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SWEDISH-AMERICAN COOPERATIVE PROGRAM ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS. PROGRAM SUMMARY

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SWEDISH-AMERICAN COOPERATIVE PROGRAM ON
RADIOACTIVE WASTE STORAGE IN MINED CAVERNS

by

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May 1978

PREFACE

This report is the first of a series documenting the results of the Swedish-American cooperative research program in which the cooperating investigators explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a large crystalline rock mass as a geologic repository for nuclear waste. This program has been sponsored by the Swedish Nuclear Power Utilities through the Swedish Nuclear Fuel Supply Company (SKBF), and the U.S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory (LBL).

The principal investigators are L.B. Nilsson and O. Degerman for SKBF, and N.G.W. Cook, P.A. Witherspoon, and J.E. Gale for LBL. Other participants will appear as authors of subsequent reports.

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SWEDISH AMERICAN PROGRAM ON
RADIOACTIVE WASTE STORAGE IN MINED CAVERNS

INTRODUCTION

Final and safe storage of radioactive waste is one of the critical problems that must be solved in a satisfactory manner before the use of nuclear power can be developed to its full potential. One promising way is to place the waste products deep underground in some rock formation such that whatever migration process may take place, dangerous amounts of radioactivity cannot reach the biosphere.

Investigations have been carried out for several years on the possibility of using mined caverns in salt as waste repositories, but only recently has attention begun to focus on other rock types. One of these is granite (or gneiss), and several countries including Sweden, France, Canada, and the United States are currently considering the use of this hard, crystalline rock for permanent storage of radioactive waste.

There are some significant limitations on the present state of knowledge concerning the suitability of hard rock for waste repositories. Before such repositories can be designed, a number of questions relating to the stability of excavations and the rate of water movement through the rock walls must be answered. Crystalline rock masses are not homogeneous systems, but contain complex networks of discontinuities, or fractures. The flow of fluids through such fractures is a subject that has received much study in recent years, but not under the conditions that will prevail in and around an underground opening containing radioactive waste.

A great deal of practical experience relating to the behavior of underground excavations is available from the extensive mining operations that are conducted each year. For storing nuclear waste, however, the factors complicating the design of an underground repository are the thermal and radiological loadings on the surrounding rock. Calculations show that radioactive decay will cause energy to be released from waste canisters that, depending on the concentration of the waste and how long it has been stored at the surface, can increase adjacent rock temperatures by several hundred degrees centigrade.

It should be mentioned that the current Swedish concept for an underground repository is first to provide about forty years surface storage and second, to place the waste canisters in the rock mass so that heat loads on the rock cannot increase temperatures above 100°C at any point in the underground system.

As temperatures exceed this level, the question arises as to whether or not the low thermal conductivity of rock might lead to thermally-induced stresses that could cause rock failure. The extent to which thermal stresses will influence the process of rock failure and/or the consequent movement of water through the nonhomogeneous rock mass is too complicated to be treated as a simple analytical problem. Nor can laboratory experiments be performed easily to simulate fluid flow through a large, fractured rock mass undergoing changes in temperature. These limitations have motivated a search for an existing underground opening in hard rock where a comprehensive program of investigations could be carried out.

The idea of a cooperative program between Sweden and the United States to investigate radioactive waste storage in mined caverns was first discussed during a workshop on "Movement of Fluids in Largely Impermeable Rock"¹ that was held January 27-29, 1977, in Austin, Texas, under the sponsorship of the Office of Waste Isolation (OWI), U.S. Energy Research and Development Administration (now part of the U.S. Department of Energy). P.A. Witherspoon from the Lawrence Berkeley Laboratory (LBL), University of California organized the workshop and served as moderator. The Swedish Nuclear Fuel Safety Program (Kärnbränslesäkerhet or KBS), which is a group temporarily organized within the Swedish Nuclear Fuel Supply Company (Svensk Kärnbränsleeförsörjning or SKBF) sent a representative to attend this workshop and indicated during the meetings that an abandoned iron ore mine at Stripa was to be used in their program of investigations on underground radioactive waste storage. As shown in Fig. 1, the Stripa mine is located in central Sweden about 150 km west of Stockholm.

The mining operations that had been carried out for many years at Stripa by a mining firm, Ställbergsbolagen, had revealed that a massive body of granite lies adjacent to the underground workings. When mining operations were about finished, SKBF took over, and an experimental drift (5 m diameter) was driven far enough into the granite rock mass to reveal that rock conditions

