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UCRL-50050-77

WASTE ISOLATION PROJECTS – FY 1977

Technical Editor: L. D. Ramspott

January 18, 1978

Work performed under the auspices of the U.S. Department of Energy by the UCLLL under contract number W-7405-ENG-48.

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CONTENTS

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1. INTRODUCTION

LLL Program Goals

The primary goal of the ongoing LLL program is to develop the technology and data base required to license a nuclear repository in a crystalline rock medium, located at or near the Nevada Test Site (NTS). Our secondary goal is to apply this technology in helping the Department of Energy (DOE) develop repositories in other media and locations.

Technical Approach

Currently, our program consists of three related project areas:

- Field and laboratory studies of the availability and migration of radionuclides in ground water.
- Thermomechanical response of granite, through heater tests at the Climax stock of the Nevada Test Site.
- Laboratory measurements of physical properties of rocks at elevated temperatures and pressures, including physical/chemical factors that inhibit water transport in deep silicate rocks.

With respect to our first project area, the Nevada Test Site represents a unique laboratory for studying radioactive waste disposal. Large amounts of radioactivity have been "stored" underground there for two decades; also, ground water has been exposed to radioactivity at more than 75 NTS locations. We are making field tracer measurements and analyzing water samples from nuclear chimneys at site locations, for correlating results with those from laboratory studies of leaching and sorption.

In the Climax stock heater tests, we are measuring the thermal and mechanical response of granite rock to a heat load comparable to that radiating from nuclear waste canisters. The overburden pressure and lack of surface weathering at the 1400-ft depth of our measurements simulate repository conditions more realistically than do laboratory measurements or near-surface heater tests.

Our approach in the third project area is to make laboratory measurements of the physical properties of rocks at elevated temperatures and pressures simulating repository conditions. The parameters that we will measure include permeability to fluids, acoustic velocity, electrical and thermal conductivity, heat capacity, and principal stresses and principal strains.

Ultimately, we plan to integrate these three project areas of study into a unified program, leading to the establishment of a repository in crystalline rocks in Nevada.

Funding Background

The overall funding for LLL's FY-1977 studies in nuclear waste isolation came from the National Waste Terminal Storage (NWTS) program. Each LLL project was part of a larger program, and it was funded through reconciled transfers from the appropriate ERDA (now DOE) area office.

Our studies of radionuclide availability and migration (Section 2) were part of the Waste Isolation Safety Assessment Program (WISAP), led by Battelle Pacific Northwest Laboratory and funded through ERDA's Richland Operations Office; we received initial funds in March 1977.

The thermomechanical studies of the NTS Climax granite, under terminal storage R&D (Section 3), were part of a larger study of the waste isolation potential of the Nevada Test Site and were funded through ERDA's Nevada Operations Office; initial funding was received at LLL in May 1977.

Our study of physical/chemical factors that inhibit water transport in deep silicate (Section 4) was part of a technical support program for NWTS, led by the Office of Waste Isolation (OWI) at Oak Ridge; LLL's initial funding, in June 1976, came through the Oak Ridge Operations Office. During this pre-FY-1977 period, we designed and started to build a high-pressure apparatus to investigate the physical properties of crystalline rocks under conditions that simulate possible waste repository environments.

Funding for the study of thermal properties and thermomechanical behavior of rocks under pressure came in August 1977; consequently, no technical results are available for reporting.

L. D. Ramspott

2. STUDIES OF RADIONUCLIDE AVAILABILITY AND MIGRATION

CONTENTS

Summary

This LLL project, which is part of the Waste Isolation Safety Assessment Program (WISAP), has four areas of investigation:

- Field measurement program.
- Sorption studies, emphasizing the development of techniques that more realistically represent field migration than do standard static K_d (distribution coefficient) measurements.
- Experiments in leaching radioactive material, emphasizing kinetic data.
- Analysis of problems arising from the differences between intergranular and fracture flow, stressing the relevance of laboratory measurements to field migration models.

During FY 1977, we worked in the first three areas, with the leaching experiments funded by another program. The principal technical results of LLL's efforts in the first two areas were:

- Recommendations regarding the feasibility of field studies at nuclear explosion sites in granite, basalt, and salt. Of eight sites that we investigated, additional field studies are feasible at one salt site and one granite site and they might produce data relevant to waste isolation.
- Evaluation and planning for field tracer studies at the Nevada Test Site. We evaluated and rejected the possibiilty of participating in a one-well tracer test at NTS. We plan to conduct a two-well tracer test at the Amargosa Tracer Site near NTS.

