat conduction/thermoelastic model has been employed. Typical granite properties were used. The results can be easily scaled for different rock properties.

B.1.2 Numerical Models and Results

A. Finite-Element Meshes. The finite-element meshes used for the two cases studied are illustrated in Figure B.1. The models are made to represent an infinitely long cylindrical test chamber excavated through rock, 1 m in diameter in the first case and 2 m in diameter in the second case. The coordinate system is axisymmetric about the z axis, which extends along the center line of the test chamber. Both meshes are composed of two-dimensional rectangular elements, each with 4 nodes. All the elements in both models extend from 0 to 1 m in the z (axial) direction, and they vary in length along the y (radial) direction, with shorter elements near the z axis and longer ones at greater distances.

The first several elements in each case are inside the chamber, which is filled with water. In the first case, the model extends to 63.5 m from the z axis and is composed of 65 elements and 132 nodes. The first 5 elements make up the first 0.5 m and are inside the chamber. The second model extends to 129 m from the chamber center line and contains 100 elements and 202 nodes, with the first 10 elements contained within the first meter inside the chamber.

For brevity, only the results of the 2 m diameter model are presented.

B. Thermal Models. A finite-element thermal conduction program ADINAT has been used to calculate the nodal temperatures for time periods up to 4000 days from the first application of heat. Heat is applied through the water and is allowed to conduct into the rock as time passes. All boundaries of the models are considered to be insulated, though the heat conducted by water is considered to cross the boundaries.

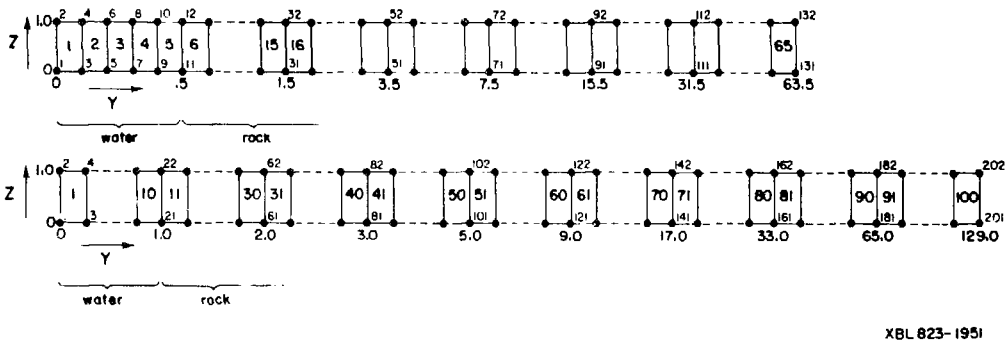


Figure B.1. Finite-element meshes used for thermal and thermomechanical analysis.

The thermal conductivity of the rock is taken to be 2.51 W/m K, or the average value for granite as quoted by Carslaw and Jaeger (1959). That of the water is taken as 100 times the nonconvective conductivity of water, or 60.2 W/m K. In a very rough manner, this allows for convection within the water. Thus a relatively constant temperature distribution is maintained through the water, which is 24 times more conductive than the rock. The specific heats of the water and the rock are given as 4.187×10^{-6} J/m K and 2.285×10^{-6} J/m K, respectively. The thermal and thermomechanical properties used are summarized in Table B.1.

In both cases, the initial temperature is set at 10°C for the entire system. For an initial period in each case, heat is applied to the water at a constant rate of 1 kW per meter of length along the chamber for the 1 m diameter chamber and 2 kW per meter of length for the 2 m diameter chamber. This initial period lasts until the water temperature at the wall reaches 100°C, which is 22 days in the first case, and 19 days in the second. During this initial period, the time step is set at 0.1 day. After the initial heating period the temperature of the water is held constant at 100°C and the rock is allowed to continue heating by conduction. The time steps used are 1 day for the period from the beginning of constant water temperature to 100 days, 10 days for the period 100 to 1000 days, and 100 days for times beyond 1000 days. The power consumed during this period is computed from the temperature gradient across the first rock element, using the heat conductivity of the rock and the cylindrical area through the center of that element. The heat used in raising the temperature of that element is considered to be negligible, since it is of small volume and the overall temperature does not change considerably during this period. The power consumption is plotted as a function of time for the 2 m models in

Table B.1. Material properties used in ADINAT and ADINA.

	Thermal Conductivity (W/m K)	Specific Heat (J/m^3 K)	Thermal Exp. Coeff. (K^{-1})	Young's Modulus (MPa)	Poisson's Ratio
Rock	2.51	2.285×10^6	1×10^{-5}	5.0×10^4	0.25
Water	60.2[a]	4.187×10^6	1×10^{-9}[b]	1.0×10^{-3}[b]	0.25

[a]Thermal conductivity of water is multiplied by a factor of 100 to approximately simulate convection.

[b]Very small values of thermal expansion coefficients and Young's modulus were used for water to "remove" the elements representing water from the thermomechanical calculation.

Figure B.2. The resulting temperature distributions are plotted for various times in Figures B.3 and B.4.

In Figures B.5 and B.6 are plotted the radii (r) to which the rock is heated to 50°C and to 12°C (2°C temperature rise), respectively, as a function of time. Also computed from the radii are the approximate volumes of rock heated to these temperatures. The shape of the heated volume (V) is assumed to be a cylinder 30 m in length with a hemispherical end cap, [illegible] with the above radii, minus the volume of the chamber:

$$V = \pi r^2 L + \frac{2}{3}\pi r^3 - \pi a^2 L,$$

where L = 30 m and a = 0.5 m or 1.0 m are the length and radius [illegible] chamber, respectively. The resulting volumes are p[illegible] as time, again for 50°C and 12°C, in Figures B.7 and B.8.

C. Thermomechanical Models. In order to compute the thermally induced displacements and stresses, the nodal temperature outputs from ADINAT are used in a sister program, ADINA, which, among other options, features a thermoelastic material model. The same finite-element mesh used in ADINAT is used with ADINA, but with the addition of thermoelastic properties and boundary conditions and a number of parameters to control the solution process. For this problem we use a linear static analysis for each of the chosen time steps, using the precalculated nodal temperatures for those time steps. The coefficient of thermal expansion for the rock is assigned constant at 1×10^{-5}/K, and Young's modulus is given as 30 GPa, [illegible] typical for granite (e.g., Clark 1966). The [illegible] water were given very small values.

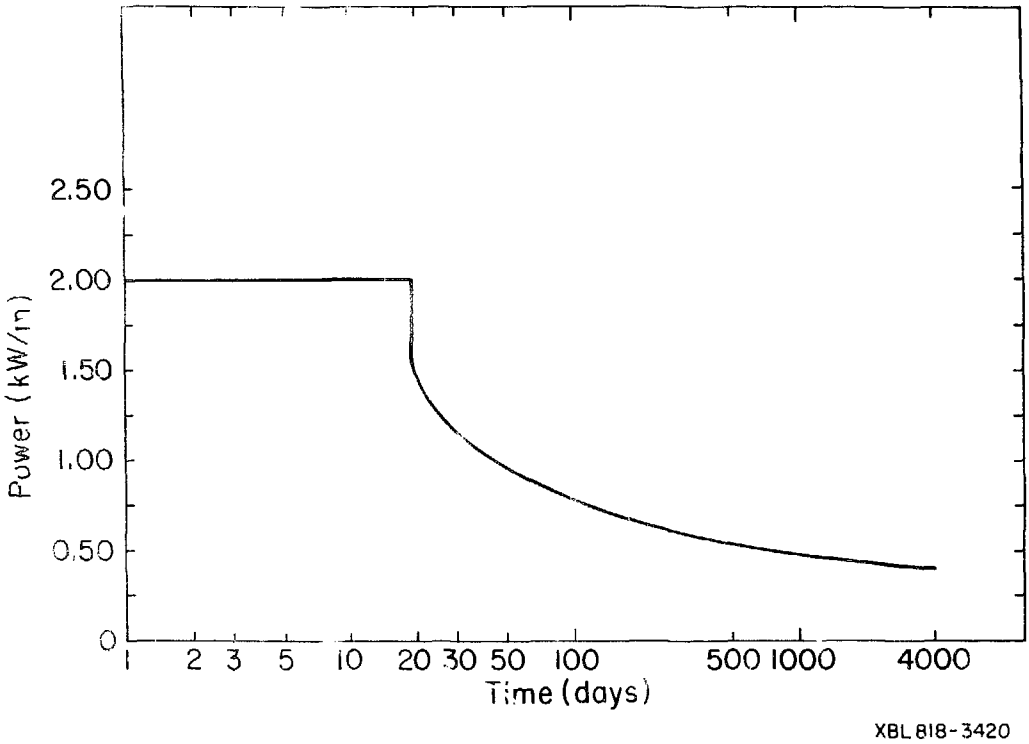


Figure B.2 Thermal power consumed per meter of length along the test chamber as a function of time (2 m chamber).

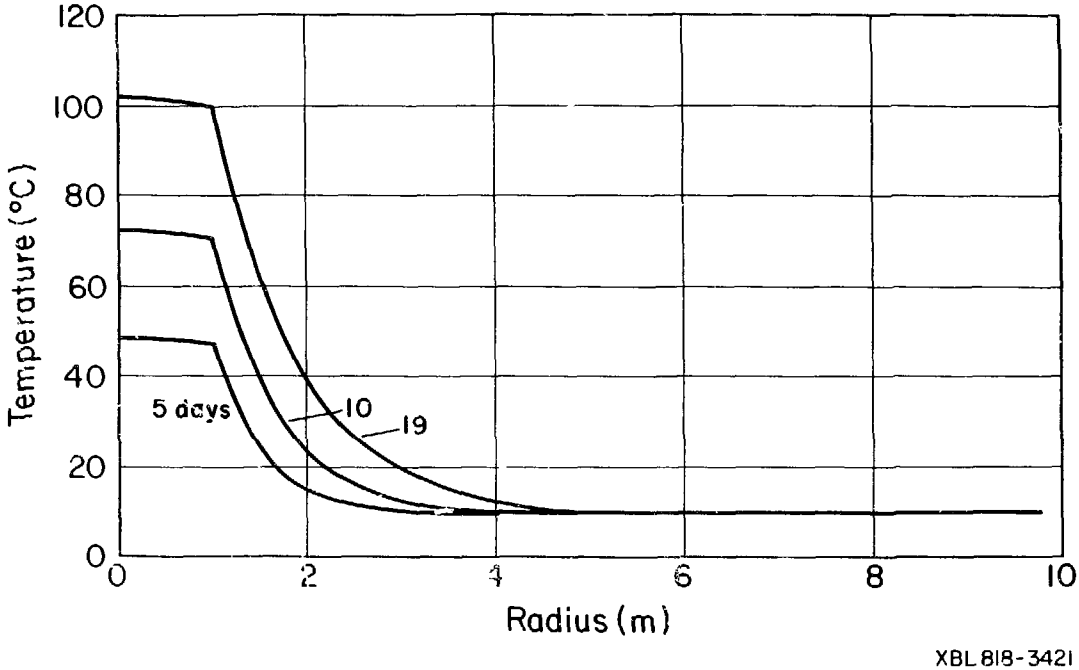


Figure B.3 Radial temperature distribution at various times during initial heating period (2 m chamber).

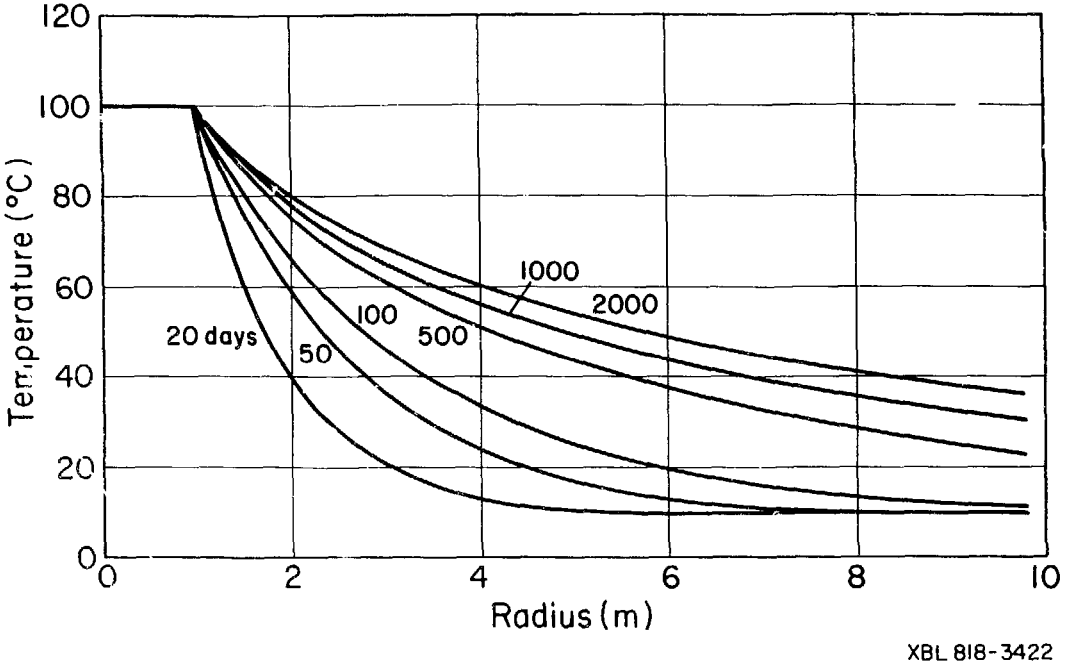


Figure B.4 Radial temperature distribution at various times during initial heating period (2 m chamber).