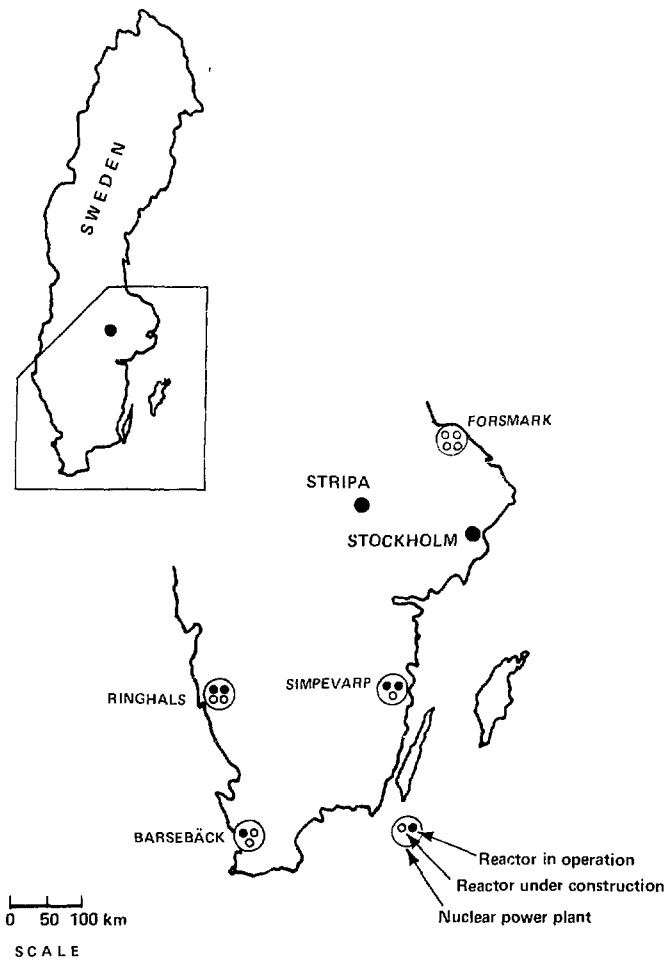


Figure 1. Location of Stripa Mine (XBL 785-968)

are very favorable for a number of field investigations on the general problem of underground waste storage.

The Swedish-American Cooperative Program was initiated in late Spring 1977. Detailed plans were drawn up for the American part of the work program and were presented to SKBF in Stockholm March 21-23, 1977, by a U.S. delegation consisting of T.F. Lomenick, U.S. Office of Waste Isolation; P.A. Witherspoon, Lawrence Berkeley Laboratory, University of California; and J.E. Gale, University of Waterloo, Ontario, Canada. Before the project could get under way officially, it was necessary for an amendment to be made to an Agreement for Cooperation Concerning Peaceful Uses of Atomic Energy, which had been signed July 28, 1966, by the governments of the United States of America and Sweden. This was accomplished through an Agreement between the United States Energy Research and Development Administration and the Swedish Nuclear Fuel Supply Company Concerning a Cooperative Program on Radioactive Waste Storage in Deep Geologic Formations, which was signed July 1, 1977, by G.W. Cunningham for ERDA (now DOE), and E. Svenke for SKBF.

THE SWEDISH KBS PROGRAM

In April 1977 a new law was passed in Sweden requiring nuclear powered utilities to describe how radioactive waste could be finally stored in a completely safe way before permission would be given to load new reactors with nuclear fuel. For this reason, project KBS was organized by the Swedish nuclear utilities and, at the same time, the test station in the Stripa Mine was established. Time for investigation was very limited; plans to fuel two reactors in Sweden within the next year had already been made. During the excavation time for the test station Stripa, the SKBF test program described below was planned and decided on. All tests were expected to be finished before the end of 1977.

The Swedish part of this cooperative program under KBS direction involves some important commitments. Anyone familiar with underground operations knows that just having access to an active mine with all of the men, equipment, and facilities that are involved is a significant factor in starting up a program

such as this. In January 1977 when the Swedes first broached the subject of a cooperative work program, there was no location in the United States readily available where the level of activities planned for Stripa could be put into operation in a matter of a few months. Fortunately for all concerned, the Swedes had the foresight to take over the Stripa mine when the ore recovery activity was about to be abandoned. In addition to continuing to operate the mining equipment and facilities they have assumed the responsibility of having Ställbergsbolagen carry out whatever mine excavations are required to prepare the working space needed for the large-scale experiments to be performed by both SKBF and LBL (Fig. 2). The area shown in Fig. 2 is located at depths between 338 m and 360 m below the surface. The main tunnel (5 m in diameter) is shown in Fig. 3. The different experimental rooms have been excavated by using smooth-wall blasting methods so that the researchers may investigate the influence of blasting on the fracture system near the tunnel walls.

SKBF has also arranged for an experienced drilling contractor, Hagby Bruk, to core drill some 3,500 m of boreholes. This operation involves over 150 boreholes ranging in size from 38 mm to 406 mm. Conformance of borehole drilling to the tight specifications that have been set up by SKBF and LBL is a matter of major importance, and Hagby Bruk has employed two Swedish firms, Viak AB and Fotobar AB, to conduct the necessary borehole surveys. The continued operation of the mine for the duration of the program is under the direction of SKBF. SKBF is thus playing a key role in implementing the various components of this cooperative work program, which involves a number of important investigations.

Rock Characterization

The Swedish Geological Survey (SGU) has contracted to make investigations of the rock at Stripa, mainly:

- to assemble all available geological information on the area in question;
- to prepare maps of the fracture networks of those rock surfaces which have been exposed for the tests;
- to conduct core surveys and TV examinations of diamond boreholes near the tunnels before and after blasting;

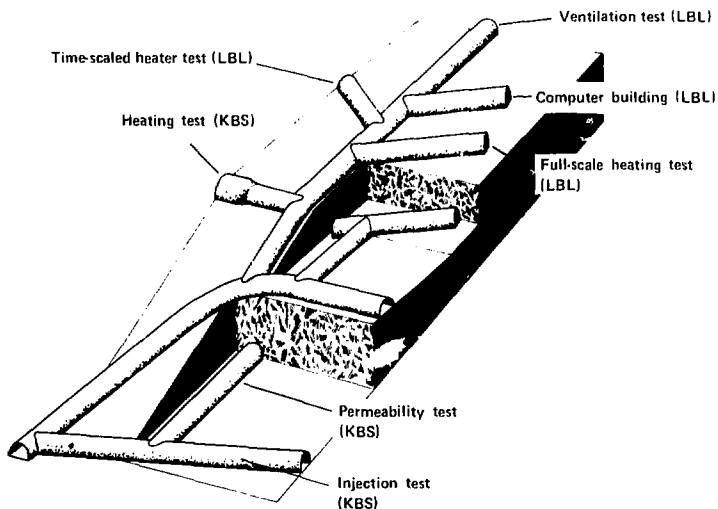


Figure 2. Location of experimental rooms in granite rock mass at Stripa. (XBL 787-2596)



Figure 3. Example of Swedish smoothwall blasting in granite rock at Stripa. Five meter diameter tunnel with rib of the old iron ore mine in center background. (XBB 776-5846)

- to study fracture networks in a deep borehole at the bottom of the mine (from the 410 m level to the 900 m level); and
- to carry out water injection tests in all diamond boreholes ordered by KBS. In cases where blasting has been carried out near the hole, this test is performed both before and after blasting.

Rock Stress Measurements

Under the direction of Professor O. Stephansson, University of Luleå, the *in situ* rock stress measurements were carried out by research engineer H. Carlsson. Three-dimensional stress conditions were measured in a side drift at 19 points along a 20-m-long borehole. Measurement cells based on Leeman's method (overcoring) were first used in the measurements.

The purpose of these tests is to establish data on the primary stress state in the Stripa granite. This information is required for certain other tests and as a basis for theoretical calculations of stress and flow conditions.

Properties of Stripa Granite

In order to interpret the data to be collected and carry out the theoretical calculations, information is required on the mechanical and physical properties of the rock. All analyses have been made by Dr. G. Swan, University of Luleå, who has made the following measurements:

- Young's modulus, Poisson's ratio, compressive fracture stress and expansion coefficient, all as a function of temperature between 20°C and 200°C;
- Young's modulus and compressive fracture stress as a function of confining pressure;
- Brazilian tensile fracture stress;
- Residual shear stress as a function of normal stress;
- Anisotropy ratios for Young's modulus and compressive fracture stress; and
- Dilatational wave velocity and the dynamic Young's modulus.

Effect of Pressure and Temperature on Rock Permeability

Tests of the local effects of pressure and temperature gradients on rock permeability were carried out by the consulting company, Hagconsult. The test setup is shown in Fig. 4. The leakage water outflow into a 300-mm-diam. and 10-m-long vertical borehole was measured. Sixteen 3-inch holes were drilled in a circle, at a distance of approximately 1.5 m from the 300-m hole. Water was pumped into these holes at a given pressure and temperature, and the rock mass heated to the desired temperature by circulating hot water through the boreholes. By changing the water pressure at different temperatures and by measuring the quantity of water leaking out of the center hole, the permeability of the rock can be determined as a function of pressure and temperature. The results of the tests will be compared with theoretical calculations. The experiment also includes a tracer test, where effective porosity in the local rock mass is determined.

Thermal Stress

Changes in the existing rock stresses and fracture conditions that occur in a rock formation in connection with local heating are being examined in this test. Due to the low thermal conductivity of the rock, a relatively long test period is required. The test is being carried out by research engineer H. Carlsson under the direction of Professor O. Stephansson, University of Luleå. A number of practical and important observations have been made during this experiment which will be useful in future LBL heater experiments.

The test setup is illustrated in Fig. 5. The primary three-dimensional rock stresses in the rock adjacent to the test drift were measured. The heaters and measuring holes are oriented so that their direction coincides with the direction of one of the main stresses.

The heat source consists of a specially-designed 5-kW electric heater, which is lowered into a 300-mm borehole. Three 1-kW auxiliary heaters are lowered around this center hole at a distance of 1.25 m. Temperature and rock stresses are then measured continuously in ten boreholes parallel to the center hole and at distances varying between 2 m and 6 m from the center hole. Other instruments register changes in the aperture of major fissures within the test area. Conditions during the cooling-off period are also recorded. The results obtained will be compared with theoretical calculations.

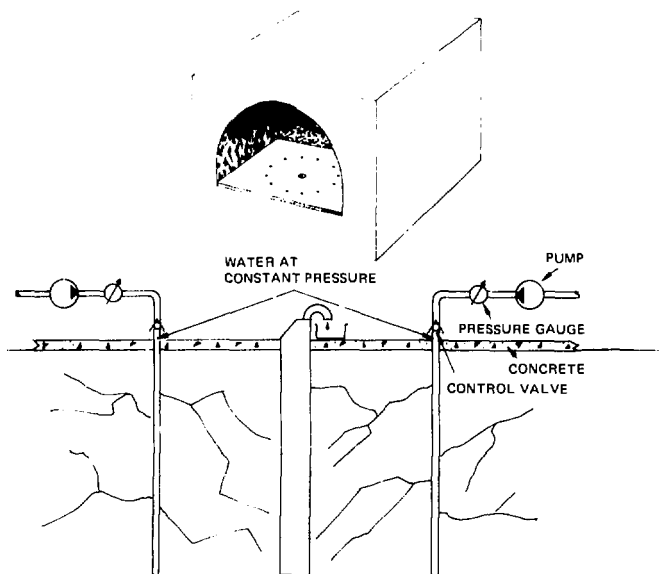


Figure 4. Test setup to investigate effects of pressure and temperature on permeability of Stripa granite. (XBL 786-9401)