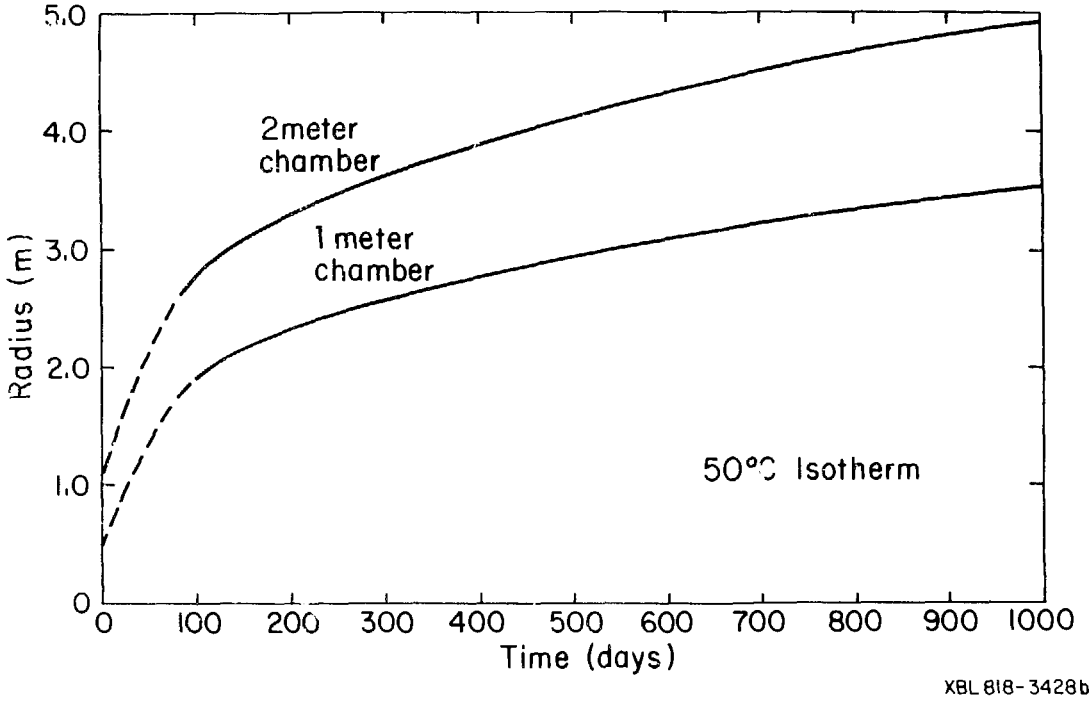


Figure B.5 Radius to which rock is heated to 50°C.

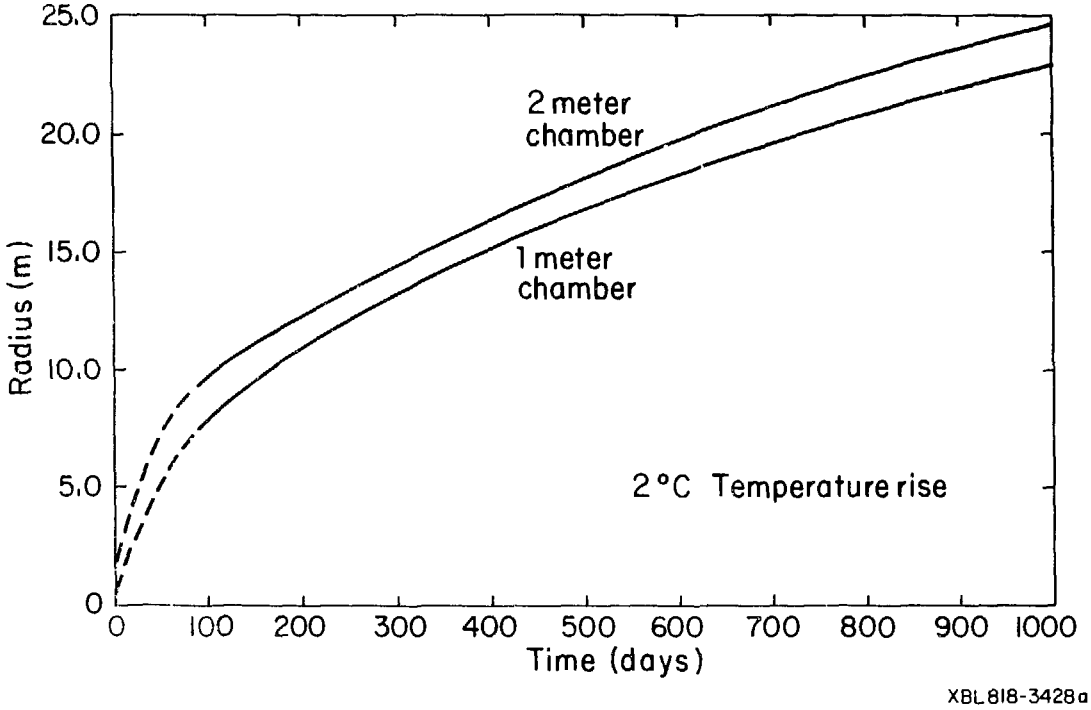


Figure B.6 Radius to which rock is heated 2°C above initial temperature.

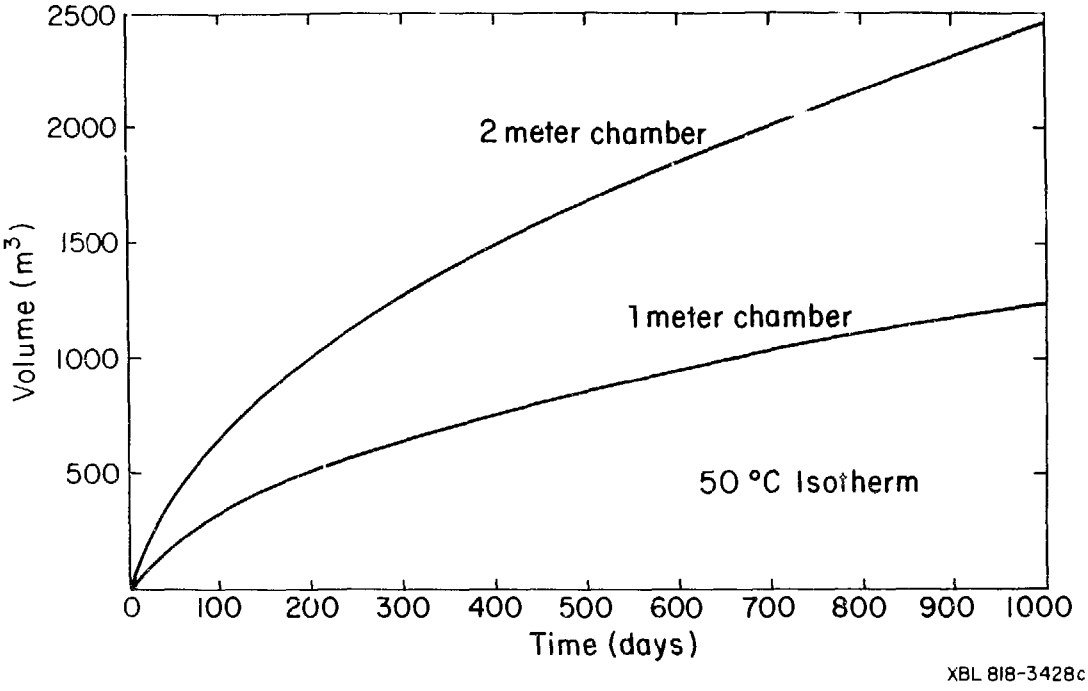


Figure B.7 Volume of . ... to at least 50°C.

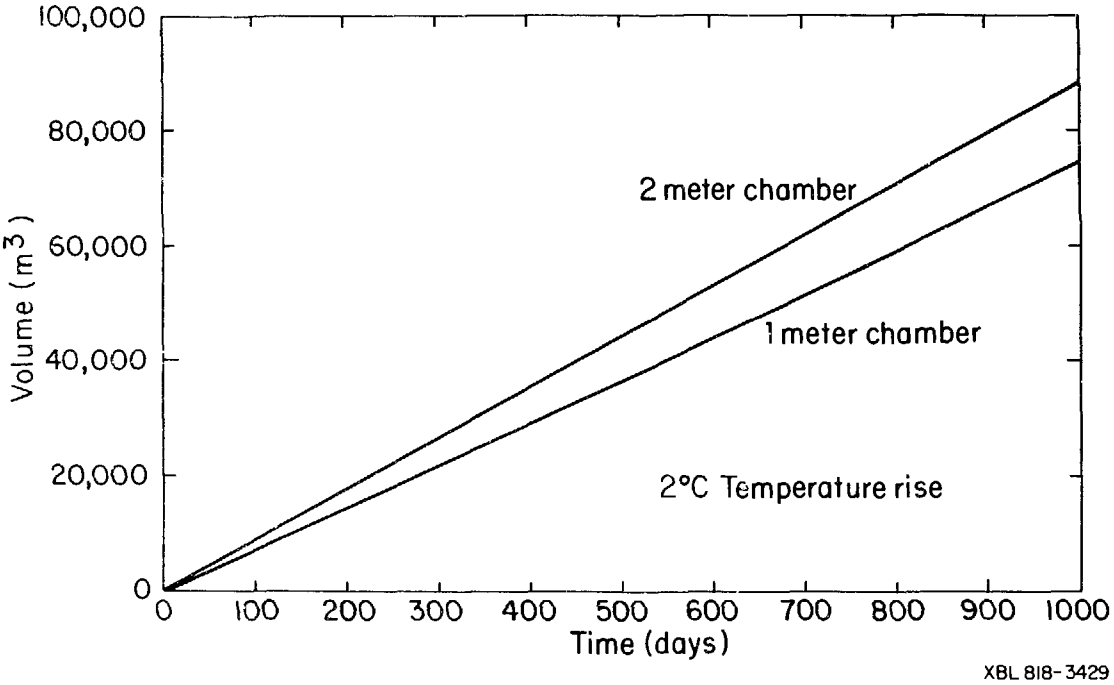


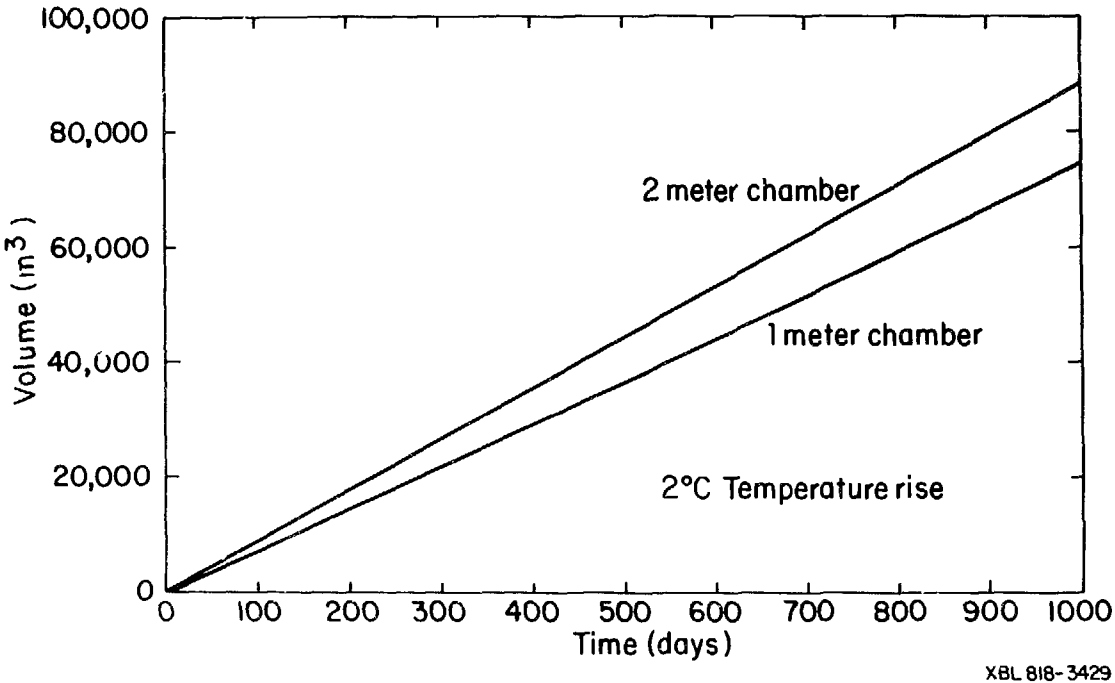
Figure B.8 Volume of rock heated to at least 2°C above initial temperature.

The initial stresses are set to 0, since the calculated thermal stresses for the linear case can be added directly to the in situ or pre-existing stress at the site. The reference temperature is set at 10°C, the same as the initial temperature with 0 thermal stress. In each model, the first two nodes (those along the z axis) and the last two (outermost) nodes are completely fixed. The remaining nodes are allowed to displace only along the y (radial) axis. The resulting thermally induced displacements are plotted in Figures B.9 and B.10 for the 2 m chamber. The calculated stresses are plotted at the Gaussian integration points within the elements for all three coordinate directions. These values correspond to the principal stresses, as the shear stresses along these directions remain at extremely small values. The calculated thermally induced stresses are plotted versus radius in Figures B.11 to B.13.

B.1.3. Confirmation of results by separate calculation

In order to confirm the temperature, displacement, and stress results obtained from ADINAT and ADINA, analytical and numerical calculations have been performed for comparison.