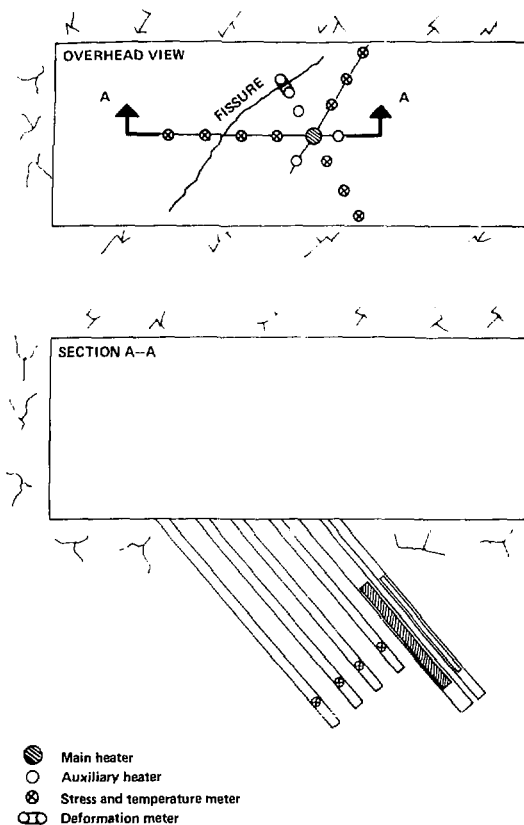


Figure 5. Test setup to measure changes in rock stress and fracture aperture in connection with local heating. (XBL 786-9402)

Injection of Silicon Dioxide Grout

It was planned to make an injection test with silicon dioxide in the Stripa granite, and some preliminary work was actually carried out. However, the permeability of the rock at the test site was found to be so low that injection into the rock mass was almost impossible.

Water Analyses

The Swedish Geological Survey has collected and analyzed ground water samples at different levels for the purpose of determining age and chemical composition. LBL has assisted in carrying out this part of the Swedish program.

THE AMERICAN LBL PROGRAM

The American part of this cooperative work program under LBL direction consists of three main activities supported by an auxiliary program of measurements. These are outlined in Fig. 6.

The objectives of the LBL program of activities at Stripa are:

1. to conduct large-scale field experiments in granite in order to establish design parameters for waste repositories in hard rock and make safety assessments for such facilities;
2. to develop new instruments and techniques that are capable of producing the required data despite the hostile environment that results from high temperatures over long time periods;
3. to collect experimental data necessary both for the development and validation of predictive models; and
4. to promote the international exchange of information and ideas.

Full-Scale Heater Experiments

One of the most critical problems in designing an underground repository for high-level radioactive wastes is to determine the level to which temperatures can be raised in the rock mass without having undesired effects. This is further complicated if the design effort must include a provision for recovering the waste canisters at some future date. The problem is being approached at Stripa from two standpoints: (1) the short-term effects, and (2) the long-term effects.

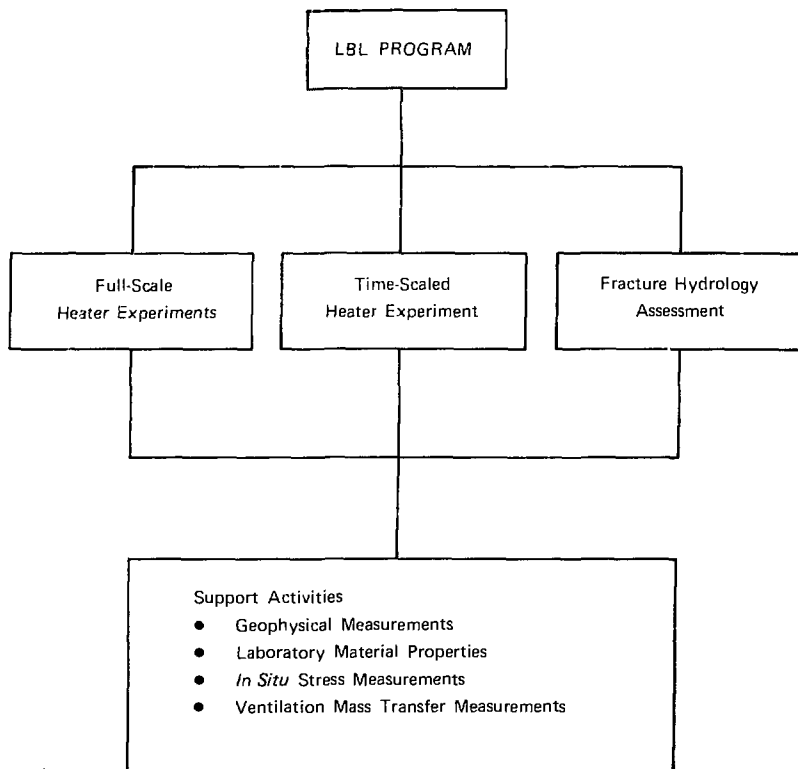


Figure 6. The LBL program of investigations at Stripa.