A. Temperature results. For several time steps in both models, during the constant heat input period, the total heat input was verified from the temperature output results by numerically integrating the temperature increase over all the elements, multiplied by the specific heat of the material. In every case, the total heat input was confirmed to within 0.5%. The heat input was also back-calculated during this early period from the



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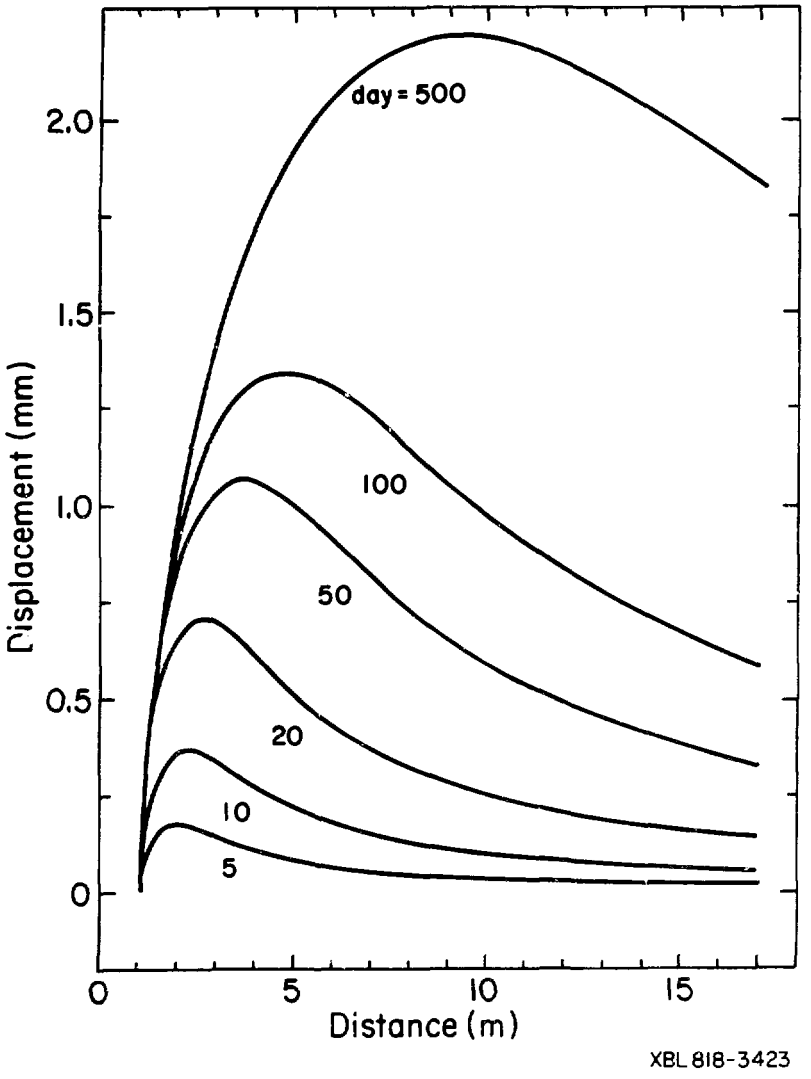

Figure B.9 Radial displacement for 5 to 500 days (2 m chamber).

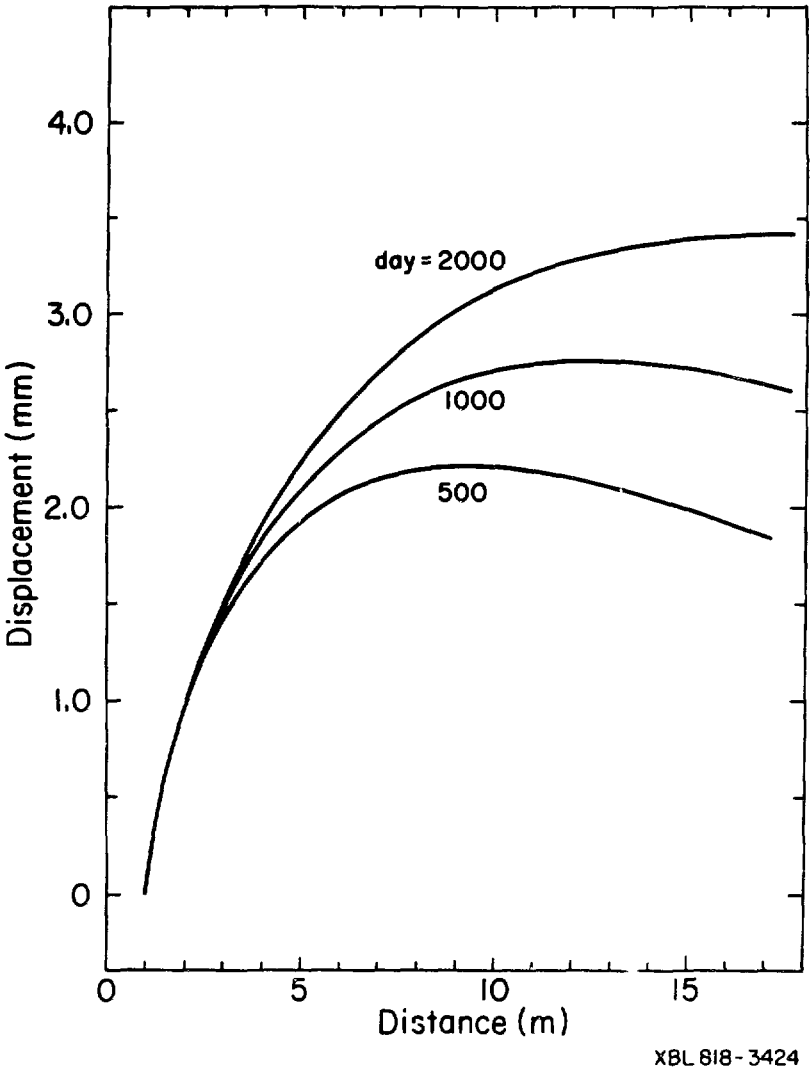

Figure B.10 Radial displacement for 500 to 2000 days (2 m chamber).

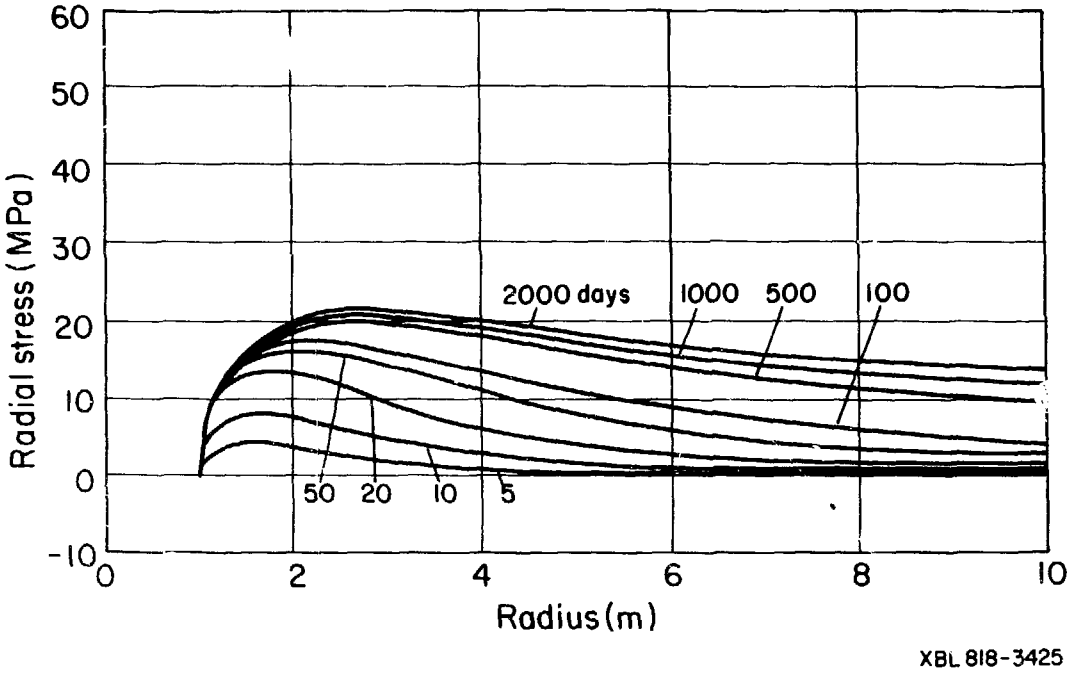

Figure B.11 Radial stress component as a function of radius for various times (2 m chamber).

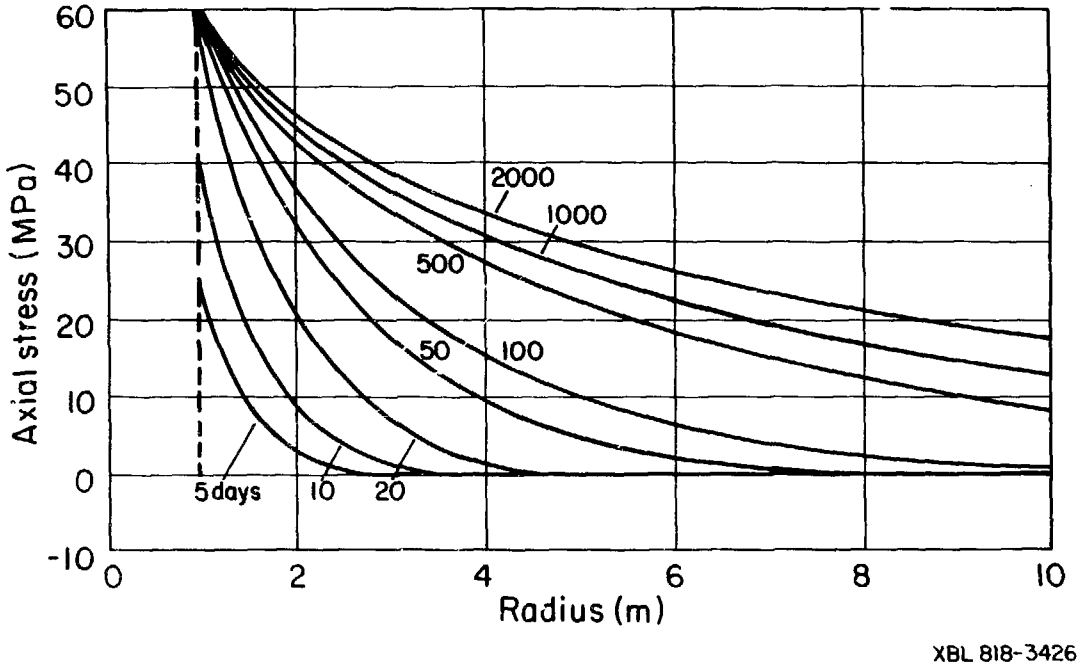

Figure B.12 Axial stress component as a function of radius for various times (2 m chamber).

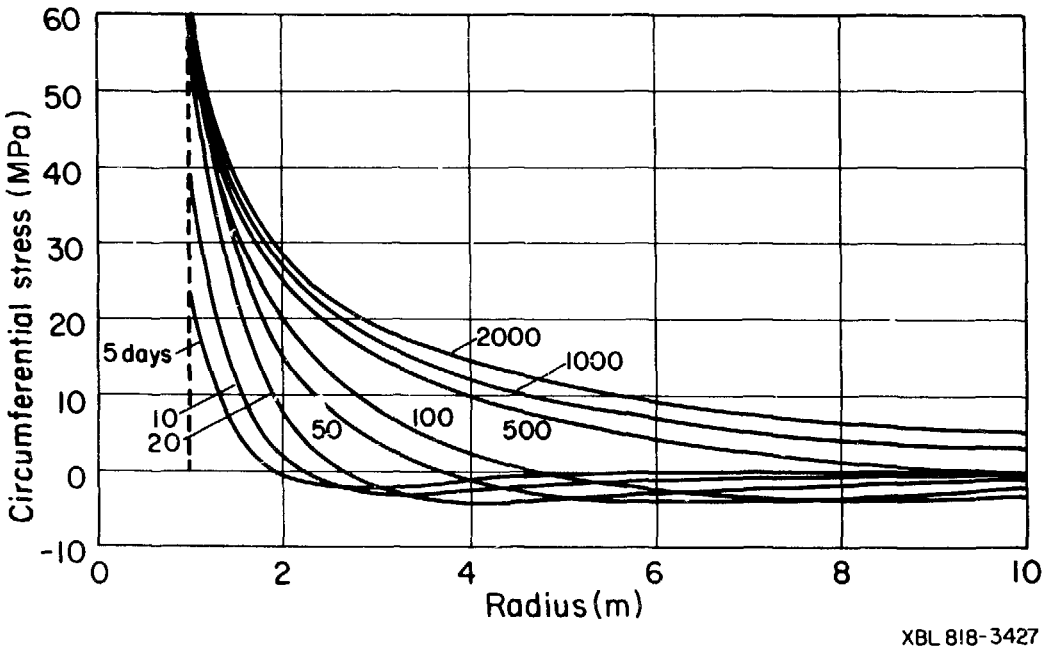

Figure B.13. Circumferential stress component as a function of radius for various times (2 m chamber).

temperature difference across the first rock element. This also confirmed the heat input rate to within 0.5%, giving confidence in the heat input rates back-calculated at a later stage of the experiment, since they were computed using the same technique.

B. Displacement and stress results. The displacements and stresses were calculated for several points at two different time steps for each model using expressions given by Chan and Cook (1979) for an infinitely long hollow cylinder subjected to a radial temperature distribution. This analytical model differs from the ADINA model in that the ADINA model has a fixed boundary condition at the distal end of the cylinder, whereas the analytical model assumes a free boundary at infinity. The two models should be in good agreement, as long as the temperature field is relatively close to the chamber compared to the boundary of the ADINA model.

Table B.2 shows values calculated analytically along with the corresponding numerically computed values (in parentheses) for displacements (u_r) and stresses (σ_r, σ_θ, σ_z being radial, circumferential, and axial components, respectively) as functions of radius from the chamber center line for the 1 m and 2 m chamber models. Both the analytical and numerical approaches use the radial temperature distribution calculated by ADINAT for 100 days after the beginning of heating. The numerical stress values shown for the nodal points were obtained from the ADINA output for the integration points by averaging the values for the two integration points adjacent to the given node. As shown in the tables, the results agree reasonably well, given the coarseness of the finite-element models and the difference in assumptions between the analytical and numerical models. The displacement values typically differ by 3% and never more than 10% for the 1 m chamber, and never more than

Table B.2. Comparison of stress and displacement values after 100 days of heating as calculated analytically and from ADINA (in parenthesis).

1 m Chamber

r (m)	u_r (mm)	σ_r (MPa)	σ_θ (MPa)	σ_z (MPa)
0.6	0.132 (0.132)	8.81 (8.08)	46.67 (58.9)	55.48 (61.1)
1.0	0.465 (0.46)	18.59 (18.6)	24.23 (24.3)	42.81 (42.8)
2.1	0.735 (0.86)	13.99 (16.5)	10.70 (8.4)	24.69 (24.7)
3.1	0.909 (0.99)	11.73 (12.9)	4.04 (3.07	15.77 (15.8)
3.9	0.960 (1.02)	9.84 (10.6)	1.17 (0.65)	11.02 (11.0)
5.1	0.956 (1.00)	7.50 (8.0)	-1.20 (-1.44)	6.29 (6.4)
6.3	0.902 (0.93)	5.73 (6.1)	-2.28 (-2.4)	3.45 (3.5)
7.5	0.827 (0.85)	4.41 (4.7)	-2.62 (-2.6)	1.79 (1.8)
9.9	0.671 (0.69)	2.73 (2.9)	-2.32 (-2.3)	0.42 (0.5)

2 m Chamber

r (m)	u_r (mm)	σ_r (MPa)	σ_θ (MPa)	σ_z (MPa)
1.05	0.072 (0.071)	2.75 (2.67)	55.64 (55.71)	58.39 (58.38)
1.55	0.636 (0.584)	16.41 (15.10)	29.12 (30.48)	45.53 (45.55)
2.1	0.948 (0.909)	18.06 (17.35)	17.54 (18.31)	35.60 (35.62)
3.2	1.259 (1.233)	15.74 (15.45)	6.60 (6.98)	22.35 (22.37)
4.2	1.357 (1.335)	12.92 (12.76)	1.66 (1.89)	14.58 (14.61)
5.4	1.354 (1.336)	10.03 (9.93)	-1.54 (-1.35)	8.50 (8.54)
7.4	1.218 (1.202)	6.58 (6.56)	-3.46 (-3.34)	3.12 (3.15)
9.8	1.007 (0.993)	4.11 (4.61)	-3.34 (-3.24)	0.77 (0.80)

8% for the 2 m chamber. The stress values for the radial and circumferential directions differ by as much as 20%, but are typically within 10%. The axial stress values are withir 2% in most cases, and typically differ by 0.1%.

B.1.4. Discussion

This section addresses the questions posed in the introduction.

1. Is the reasonable power input of 2 kW per meter of chamber adequate? The maximum power used, 2 kW per meter of chamber length, is well within the range of available equipment. This power level is sufficient to raise the chamber water temperature by 90°C within 19 days of heater turn-on, and is more than adequate for a timely response during the heating phase of this experiment.

2. What volume of rock will be heated? Figures B.7 and B.8 show the volume of rock heated to 50°C and to 2°C above the initial temperature, respectively, for both the 1 and 2 m chambers. On the basis of a 500 day time scale for the experiment, the volumes of rock heated to 50°C would be approximately 850 m^3 and 1670 m^3 for the 1 and 2 m cases, respectively. The corresponding volumes heated by 2°C in the same time scale are 36,500 m^3 and 43,500 m^3, respectively. These results are summarized in Table B.3, along with comparable volumes computed for the Stripa full-scale heater experiment. Also shown in parenthesis are the factors by which the heated volumes exceed the comparable volumes heated in the Stripa experiment. These greater volumes heated are especially significant in view of the scale dependence observed for rock properties by Witherspoon et al. (1979) and Heuze (1980).

3. Is the proposed time schedule for the field experiment adequate? Limiting the maximum radius at which stress and displacement measurements will be made to about 10 m, a duration of 500 days appears reasonable for the

Table B.3. Volume of rock heated by 2°C and to 50°C, Stripa full-scale heater experiment and hydro/thermomechanical experiment.

	Volume (m^3)	
	2°C temp rise	50°C isotherm
Stripa Full-Scale Heater Experiment		
(365 days)[a]	4200[b]	33[b]
Hydro/Thermomechanical Experiment		
(500 days)		
1 m chamber	36,500	850
2 m chamber	43,500	1670

[a]Time after start of heating.

[b]Computed from results of T. Chan et al. (1978).

experiment. At that time, the peak of the displacement curve is approaching the 10 m limit for both the 1 and 2 m cases, as can be seen in Figure B.9. Also at that time, the stress field has reached a significant value of about 7 to 10 MPa, in the radial and axial directions, at the 10 m radius (Figures B.11 and B.12), and the circumferential stress has returned to 0 after having been negative since the beginning of heating, as shown in Figure B.14. The slopes of these curves have reached nearly constant values by 500 days. Also by this time, the slopes of the 50°C volume curves (Figure B.7) are becoming nearly constant.

4. <u>What are the optimal locations for (a) thermocouples, (b) extensometers, and (c) stress meters?</u>

(a) <u>Thermocouples</u>. In distributing thermocouples over the radial distance, it would be desirable to compress the distribution toward the chamber, since first and second derivatives of temperature over radius are greatest near the chamber. It would be useful during the initial heating phase to install several thermocouples within the first 0.5 m of rock to observe the relatively local heating during this early period. The thermocouples at 10 m radius would respond at about 100 days and would indicate temperatures around 20°C at 500 days. One or two thermocouples could be placed at radii of 15 to 20 m to verify the predicted temperatures over a large distance from the heat source.

(b) <u>Extensometers</u>. Assuming that extensometers are to be placed in holes radiating from the test chamber and that there are no unsolvable problems with operating the extensometers in the hot water environment, it would be reasonable to measure displacements relative to the inside wall of the chamber. An anchor point placed at 0.5 m into the rock would show a major response in the first 20 to 50 days of the experiment and should

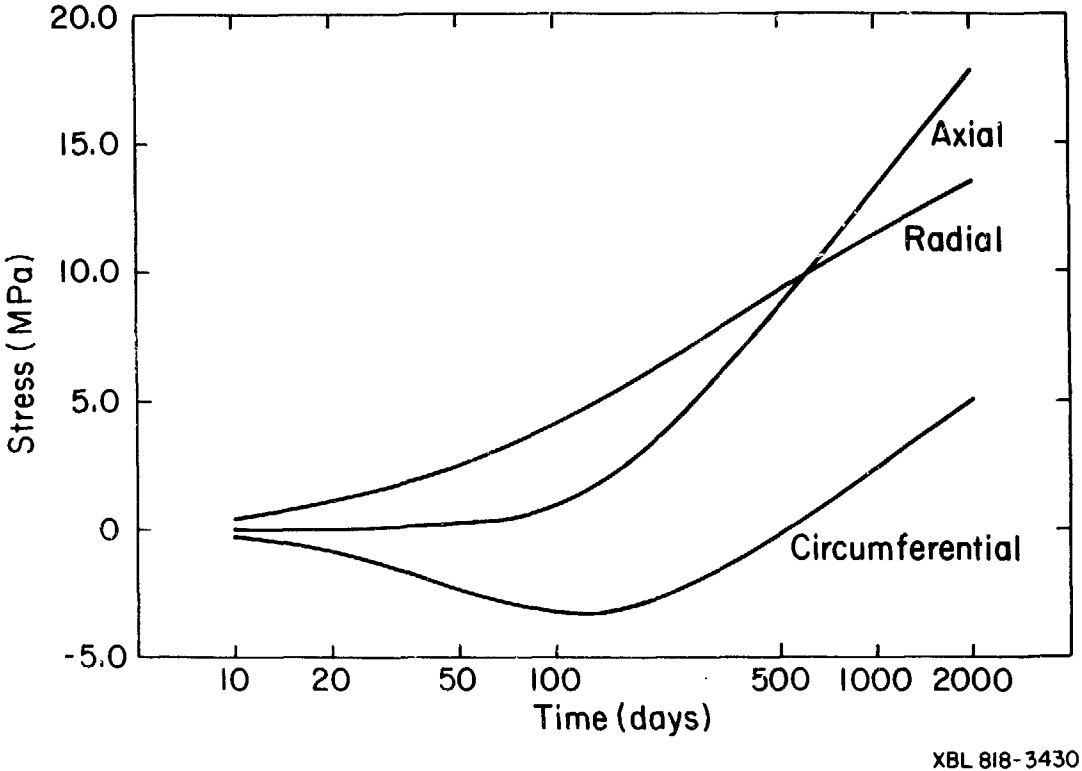

Figure B.14 Stress values at 9.8 m radius as functions of time (2 m chamber).

stabilize after that. This would give a good idea of the initial slope of the displacement curve at later times. Assuming that each extensometer would have 4 anchor points, as did those used previously, additional points would be well located at 3, 5, and 10 m radii. From these data, displacement curves could be reasonably approximated for any point in time. From previous experience, it is expected that because of the elongated shape of the heat source and hence of the isotherms, rock displacements parallel to the axis of the test chamber would be significantly greater than radial displacements calculated here. It is therefore important to place extensometers in the axial direction as planned.

(c) Stress meters. From the USBM or IRAD gauges, the state of stress perpendicular to the borehole is obtained--i.e., axial and circumferential stress data from a radial borehole. For locating these devices in radial boreholes, consideration is given to the direction of the stress components. It is desirable to have data points concentrated at smaller radii and as close to the wall of the chamber as possible. Again, 3, 5, and 10 m would appear as reasonable radii for placement of additional IRAD and USBM gauges in radial boreholes. For measurement of radial stress, gauges must be placed in axial boreholes, and measurements taken at about the same radii would be useful.

5. What are the effects of different rock properties? Results of the thermoelasticity calculations given here are based on material properties which are typical for crystalline rocks. A rough comparison between these properties and those for Columbia Plateau Basalt and welded tuff from the Nevada Test Site is presented in Table B.4. Because of e lower thermal conductivity and higher specific heat of basalt as compared with the properties employed for the thermoelasticity calculations, the temperature at a

Table B.4. Typical rock properties.

Property	Rock Type		
	Granite[a] (generic)	Basalt (Columbia River)	Tuff (welded) (Nevada Test Site)
Thermal Conductivity (W/m K)	2.5	1.5	1.6
Specific Heat (J/kg K)	880	1470	850
Thermal Exp. Coeff. (K^{-1})	10.0×10^{-6}	5.4×10^{-6}	7.0×10^{-6}
Young's Modulus (MPa)	5.0×10^{4}	7.0×10^{4}	3.7×10^{4}
Poisson's Ratio	0.25	0.26	0.19
Density (kg/m^3)	2600	2870	2200

[a]Properties used for calculations given in Table B.1.

specific point and time within the rock surrounding the test chamber will be less than that indicated by the results given in Figures B.3 and B.4. As a result the thermal stresses will also be less. This reduction in thermal stress is further enhanced by a lower thermal coefficient of expansion, although partially offset by a higher Young's modulus (thermal stress is approximately proportional to the product of change in temperature, thermal coefficient of expansion, and Young's modulus, ignoring the minor effect of Poisson's ratio).

In general, the properties of tuff, as they differ from granite, will also result in basically the same trends for the thermoelastic response as described for the basalt. Because the specific heat of tuff is nearly the same as that for granite and the thermal conductivity is not nearly as low as that for basalt, the temperature at a specific point and time will not be reduced to the extent as that described for the basalt. The lower value of Young's modulus for tuff, however, will further enhance the reduction in thermal stress.

On account of the interaction of the various physical properties and transient response, it is simpler to recalculate the temperature, stress, and displacement fields for site-specific material properties after they become available, rather than attempt to scale the results presented here.

B.1.5. Summary, Conclusion, and Recommendations

Preliminary thermal and thermomechanical calculations have been carried out using 1-D axisymmetric finite-element models for a 1 m diameter hot water test chamber and a 2 m diameter test chamber in a typical granitic rock. It was found that for the 2 m test chamber, which is the more likely size for operational convenience, a modest thermal power input of 2 kW per

meter of chamber length suffices to heat the water from 10°C to 100°C in approximately 20 days. Thereafter, the thermal power would have to be reduced to maintain a 100°C water temperature. At the end of a heating period of 500 days, approximately 2000 m^3 of rock would be heated to 50°C and 40,000 m^3 of rock would have a measurable temperature rise in excess of 2°C. Maximum compressive stress on the order of 60 MPa and radial displacement of about 2 mm are expected.

It is concluded that a relatively large volume of rock (approximately 50 times that in the Stripa full-scale heater test) can be influenced within a reasonable time period in the proposed experiment, thereby largely mitigating the size effect.

The calculations presented here represent only a first approximation. Further modeling work is recommended, in particular, a 2-D axisymmetric model to obtain axial displacements which are expected to be several times greater than the radial displacements.