The full-scale heater experiments are designed to permit the investigation of the short-term temperature effects in granite by using a full size canister that can simulate the energy output of radioactive waste. Electric heaters housed in a canister 3 m (10') in length and 0.3 m (1') in diameter will be used to generate the required energy levels. Two such canisters, each containing four heater elements, will be positioned in vertical holes drilled in the floor of the full-scale heater drift as shown in Fig. 7. This is the container size that is expected to be used in the United States; a canister of different size and design has been proposed by SKBF for use in Sweden. The energy output from canisters containing high-level radioactive waste is currently designed to be as much as five kW per canister. This energy output drops significantly in the first few years after emplacement, but an energy release of this magnitude when coupled to the rock mass can produce temperature increases of several hundred degrees centigrade. It is therefore important that definitive field experience be gained as rapidly as possible concerning the temperature effects in the crystalline rock mass immediately adjacent to the canister.

Figure 7 shows a cutaway drawing of the two full-scale heaters and some of the horizontal boreholes that will be instrumented from an adjacent, lower-level drift. The two heater holes are spaced sufficiently far apart that the canisters will be thermally isolated from each other for the duration of the experiment. This will enable two separate experiments to be conducted in parallel. It is planned to adjust the power output of one of the canister-heaters to 5 kW in order to represent a typical power level of reprocessed fuel after some three years. The other canister-heater will have a power output of 3.5 kW to represent similar waste products approximately five years old. The rock mass adjacent to these two canisters will be monitored extensively by using instruments of various designs to measure displacements, and thermocouples to measure rock temperatures. For this experiment, it is planned to use 30 extensometers, 30 borehole deformation USBM gauges, and 30 vibrating-wire Irad gauges. Each of these instruments will have associated thermocouples placed adjacent to it to enable temperature corrections to be applied to each instrument. Additional thermocouples will be positioned around each heater to enable the temperature field to be plotted in three dimensions.

Because of the low thermal conductivity of rock, it is known that the temperatures, and therefore the temperature gradients within the rock in the

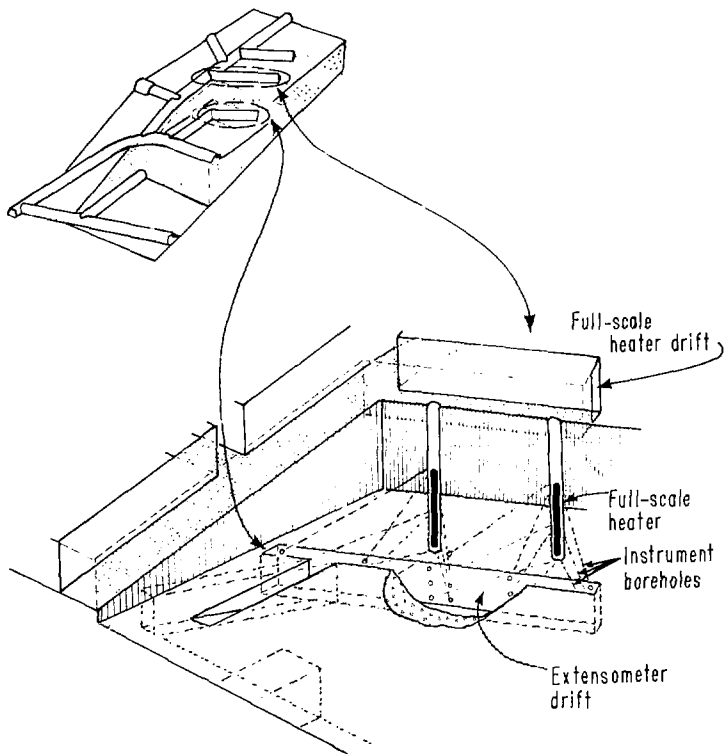


Figure 7. Detail of heater and instrument arrangement for LBL full-scale heater experiments. (XBL 785-970A)

immediate vicinity of the heaters will approach their maximum values within a period of a few months. Consequently, within a relatively short period, this test program will establish the temperature and stress gradients for two values of output power in a typical, hard, crystalline rock. Definitive data will be collected to establish the extent to which these temperature gradients are influenced by rock fractures, and how the thermally-induced stress fields affect the movement of fluid in the rock. Also, any locally-induced thermal fracturing of the rock will be noted.

A second phase of the 5-kW, full-scale heater experiments that is aimed at long-term effects has been designed to permit evaluation of the effects of sequential canister emplacement and thus sequential heat loadings. It is planned to place a ring of eight, small, 1-kW heaters on a 0.9 m radius around the 5-kW canister-heater unit. After the initial phase has been completed, the ring of small heaters will be switched on. The purpose of this second test phase is to raise the ambient temperature of the rock mass adjacent to the 5-kW heater unit by more than 100°C. This high ambient temperature is typical of conditions that might prevail in an actual repository where, over a period of several decades, heat from the interaction of large arrays of waste canisters has raised the temperature of the surrounding rock.

It is expected that the stress gradients measured in this second phase of the experiment will be similar to those measured during the initial part of these tests. The rock adjacent to the canister may respond differently, however, because of the effects of the increased temperatures on fractures and fluid flow. Determinations of rock fracture and fluid flow have also been incorporated in the experiment.