B.2 COOLING PHASE

B.2.1. Introduction

The thermal and thermomechanical calculations discussed in Section B.1 have been continued in order to study the cooling phase of the hydro/thermomechanical experiment, beginning at 500 days after the start of heating. The calculations were done to compare the effects of forced cooling by refrigeration of the water in the chamber with those of natural cooling only by conduction, and to evaluate the feasibility of studying the effect of thermal cycling on the rock properties.

B.2.2. Models

The same finite-element models were used as for the heating phase, with the exception that for the thermomechanical calculations six-node elements were employed. Both the 1 and 2 m diameter chambers have been modeled as before, but only the results of the 2 m case are presented. The initial temperature conditions used were those calculated in Section B.1 for 500 days. Three different cooling cases were modeled for each of the chamber sizes. The first involved simply turning off the heaters at 500 days and allowing the system to relax toward equilibrium temperature through conduction. In the second case, active cooling was applied through the water in the test chamber, again beginning at 500 days. The initial rates of cooling were 1 kW/m of length along the chamber for the 1 m chamber and 2 kW/m for the 2 m chamber. These rates of cooling were maintained until the water temperature reached 10°C (9 days for the 1 m chamber and 13 days for the 2 m chamber). At this point, the cooling was stopped, and again the system was allowed to approach equilibrium through conduction alone. The third case begins exactly the same as the second case, but when the water temperature reaches 10°C, it is held fixed at 10°C, and it is assumed that heat is removed from the water at such a rate as to maintain this temperature.

B.2.3. Results

Since the major interest is in the 2 m design, we focus our remarks on this model, but the same comments will apply at least qualitatively to the 1 m chamber as well.

A. Thermal calculations. The radial temperature distributions which result from the three cooling cases are shown in Figures B.15 to B.17 for

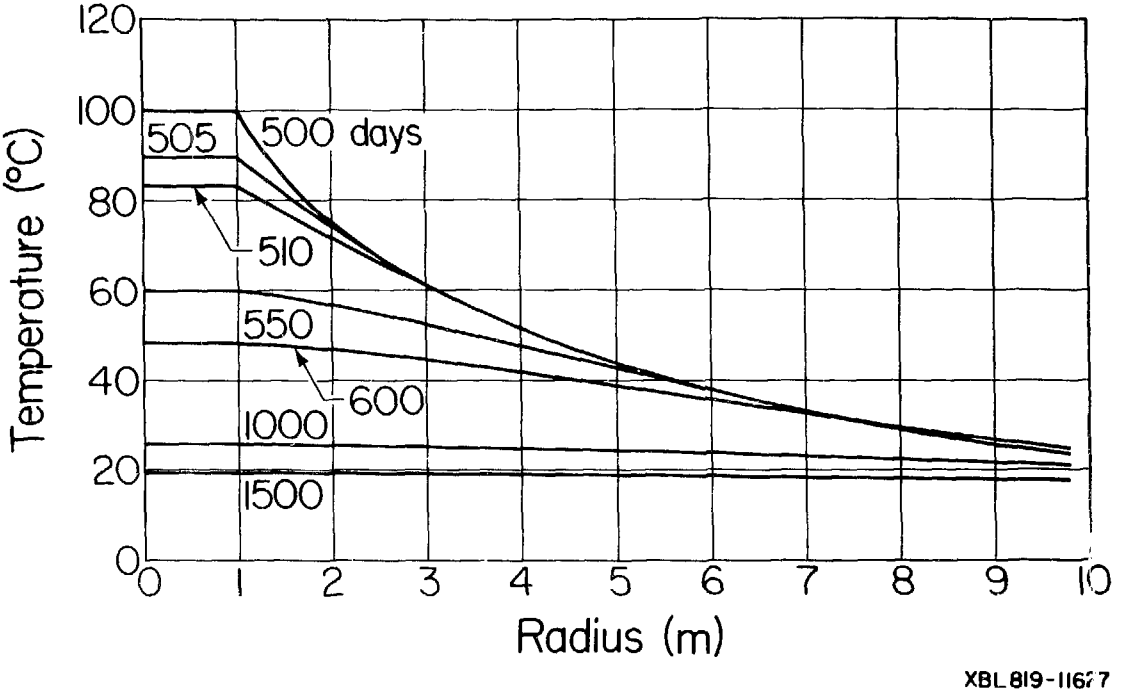

Figure B.15 Temperature distribution for various times; natural cooling beginning at 500 days (2 m chamber).

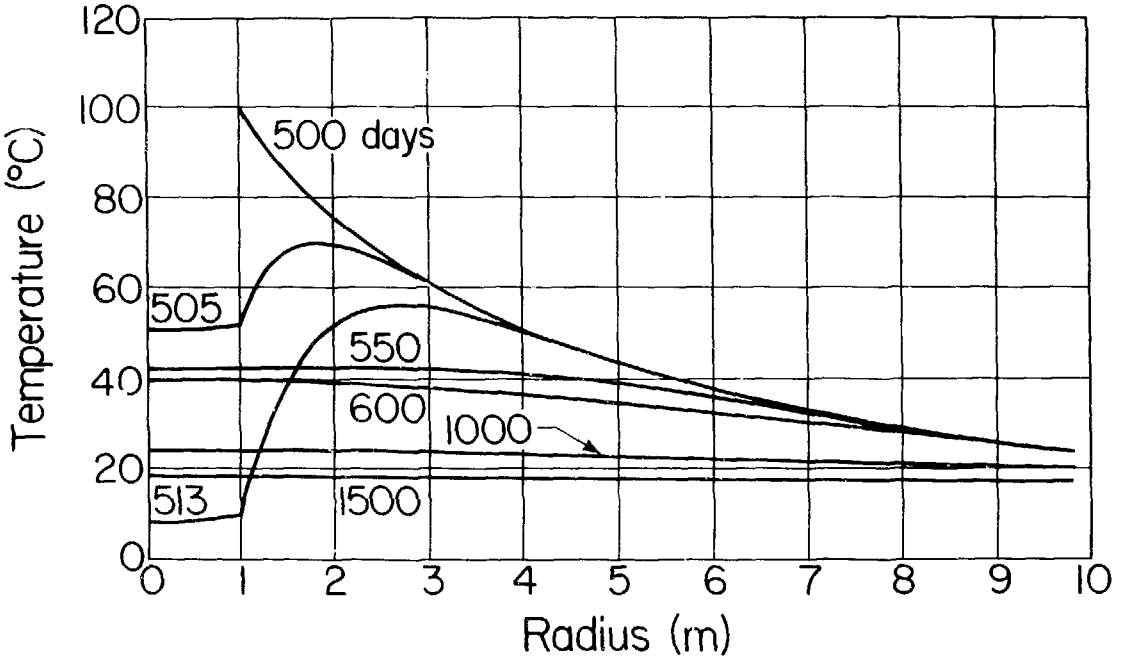

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Figure B.16 Temperature distribution for various times; forced cooling to 10°C water temperature (500 to 513 days) followed by natural cooling (2 m chamber).

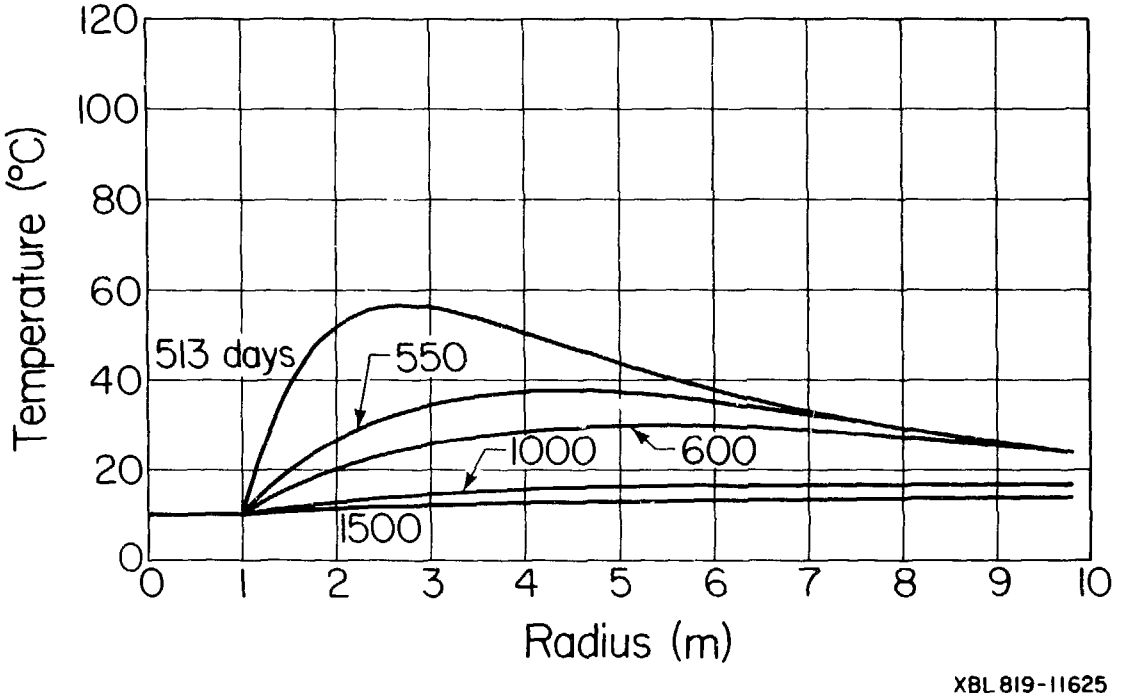

Figure B.17 Temperature distribution for various times; forced cooling to 10°C water temperature (500-513 days) followed by holding at 10°C (2 m chamber).

natural cooling, for forced cooling to 10°C followed by natural cooling, and for forced cooling followed by holding at 10°C, respectively. For the first case (pure relaxation), the water temperature decreases relatively rapidly at first and more slowly at later times as the temperature gradient decreases. It is clear that the peak in the temperature curve is always at the center line of the chamber, with the temperature decreasing monotonically with radius.

In the second case (forced cooling followed by natural cooling), the water temperature drops much more rapidly during the initial forced cooling period, forming a peak in the temperature curve which moves outward. When the active cooling is turned off, the water temperature again rises due to conduction back from the rock. By 600 days, the temperature has risen to about 7°C below the corresponding temperature for the pure relaxation case, and the temperature peak has shifted back to the chamber centerline. The difference between the 600 day curve for the first and second cases is detectable (greater than 2°C difference) out to about 8 m. At longer times, the two curves become progressively more similar, until at 1500 days they are virtually indistinguishable. The effectiveness of this short-term cooling is questionable, since the total energy removed is severely limited by the short duration of the cooling. For this reason, no thermomechanical calculations were done for this case, but only for the other two cases.

The third case (forced cooling to 10°C and then maintaining that temperature) yields results that differ significantly from those of the first case, as shown in Figure B.17. The first 13 days of cooling are identical to case two, and the temperature curves for 500 and 505 days are not repeated from Figure B.16. For this cool-and-hold case, the temperature peak continues to move outward as it decreases, until by 1000 days it is at about

10 m radius. Comparing with the pure relaxation case (Figure B.15), it is clear that at 600 days the difference between the two cases is detectable to about 8 m radius, indicating that the significant effect of the cooling has reached about that far. By 1000 days, the difference is easily detectable at 10 m. The maximum temperature in the entire system is plotted as a function of time for the first and third cases in Figure B.18. It is seen that the maximum temperature for the forced cooling case is about half that for the case of natural cooling (relative to the reference temperature, 10°C), being somewhat more than half before about 700 days and less than half for longer times. The cooling power required to maintain the 10°C water temperature is plotted vs. time in Figure B.19.

B. Thermomechanical calculations. ADINA has been employed for the first and third cooling cases, representing natural and forced cooling (cool to 10°C and hold), respectively. The input parameters used were exactly as for the heating phase, with the following exceptions: (1) as previously mentioned, six-node elements were used here rather than the four-node elements of the earlier analysis; (2) the temperature inputs were as described in the previous section; and (3) the time increments were reduced to 0.1 day beginning at 500 days through the period of constant cooling power, 1 day from that time to 600 days, and 10 days for 600 to 1500 days (for the natural cooling case, increments of 1 day were used from 500 to 600 days). The resulting radial displacements are shown as functions of radius for various times in Figures B.20 and B.21 for the two cases. In both cases, the displacements decreased beginning at 500 days, with the initial rate of drop at 10 m radius being over three times as fast for the case of forced cooling

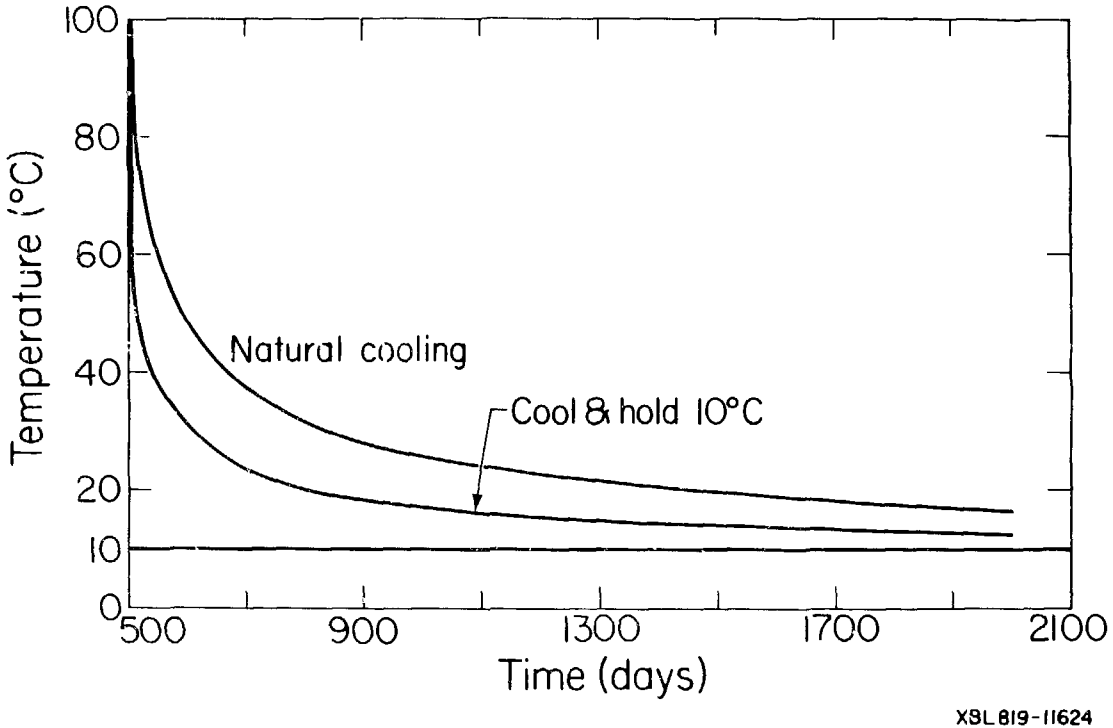

Figure B.18 Maximum temperature in the system as a function of time for natural cooling and for forced cooling (cool-and-hold case) (2 m chamber).

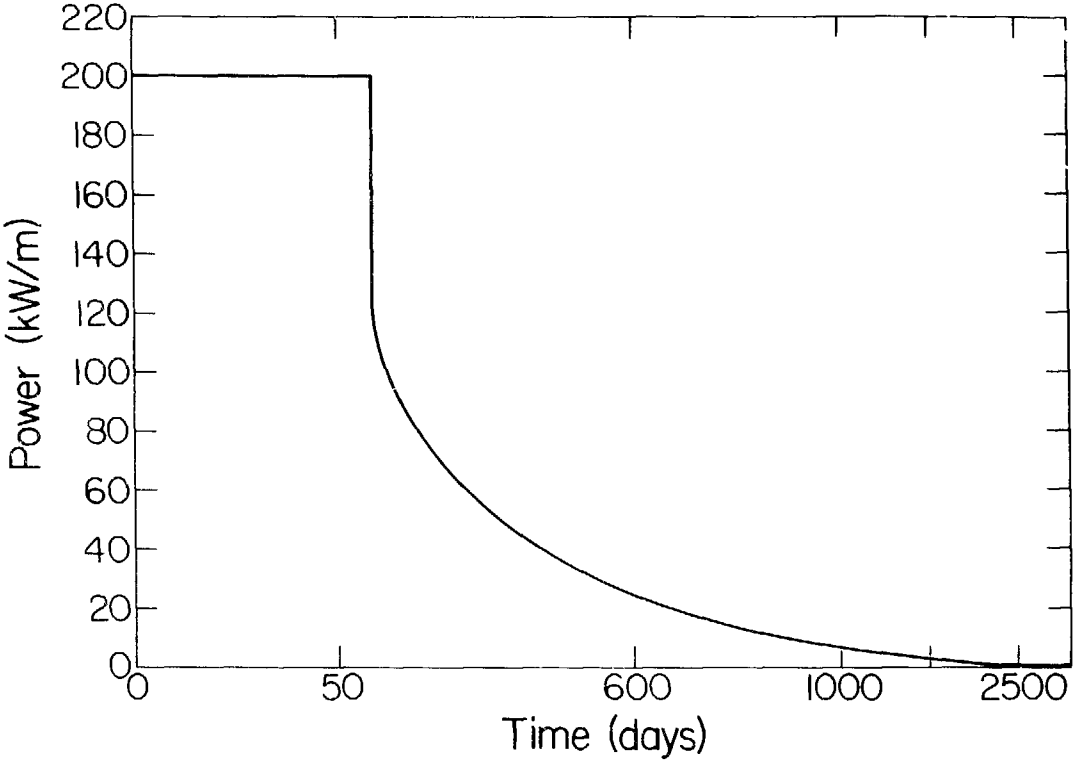

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Figure B.19 Cooling power (rate at which energy is removed from the water) required to maintain 10°C water temperature from 513 days onward.

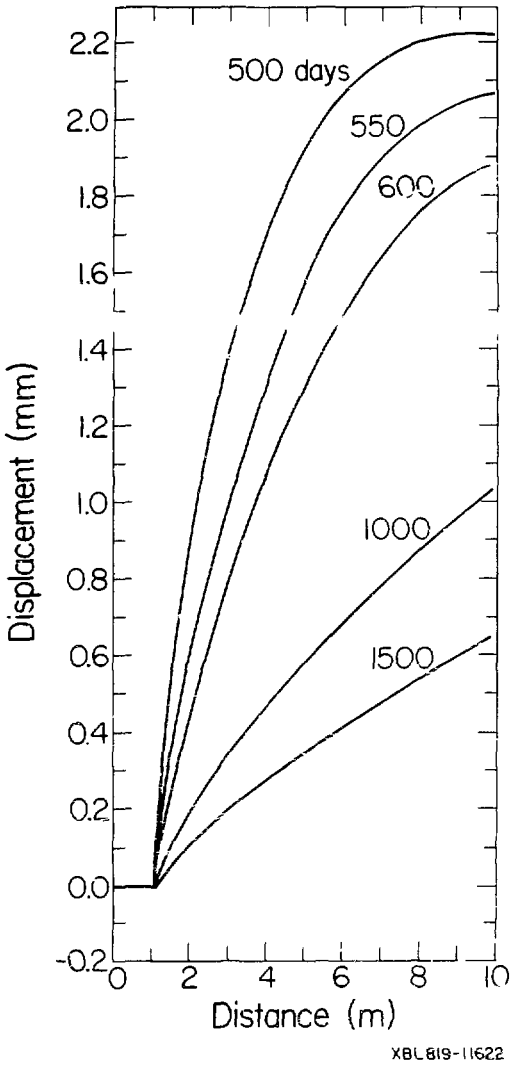

Figure B.20 Radial displacement distribution for various times; natural cooling beginning at 500 days (2 m chamber).

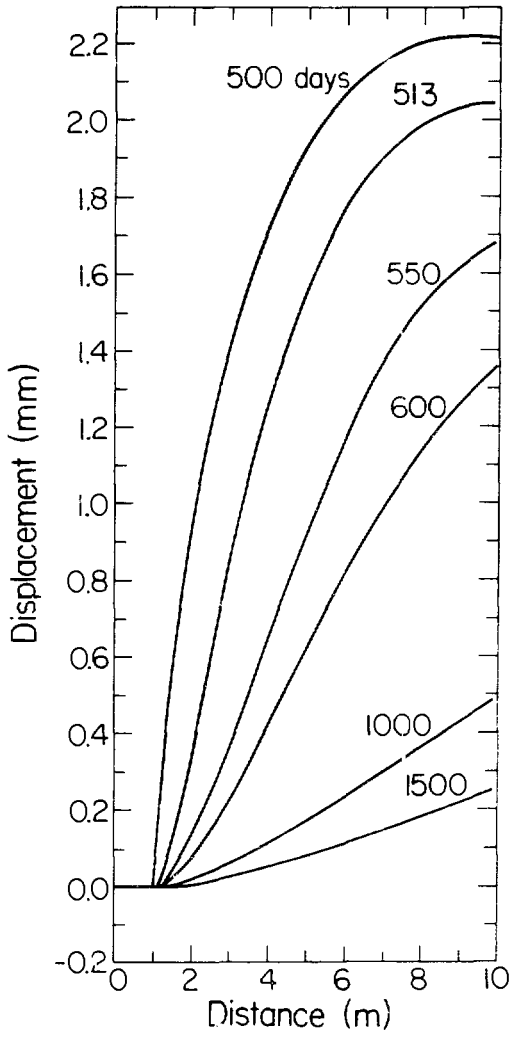

Figure B.21 Radial displacement distribution for various times; forced cooling to 10°C water temperature (500 to 513 days) followed by holding at 10°C (2 m chamber).

as for natural cooling. For longer times (1000 and 1500 days), the displacements for the forced cooling case at 10 m is less than half that for the natural cooling case.

The resulting stress components are shown as functions of radius in Figures B.22 to B.24 for the case of natural cooling and in Figures B.25 to B.27 for the forced cooling case. The effect of forced cooling on the stress is restricted to the relatively near field, with dramatic effects on all three components in the first 5 m, but with insignificant effects at 10 m after 100 days of cooling. For longer times, the radial and axial components for the forced cooling are about half the values for the natural cooling case at 10 m and the circumferential component is still unaffected at that distance.

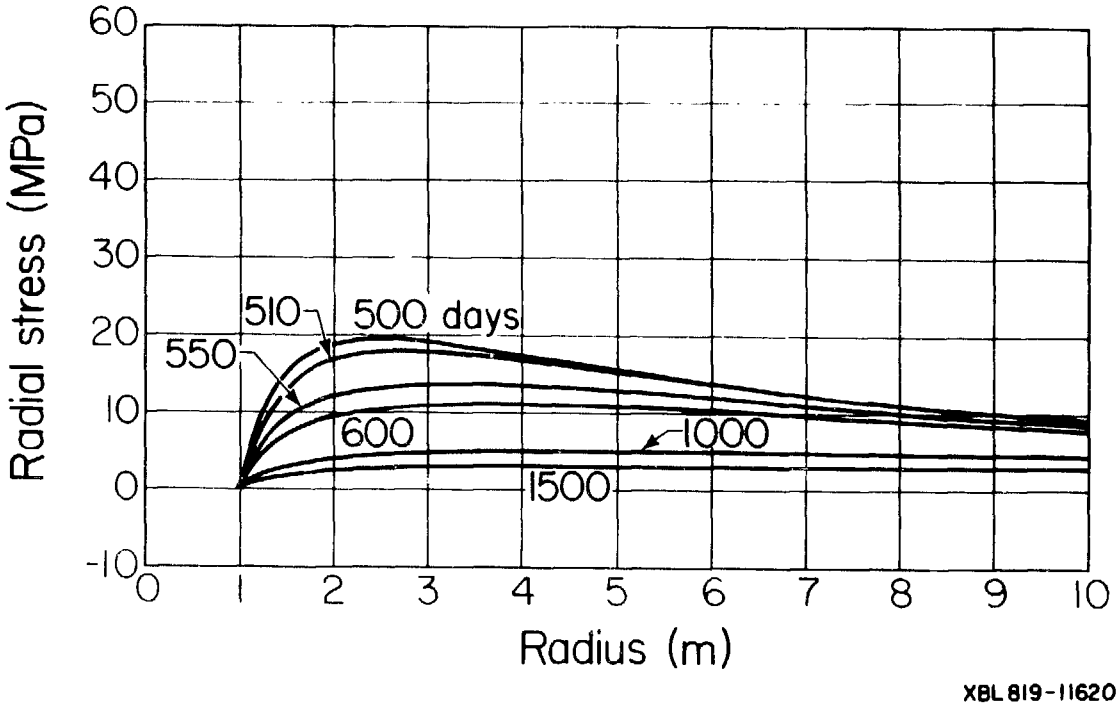

Figure B.22 Radial stress distribution; natural cooling beginning at 500 days (2 m chamber).

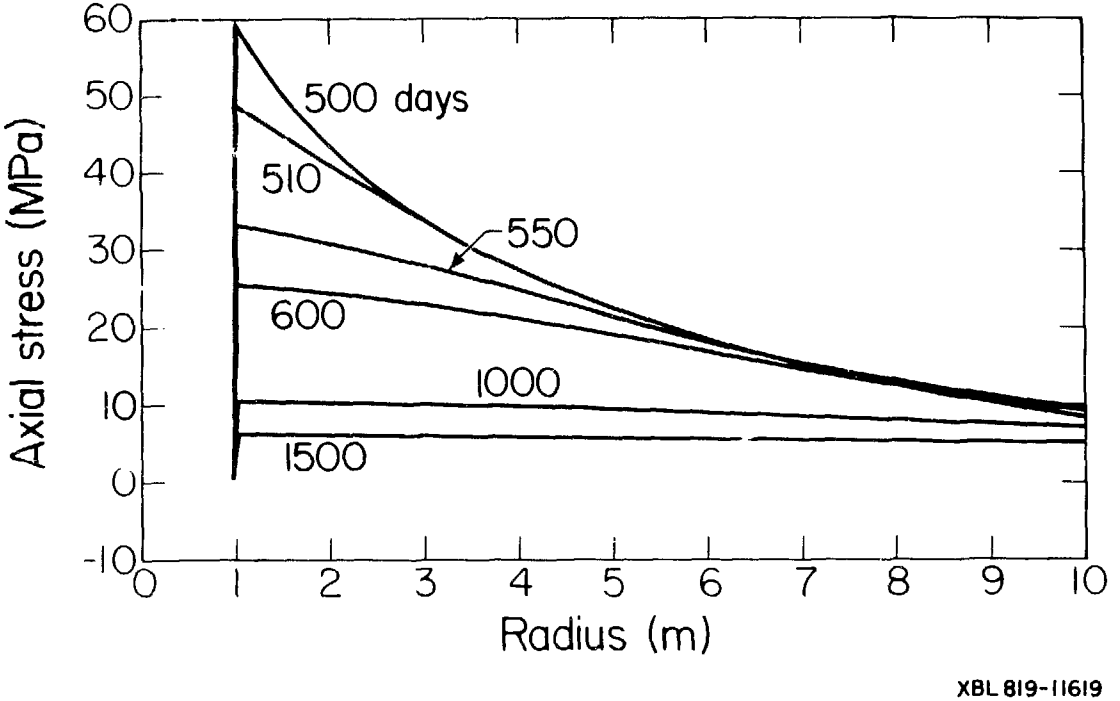

Figure B.23 Axial stress distribution; natural cooling beginning at 500 days (2 m chamber).