Time-Scaled Heater Experiment

One of the more important factors affecting a radioactive waste repository is the long-term thermal loading effect on a rock mass at significant depths. The time-scaled experiment is designed to permit investigation of this long-term effect by the use of a scaled array of one-kilowatt electric heaters. Calculations show that thermal interaction begins to occur between full-scale canisters in an actual repository within a period of three years if the spacing

between the canisters is 10 m. This is illustrated by the migration of the 30°C incremental isotherm over a period of one to ten years as shown on Fig. 8. Thereafter the effect of individual canisters diminishes and, in a period of ten to one hundred years, heat should flow upward and downward from a plane containing the canisters such that the 100°C isotherm will have migrated distances of the order of 50 meters from the plane of the repository. The resulting thermal expansion of the roughly oblate spheroid of rock with these isotherms will be of the order of 10^{-3} , which is significant.

It is impractical to check these thermo-mechanical effects in the critical period of from 10 to 100 years by using a full-scale heater experiment. Fortunately, the laws of heat conduction allow for compressing the time scale. The dimensionless quantity used in solutions of heat conduction calculations is the ratio of a linear distance to the square root of the product of the thermal diffusivity of the material and time. Therefore, an experiment is planned in which the times will be compressed in the ratio of 1:10, that is, two years of time-scaled experiments will yield 20 years of data from full-scale heater performance. In order to accomplish this, the linear scale must be reduced to $1/\sqrt{10} \approx 0.32$ of the full scale; this still allows realistic absolute dimensions for a field experiment. Measurement of rock temperatures and deformation will be made in the time-scaled experiments so that these data can be compared with those of the full-scale heater experiments and with theoretical predictions for the behavior of a repository over a period of several decades.

An array of eight heaters, spaced 7 m apart along the axis of the time-scaled heater room and 3 m apart in the other direction will be used in this investigation (Fig. 9). Each heater, consisting of two heater elements, will be installed in a canister 1 m in length, which will be placed at the bottom of a borehole drilled to 11 m below the surface. Appropriate scaling of the power output for these heaters demonstrates that 1 kW per heater is representative of an initial power output. This power level can be varied during these tests to simulate the decay in power output of radioactive waste over 20 years. The configuration of the heaters in the array was chosen to establish a three-dimensional pattern of thermal interaction between the heaters and surrounding rock, such as may be found in a practical repository.

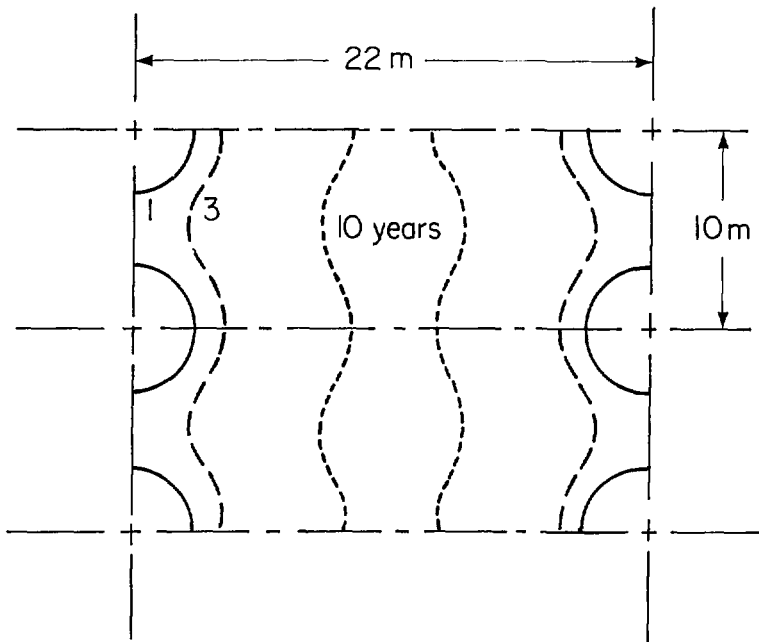


Figure 8. Migration of 30°C incremental isotherm after 1, 3, and 10 years with 5-kW canisters spaced at 10-m intervals in rows that are 22 m apart. (XBL 787-2597)

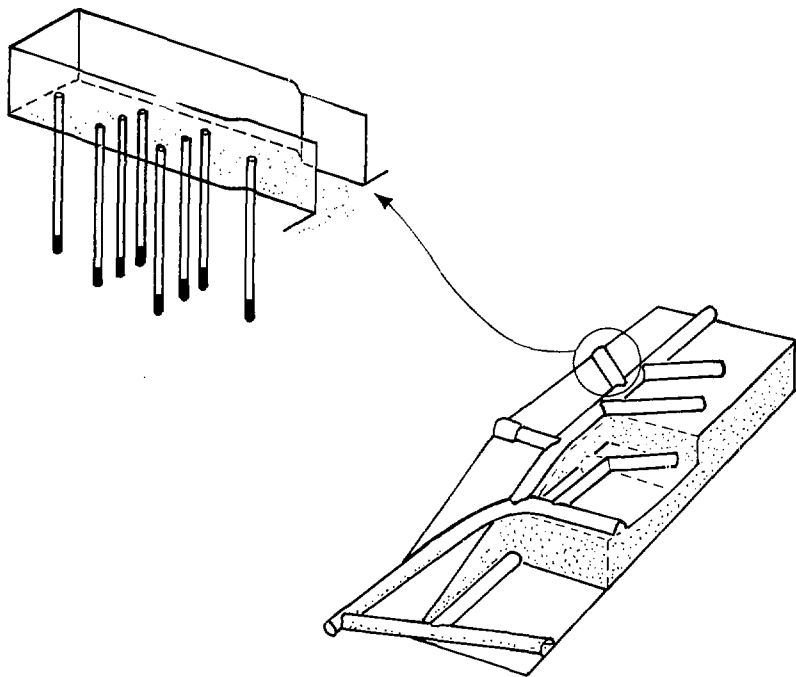


Figure 9. Detail of heater arrangement for LBL time-scaled heater experiment. (XBL 785-969)

It is calculated that this interaction will occur within a few months from the start of the experiment.