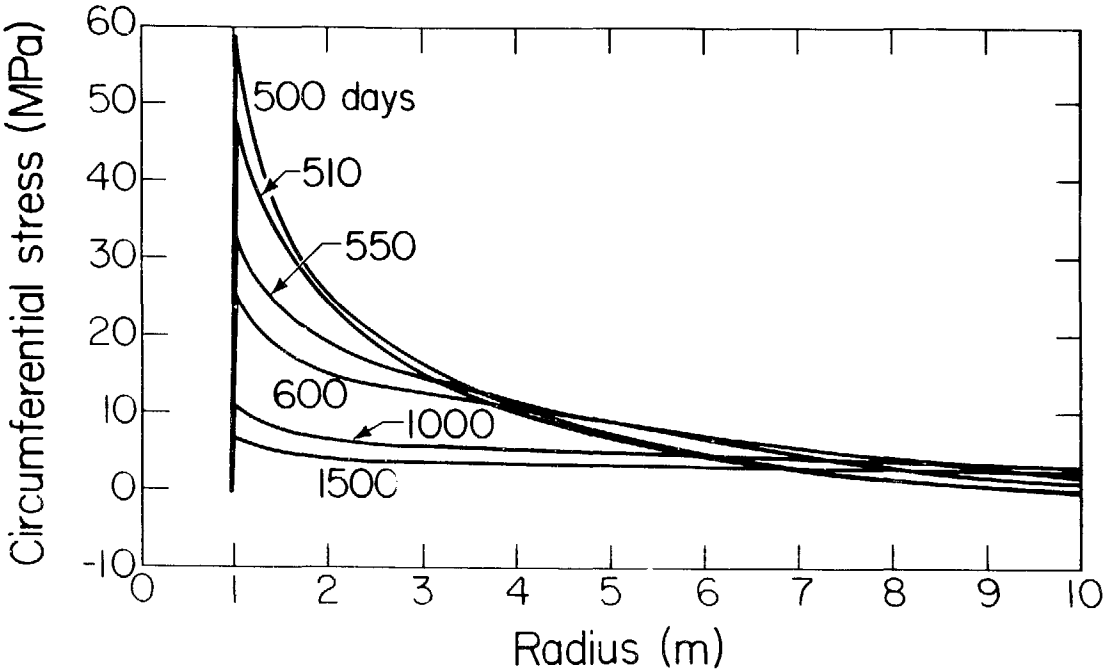

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Figure B.24 Circumferential stress distribution; natural cooling beginning at 500 days (2 m chamber).

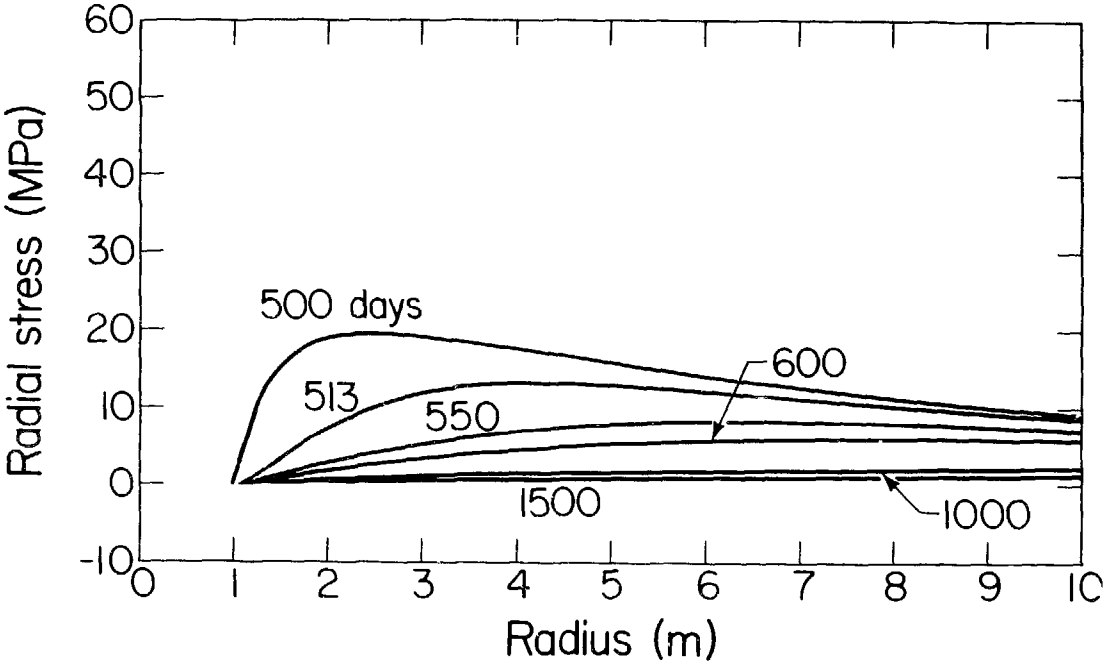

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Figure B.25 Radial stress distribution; forced cooling to 10°C water temperature (500 to 513 days) followed by holding at 10°C (2 m chamber).

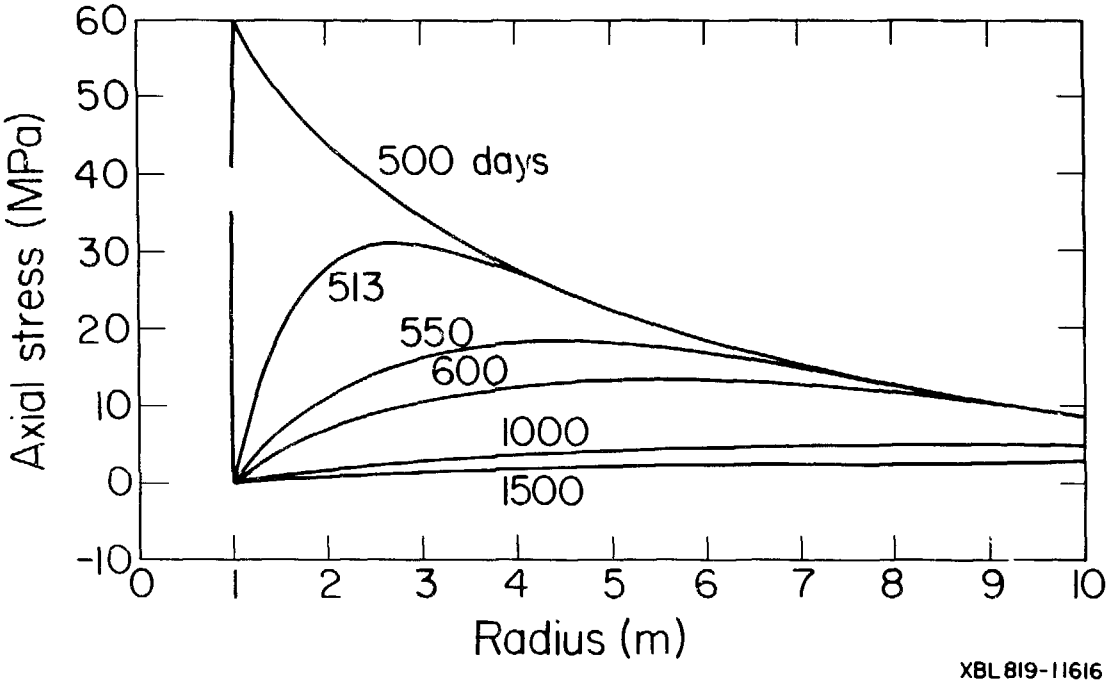

Figure B.26 Axial stress distribution; forced cooling to 10°C water temperature (500 to 513 days) followed by holding at 10°C (2 m chamber).

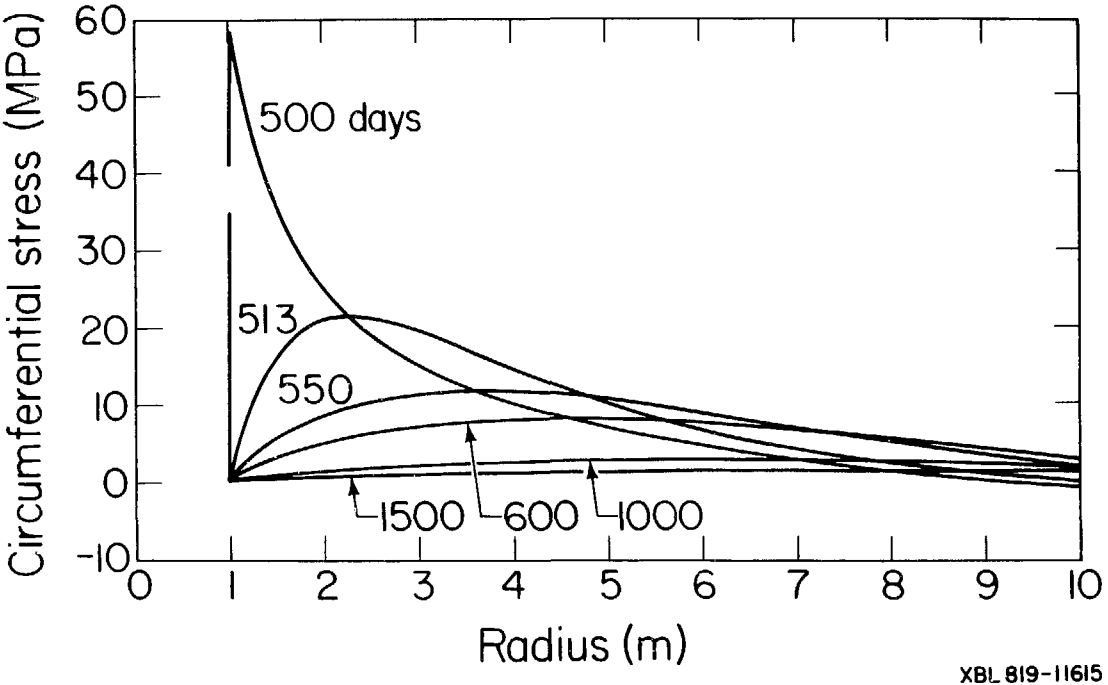

Figure B.27 Circumferential stress distribution; forced cooling to 10°C water temperature (500 to 513 days) followed by holding at 10°C (2 m chamber).

B.2.4. Discussion and Conclusion

These thermal and thermomechanical calculations indicate that forced cooling can be quite effective in decreasing the peak temperature and thermal stresses in the experimental system described, given that the cooling is maintained over an extended period of time. For the study of the effects of thermal cycling on rock properties, however, there are serious disadvantages to forced cooling. Ideally, for direct comparison of thermomechanical effects, the temperature distribution at a given time for a given radial distance in the cooling phase should be identical to the temperature distribution at a comparable time and distance in the heating phase. This idealization, of course, is impossible to achieve in an experiment of this configuration, but the forced cooling creates a distribution diverging much more radically from the ideal than does a natural cooling scheme. The natural cooling maintains the monotonic decrease in temperature with radius that was indicated for the heating phase (although the second derivative is reversed in sign for longer times), whereas the forced cooling creates a steep positive gradient in the near field. One advantage to forced cooling would be the time factor (which could be considerable). For example, to achieve a maximum temperature of 30°C would take just over 100 days if the cooling is forced, whereas the same maximum temperature is not reached by natural cooling until about 340 days (see Figure B.18).

APPENDIX C. COST ESTIMATES

C.1 HYDRO/THERMOMECHANICAL EXPERIMENT

1. Construction and Fabrication

(a) Drilling gallery, 30 ft long, 15 ft wide, 30 ft high (est. by T. McCusker):

- direct cost	=	$126,242
- mobilization	=	$ 24,500
- standby, 16 hr @ 727/hr	=	$ 11,632
- indirect cost, 0.53 mo @ $46,650/mo	=	$ 24,582
subtotal	=	$186,956
- markup, 20% of sub total	=	$ 37,391
contract total	=	$224,347
- architect/engineer, 16% of contract	=	$ 35,896
total	=	$260,243 w/o overhead
		$390,364 w/ overhead @ 50%

(b) monitoring drill holes:

Fifty-two axial boreholes, avg length 150 ft: 30 for pressure/flow/tracer/temperature instrumentation, 10 for stress meter/temperature instrumentation, 12 for extensometer/temperature instrumentation, several of which can be used for geophysical tests.

Eight radial boreholes, avg length 25 ft, for extensometer/temperature and stress meter/temperature instrumentation.

- drilling, 8000 ft @ $35/ft	=	$280,000
- survey, 60 holes @ $300/hole	=	$ 18,000
total	=	$298,000 w/o overhead
		$447,000 w/ overhead @ 50%

(c) Test chamber, 125 ft long, 6 ft diameter (est. by T. McCusker):

- direct costs, 125 lineal ft @ $745/ft	=	$ 93,125
- mobilization	=	$ 24,500
- standby, 16 hr @ $727/hr	=	$ 11,632
- indirect costs, 0.50 mo @ $46,650/mo	=	$ 23,465
subtotal	=	$152,722
- markup, 20% of subtotal	=	$ 30,544
contract total	=	$183,266
- architect/engineer, 16% of contract	=	$ 29,323
total	=	$212,589 w/o overhead
		$318,884 w/ overhead @ 50%

(d) Liner and bulkhead, 6 ft diameter, 1 in. steel plate liner with steel/concrete bulkhead, 3 ft thick (est. by T. McCusker):

- direct costs, 48 lineal ft @ $4120/ft	=	$197,760	
- mobilization	=	$ 24,500	
- indirect costs, 0.95 mo @ $46,650/mo	=	$ 44,429	
subtotal	=	$266,689	
- markup, 20% of above	=	$ 53,338	
contract total	=	$320,026	
- architect/engineer, 16% of contract	=	$ 51,204	
total	=	$371,230	w/o overhead
		$556,846	w/ overhead @ 50%

2. Operating Equipment and Services

(a) Instrumentation (including hardware, transducer, signal conditioning, and wiring/plumbing):

- pressure/flow, 300 channels @ $1,200/channel	=	$360,000	
- tracer injection/detection system	=	$100,000	(variable)
- flow meters or collection system	=	$ 20,000	
- temperature, 420 channels @ $300/channel	=	$126,000	
- extensometers, 100 channels @ $1,000/channel	=	$100,000	
- stress meters, 100 channels @ $800/channel	=	$ 80,000	
total	=	$ 786,000	w/o overhead
		$1,179,000	w/ overhead @ 50%

(b) Data acquisition system:

- computer (similar to Mod-Comp used at Stripa)	=	$200,000	
- software development	=	$ 40,000	
total	=	$240,000	w/o overhead
		$360,000	w/ overhead @ 50%

(c) Mechanical plant (heating and cooling):

- 20 ton refrigeration unit	=	$ 15,000	
- 60 kW heater system	=	$ 5,000	
- pumps and exchangers	=	$ 10,000	
- controls and plumbing	=	$ 5,000	
- chamber water circulation	=	$ 5,000	
- chamber water storage tank	=	$ 10,000	
total	=	$ 50,000	w/o overhead
		$ 75,000	w/ overhead @ 50%

(d) Travel and per diem (only a rough est.; cost largely dependent on the location of the scientific personnel and underground test facility):

- travel, avg 70 round trips/yr for 7 yr; 490 trips @ $1,000/flight	=	$490,000	
- per diem, avg 1,500 man-days/yr for 7 yr (4 man-yr); 10,500 days @ $50/day	=	$525,000	
- vehicles at site, 2 @ $500/mo for 7 yr	=	$ 84,000	
	total =	$1,099,000	w/o overhead
		$1,648,500	w/ overhead @ 50%

(e) Computer costs:

- design and fabrication	=	$ 95,000	
- data analysis and modeling, 6.5 yr @ avg $170,000/yr	=	$ 1,105,000	
	total =	$ 1,200,000	w/o overhead
		$ 1,800,000	w/ overhead @ 50%

(f) Consultants:

- avg of $70,000/yr for 7 yr	=	$490,000	w/o overhead
		$735,000	w/ overhead @ 50%

(g) Miscellaneous.

- shipping, avg $20,000/yr for 7 yr	=	$140,000	
- misc. equipment and supplies, avg $70,000/yr for 7 yr	=	$490,000	
	total =	$630,000	w/o overhead
		$945,000	w/ overhead @ 50%

3. Personnel

- avg cost per FTE for staff scientist level I and technician to senior scientist, $53,500/man-yr - from Table 1 avg of 12 FTE's/yr for 7 yr, 84 man-yr @ $53,500/man-yr	=	$4,494,000	w/o overhead
		$6,741,000	w/ overhead @ 50%

Hydro/Thermomechanical Experiment	Total =	$10,131,062	w/o overhead
		$15,196,594	w/ overhead @ 50%

C.2 EXCAVATION DAMAGE/SEALING EXPERIMENT

1. Construction and Fabrication

(a) Monitoring drill holes:

Drill holes will be employed for pressure, flow, tracer, stress meter, extensometer, and temperature instrumentation.

Thirty holes parallel to drifts, avg length 100 ft.
Ten holes parallel to crosscut, avg length 50 ft.
Ten holes perpendicular to crosscut, avg length 25 ft.

- drilling, 3750/ft @ $35/ft	=	$131,250	
- survey, 50 holes @ $300/hole	=	$ 15,000	
total	=	$146,250	w/o overhead
		$219,375	w/ overhead @ 50%

(b) Excavation damage drift, 100 ft long, 12 x 12 ft horeshoe-shaped opening (est. by T. McCusker):

- direct costs, 100 ft @ 1133/ft	=	$113,300	
- mobilization	=	$ 24,500	
- standby, 16 hr @ $727/hr	=	$ 11,632	
- indirect costs, 0.48 mo @ $46,650/mo	=	$ 22,347	
subtotal	=	$171,779	
- markup, 20% of subtotal	=	$ 34,356	
contract total	=	$206,135	
- architect/engineer, 16% of contract	=	$ 32,982	
total	=	$239,117	w/o overhead
		$358,675	w/ overhead @ 50%

(c) Center drift, liner and bulkhead:

Use same configuration and costs as test chamber, liner and bulkhead for hydro/thermomechanical experiment.

- direct costs, 100 lineal ft @ $745/ft	=	$ 74,500	
- mobilization	=	$ 24,500	
- standby, 8 hr @ $727/hr	=	$ 5,816	
- indirect costs, 0.41 mo @ $46,650/mo	=	$ 18,995	
subtotal	=	$123,811	
- markup, 20% of subtotal	=	$ 24,762	
contract total	=	$148,573	
- architect/engineer, 16% of contract	=	$ 23,772	
center drift total	=	$172,345	
- liner and bulkhead total	=	$371,230	
total	=	$543,575	w/o overhead
		$815,363	w/ overhead @ 50%

(d) Crosscut and bulkheads:

Use same configuration and cost as test chamber for hydro/thermomechanical experiment.

- direct costs, 50 lineal ft @ $745/ft	=	$ 37,250	
- mobilization	=	$ 24,500	
- standby, 16 hr @ $727/hr	=	$ 11,632	
- indirect costs, 0.29 mo @ $46,650/mo	=	$ 3,408	
subtotal	=	$ 86,790	
- markup, 20% of subtotal	=	$ 17,358	
contract total	=	$104,148	
- architect/engineer, 16% of contract	=	$ 16,664	
crosscut total	=	$120,812	
- bulkheads, 2 @ $50,000 each	=	$100,000	
total	=	$220,812	w/o overhead
		$331,218	w/ overhead @ 50%

2. Operating Equipment and Services

(a) Instrumentation (including hardware, transducer, signal conditioning, and wiring/plumbing):

- pressure/flow, 200 channels @ $1,200/channel	=	$240,000	
- tracer injection/detection system	=	$100,000	(variable)
- flow meters or collection system	=	$ 20,000	
- temperature, 75 channels @ $300/channel	=	$ 22,500	
- extensometer, 50 channels @ $1,000/channel	=	$ 50,000	
- stress meters, 50 channels @ @ $800/channel	=	$ 40,000	
- moisture sensor, 50 channels @ $1,000/channel	=	$ 50,000	
total	=	$522,500	w/o overhead
		$783,750	w/ overhead @ 50%

(b) Mechanical plant:

- injection system and controls	=	$ 20,000	
- chamber water storage tank and plumbing	=	$ 10,000	
- optional heating system	=	$ 25,000	
total	=	$ 55,000	w/o overhead
		$ 82,500	w/ overhead @ 50%

(c) Travel and per diem (only a rough est.; cost largely dependent on the location of the scientific personnel and underground test facility):

- travel, avg 40 round trips per year for 6 yr; 240 trips @ $1,000/flight	=	$240,000
- per diem, avg 1000 man-days/yr for 6 yr (2.7 man-yr); 6000 days @ $50/day	=	$300,000
- vehicles at site, 2 @ $500/mo for 6 yr	=	$ 72,000
	total =	$612,000 w/o overhead
		$918,000 w/ overhead @ 50%

(d) Computer costs:

- design and fabrication	=	$ 50,000
- data analysis and modeling, 5 yr @ avg $70.000/yr	=	$350,000
	total =	$400,000 w/o overhead
		$600,000 w/ overhead @ 50%

(e) Consultants:

- avg of $50,000/yr for 6 yr	=	$300,000 w/o overhead
		$450,000 w/ overhead @ 50%

(f) Miscellaneous:

- shipping, avg $20,000/yr for 6 yr	=	$120,000
- misc. equipment and supplies, avg $70,000/yr for 6 yr	=	$420,000
	total =	$540,000 w/o overhead
		$810,000 w/ overhead @ 50%

(g) Plug (seal) materials and placement equipment (only a rough est. possible at this time):

- materials	=	$100,000
- placement equipment	=	$200,000
	total =	$300,000 w/o overhead
		$450,000 w/ overhead @ 50%

Excavation Damage/Sealing Experiment	Total	$6,126,245 w/o overhead
		$9,189,381 w/ overhead @ 50%

C.3 *UNDERGROUND EXPERIMENTAL FACILITY*

1. Design and Construction (est. by T. McCusker)

(a) Main access drift:

- mobilization	=	$ 24,500
- direct cost for excavation, 1000 ft @ $991/lineal ft	=	$991,000
- direct cost for cleanup and concrete invert, $1,000 ft @ $142/lineal ft	=	$142,000
- standby, 40 hr @ $727/hr	=	$ 29,080
- indirect cost, fixed	=	$123,300
- indirect cost, time based 4.48 mo @ $46,650/mo	=	$208,947
subtotal	=	$1,518,827
- markup, 20% of subtotal	=	$303,765
contract total	=	$1,822,592
- architect/engineer, 16% of contract	=	$291,615
total	=	$2,114,207

(b) Underground shop and office:

- mobilization, 2 @ $24,500 each	=	$ 49,000
- direct cost for shop, 2000 ft^2	=	$280,100
- direct cost for office, 600 ft^2	=	$ 96,760
- standby, 8 hr @ $727/hr	=	$ 5,816
- indirect cost, 1.46 mo @ $46,650/mo	=	$ 68,159
subtotal	=	$499,835
- markup, 20% of subtotal	=	$ 99,967
contract total	=	$599,802
- architect/engineer, 16% of contract	=	$ 95,968
total	=	$695,770

(c) Short drifts off main access:

- direct costs, 4 drifts each 50 long @ $991/lineal ft	=	$198,200
- standby, 16 hr @ $727/hr	=	$ 11,632
- indirect costs, 0.81 mo @ $46,650/mo	=	$ 37,990
subtotal	=	$247,822
- markup, 20% of subtotal	=	$ 49,564
contract total	=	$297,386
- architect/engineer, 16% of contract	=	$ 47,582
total	=	$ 44,968

Design and Construction	Total	=	$3,154,945 w/o overhead
Surface facility development and/or repair and maintenance or improvement of existing underground opening			$500,000
	Total		$3,654,945 w/o overhead

2. **Operating Equipment and Services (annual basis)**

(a) **Contracted services:**

- security staff	=	$ 12,000	
- janitorial services	=	$ 6,000	
- vehicle rental, 2 @ $500/mo	=	$ 12,000	
	total/yr =	$ 30,000	w/o overhead
		$ 45,000	w/ overhead @ 50%

(b) Inventories:

- shop tools and equipment	=	$ 75,000	
- spare parts (underground transportation system)	=	$150,000	
- general supplies	=	$ 75,000	
	total/yr =	$300,000	w/o overhead
		$450,000	w/ overhead @ 50%

(c) Utilities:

- experiments and facility	=	$ 40,000	
- shaft hoist and pumping	=	$130,000	
	total/yr =	$170,000	w/o overhead
		$255,000	w/ overhead @ 50%

Operating Equipment and Services	Total/yr =	$500,000	w/o overhead
		$750,000	w/ overhead @ 50%
	Total for 7 yr =	$3,500,000	w/o overhead
		$5,250,000	w/ overhead @ 50%

3. Personnel (annual basis)

Total of 12 FTE's including:

1 administrator/public relations officer
1 secretary/clerk
1 maintenance superintendent
1 mechanic/electrician
1 electronic technician
2 hoistmen (only for facility access by shaft)
2 cage tenders (only for facility access by shaft)
1 storekeeper
2 general laborers/miners

Average cost per FTE including benefits, $45,000/man-yr

Annual cost, 12 FTE's @ $45,000/man-yr = $540,000 w/o overhead
$810,000 w/ overhead @ 50%

Total cost for 7 yr = $ 3,780,000 w/o overhead
$ 5,670,000 w/ overhead @ 50%

Underground Experimental Facility (design, construction, and operation for 7 yr) Total = $10,934,945 w/o overhead
$14,574,945 w/ overhead @ 50%
(not applied to design and construction cost)

C.4 EXISTING UNDERGROUND RESEARCH FACILITY

Lower-bound estimate of operation and development costs based on figures in Section C.3.

1. Design and Construction

   (a) Main access drift, 350 ft total
   35% of $2,114,207 = $739,972

   (b) Underground shop and office = 0

   (c) Short drift off main access, 50 ft total
   25% of $344,968 = $ 86,242

   total = $826,214 w/o overhead

2. Operating Equipment and Services (annual basis)

   (a) Contract services = 0

   (b) Inventories (only general supplies) = $ 75,000

   (c) Utilities = $ 0

   total/yr = $ 75,000 w/o overhead
   $112,500 w/ overhead @ 50%

3. Personnel (annual basis)

Total of 3-1/2 FTE's including:

1 administrator
1 electronic technician
1 general labor/miner
1/2 mechanic/electrician

Annual cost, 3-1/2 FTE's @ $45,000/yr = $157,500 w/o overhead
$236,250 w/ overhead @ 50%

Existing Underground Research Facility (design construction, and operation for 7 yr) Total = $2,453,571 w/o overhead
$3,267,464 w/ overhead @ 50% (not applied to design and construction cost)

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