High temperatures are expected to occur in the surrounding rock from the combined effects of heat flow. Special attention will be paid to the extent that these temperatures cause decrepitation of the boreholes in which the heaters are placed. An important factor in the design of a waste repository is the ease with which canisters can be retrieved after emplacement. Significant spalling of the sidewalls of the boreholes could severely impede canister retrieval and could cause damage to the waste canisters. In addition, any decrepitation of the borehole walls would affect adversely the heat path from the heater to the surrounding rock. Consequently, provision has been made in the design of these heaters to permit monitoring of any movement in the boreholes of the walls.

The behavior of the rock surrounding these heaters during the experiment will be measured by using five extensometers with their associated thermocouples, plus 60 thermocouples to monitor rock temperatures.

Data Acquisition and Storage

In order to follow the progress of events in the full-scale and time-scaled heater experiments, it will be necessary to monitor temperatures and displacements from 800 channels of instrumentation. Many of these channels represent temperature measurements associated with displacement transducers. The interpretation of displacements measured by transducers requires correction for temperature effects, and each instrument must be calibrated to make this correction. The mass of data to be handled and stored can only be done efficiently and economically by computer methods.

The computer selected for this project is a Mod Comp IV/25 and will be placed underground in the computer room shown on Fig. 2. A machine with 192 K memory has been selected and will be equipped with two discs each of 50 MByte, plus two magnetic tape drive units. This provides a redundant system with one disc and one tape to acquire data and the second disc and tape as backup. Unprocessed experimental data will be stored on both disc and tape, ensuring that in the event of a "machine crash" data would be retrievable. Of equal importance, this facility also enables the unprocessed data to be brought back to Berkeley on tape for analysis.

An additional feature of the computer system is that, with the appropriate equipment, mathematical modeling can yield graphical displays of temperatures and displacements as functions of time and/or distance. Theoretical analyses of expected results for temperatures and displacements have already been made, and these results will be stored in the computer. Thus, it will be possible to compare graphical displays of predicted results with actual results during the entire course of the experiment. This will be of great assistance in carrying out real time analyses of results.

Fracture Hydrology Assessment

The purpose of this work is to define the surface and subsurface hydrological conditions of the fractured granite rock mass at Stripa and to determine how these conditions vary as a function of time and temperature. To accomplish this, it is necessary to: (1) define the geometrical properties of the fracture system, (2) determine the distribution of fluid pressures and permeabilities associated with this system, (3) collect and analyze samples of ground water from various parts of the rock mass, and (4) analyze the above data to provide a coherent description of the nature and magnitude of the ground water flow in the vicinity of the underground openings. To achieve these results, it has been necessary to develop new borehole tools and new methods of data collection and analysis.

Detailed mapping of the fracture system will be necessary, and some of this has already been initiated by SKBG with members of the Swedish Geological Survey (SGU). They have concentrated on fracture patterns as expressed in surface outcrops along the main tunnels of the mine. LBL staff will be involved in 1) line sampling of the fracture data in selected areas, 2) detailed mapping of fractures in the full-scale and time-scaled rooms, and 3) careful logging of fractures found in the core samples from all instrument and heater holes. When all of the fracture mapping is complete, the combined data will provide a basis for a complete three-dimensional description of the fracture systems associated with the heater experiments.

To obtain a complete picture of the fracture system in the granitic rock mass as a whole, it will be necessary to drill three oriented boreholes from the surface down to the depth of the underground experimental tunnels.

These will be diamond-cored 76-mm boreholes up to 500 m in length and oriented so as to intercept the principal fracture sets. The boreholes will be surveyed and logged with a TV camera; pressure measurements will be made every 10 to 15 m during drilling. To measure permeabilities, injection tests with inflatable packer assemblies will be performed at intervals after drilling is complete in each borehole. At the termination of these injection tests, each borehole is to be equipped with packers and piezometers to monitor water movement in the granite rock mass.

Water samples will be collected at different depths within the deep borehole that was driven from the 410 m mine level and at a number of other locations. The samples will be analyzed for gas content, water chemistry, isotope concentrations, and field geochemical conditions to provide further information on the long-term hydrology. These analyses are part of a cooperative effort between laboratory groups in Canada, Sweden, and the United States.

The fracture system in the surface outcrops will be analyzed, and a site selected for a vertical percussion hole (150 mm diameter) to be drilled to a depth of 300 to 400 m. This well will be used in a program of pumping-out tests that is designed to determine the average flow properties of the rock mass. In order to monitor changes in water table levels that may occur during the total period of the cooperative program, a series of seven, shallow surface boreholes about 150 mm in diameter and 10 to 15 m deep have been included. These wells will be equipped with standard water level recorders.

Support Activities

Supporting the three major investigations of the LBL program at Stripa are several other activities. First, there is the geophysical assessment of fractured rock to study fractures and other rock characteristics. This will assist in the interpretation of the measured response of the rock to thermal loading. The second and third activities are laboratory material property measurements and in situ stress measurements, respectively, both providing essential inputs to modeling and design used to assess the response of fractured rock systems. Fourth, a ventilation mass transfer experiment is planned to evaluate our capability to measure extremely low permeabilities—a part of the fracture hydrology assessment. Finally, several elements of the Swedish activities will provide input to the U.S. investigations.

The determination of fracturing and other rock characteristics by geophysical methods can be subdivided into three categories based upon the scale of the measurement and the techniques employed: borehole measurements on the scale of one meter, done with tools in a single borehole; crosshole measurements on the scale of tens of meters, done with tools in different boreholes or with arrays in a single borehole; and surface measurements, on the scale of hundreds of meters, done with surface survey equipment.

A portable logging system for the borehole measurements that is capable of operating both underground and on the surface, will be used at Stripa. The system and associated tools include: a temperature log, a neutron log for water content, a gamma-gamma log for rock density and fracture delineation, a natural gamma log, a variety of electrical measurements, and a caliper log. In addition, acoustic velocity measurements will be made with equipment from the Tennessee Valley Authority geotechnical group. The results will be carefully compared to core observations to assess the logging techniques and, in turn, the logs will supplement and extend the core data.

The Swedish Geological Survey also operates a logging program to investigate boreholes at their proposed storage sites. They have found that a focused resistance log technique holds promise for delineating fractures in the case of crosshole measurements. This method has been incorporated in the U.S. measuring scheme.

Methods to assess the rock between boreholes are not as well developed as borehole logging methods. LBL will test an electromagnetic radio frequency wave propagation method at Stripa, a method developed by J. Lytle at the Lawrence Livermore Laboratory. These measurements will be made in a set of 30 m boreholes, which will also be used for hydrological measurements. The combination of geophysical, hydrological, and core observations provides a unique opportunity to cross-check the effectiveness of a diverse set of techniques in a single rock mass.

Seismic measurements have good potential for crosshole investigations. The Engineering Geoscience group at the University of California has proposed a plan for an array of shear and pressure-wave transducers. Although this method requires a longer lead time, the resultant system could conceivably be tested at Stripa where a broad data base will be available.

Acoustic velocity measurements in the heater rooms will provide direct information on the change in acoustic propagation in the thermally-stressed rock mass. An experiment to measure this effect has been designed by LBL with the assistance of a U.S. company, Terra Tek. The information may be useful in designing monitoring systems for waste repositories after waste has been stored.

The problem of defining the rock properties through surface surveys has received attention at Stripa. The Swedish Geological Survey relies heavily on very-low-frequency (VLF) survey systems, which are very effective in shield areas where the soil cover is thin or absent. Unfortunately, at Stripa the high density of power lines and other grounded structures precludes a VLF survey. Two other survey techniques, electrical resistivity and seismic, can be deployed, however, and a resistivity survey is planned.

Laboratory measurements of material properties have been initiated by LBL and SKBF to examine selected rock samples to assess the hydraulic, thermal, and mechanical behavior of the Stripa granite. Oriented core samples will be drilled from both unfractured rock and rock containing natural fractures. A large rock core (about 1 m diameter) will be drilled and shipped to the University of California, Berkeley, for special tests. The core will be examined in a triaxial testing facility to determine changes in fracture permeability as a function of axial stress and fluid pressure changes. For design purposes, preliminary measurements of physical, thermal, and mechanical properties of selected samples of Stripa granite have been made by Terra Tek.

Plans have been initiated for measuring in situ stresses by using hydraulic fracture techniques. The magnitude of the stress concentrations induced around an underground opening is an important factor. These stresses can induce fractures and change the hydraulic conductivity of joints as well as the response of rock mass to thermal loads.

A ventilation test is designed to permit determination of the gross seepage rate through granitic rocks of low permeability. A section of test tunnel (see Fig. 2) has been designated for the measurement, which will be conducted by isolating a portion of the tunnel and monitoring the difference between the humidity of air forced into and that flowing out of the special section of this tunnel. This experiment is designed to permit detection of

minute seepage into an underground opening. From measurements of hydraulic gradients in the rock walls outside the ventilation room, it will be possible to determine an overall permeability of the rock mass that can be compared with the results obtained through the fracture hydrology investigations.

SUMMARY

The Swedish-American cooperative program of investigations at the Stripa iron-ore mine is the first international effort of its kind in which field work will be carried out aimed at the general problem of *underground* radioactive waste storage. The program will focus on a number of problems that must be solved in developing the technology needed to design and operate waste repositories in crystalline rock. These involve such items as the appropriate mining techniques for repository construction, the effects of pressure and temperature on rock permeability, *in situ* rock stress measurements, and geochemical groundwater investigations.

Two critical problems that will receive considerable investigation are: (1) the effects of elevated temperatures on the geomechanical behavior of granite, and (2) the fracture hydrology of the granite rock mass at Stripa. The investigation of temperature effects will be approached from two standpoints: (1) the short-term effects will be studied by using full-size canisters equipped with electric heaters to simulate the energy output of radioactive waste, and (2) the long-term effects, by using a time-scaled array of electric heaters to simulate the thermal loading on a rock mass over periods of several decades.

The purpose of the hydrology studies is to define the surface and subsurface hydrological conditions of the fractured granite mass at Stripa and to determine how these conditions vary as a function of time and temperature. An understanding of the rate at which water is able to seep through the rock walls of an underground opening and of the level of accuracy required for the necessary field measurements is vital to the design of a waste repository.

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