- Design and partial fabrication of a system for studying sorption in rock cores at elevated pressures. The system should simulate intergranular flow under field conditions. We will use it for comparing static and core methods of determining sorption ratios.

- Design and testing of a laboratory system for collecting and analyzing water samples from the rock sorption and leaching systems. This simple system collects effluent in a plastic bag that is subsequently pelleted for gamma-counting.

- Design of a field concentration apparatus to collect large-volume samples for low level gamma-counting. The apparatus will rapidly concentrate 4000 litres of water to about 2 kg of salts. Such concentration will improve the sensitivity of our water-well analyses by several orders of magnitude.

Although we developed a one-pass leaching system in FY 1977 with funds from another program, we plan to use the system in FY 1978 for WISAP studies. Consequently, this section contains a brief description of it.

Introduction

Twenty years of underground nuclear tests at the Nevada Test Site represent a reservoir of untapped information on the interaction of radionuclides and the local ground-water system. Large amounts of radioactivity have been "stored" at this site for nearly two decades; also, ground water at over 75 site locations has been exposed to radioactivity for years.[1] We are using this information in our studies, whose eventual results will enable us to formulate some conclusions on the safe disposal of radioactive waste.

The LLL studies of radionuclide availability and migration at NTS are part of the Waste Isolation Safety Assessment Program (WISAP). They are related to and complement an NTS weapons-related research program: Radionuclide Migration in the Ground (RNM). For WISAP, we planned four areas of investigation in FY 1977:

1. Field studies—injection and recovery of tracers, analysis of large-volume water samples from nuclear test locations, and analysis of the feasibility of sampling operations at various old test locations.
2. Sorption studies—mainly laboratory measurements of the distribution of specified radionuclides between the liquid and solid phases of rock/water systems that characterize nuclear test sites.
3. Experiments with the leaching of radioactive material.
4. Analysis of the problems stemming from differences between intergranular and fracture flow, emphasizing the relevance of laboratory measurements (e.g., K_d) to field migration models.

This section covers primarily items 1 and 2. During FY 1977, all work on item 3 was funded by the RNM program; consequently, we include only a brief summary of the leaching apparatus. We have not yet started work on item 4.

Our studies at LLL were funded in March 1977. After completing our staffing, we were able to obtain a stable level of effort by May. Thus, the results we report here represent about six months of work at the originally proposed level of two FTE's (Full Time Equivalents) per year.

Field Studies

We had planned two basic goals for our field studies:

- To conduct field tracer experiments for comparison with laboratory experiments.
- To obtain, concentrate, and analyze large-volume pumped water samples from the sites of underground nuclear explosions, to determine the *in situ* availability of radionuclides (especially Pu) to ground water.

During the year, three changes affected our original plan. First, our field experiments depended on drilling performed for the RNM project, which proved to be a major inconvenience and forced us to develop an independent program. Second, we evaluated the feasibility of field work at nuclear test sites other than NTS, for which there was a need. Third, we obtained large-volume water samples from several locations not originally included in our plans.

Basic Field Program

During FY 1977, we evaluated several options, described below, for meeting our original goals.

One-Well Tracer Tests. To obtain information on the velocity of ground water flow at the Nevada Test Site, the U.S. Geological Survey (USGS) is developing a technique for one-well tracer tests, in which a tracer is injected into a well and allowed to drift for several months. The ground water is then pumped back into the well, and its flow rate (drift of the tracer) is inferred from the time it takes the tracer to return to the well.

The USGS has expended considerable effort in finding tracers that are *not* sorbed. (Use of tritium as a tracer is not allowed at NTS because of possible confusion with tritium from nuclear explosions.) Our original idea was to add radionuclides other than tritium to the USGS tracer slug, obtaining data of the radionuclides' retardation or sorption relative to the nonsorbed tracer monitored by the USGS. But we were faced with a severe technical problem, because the USGS injects only a 50-millilitre tracer slug into the wells—a reasonable amount if the tracer is not sorbed. In our case, the tracers of interest would be strongly sorbed, preventing us from getting measurable quantities of tracer in the pumped water. Mainly for this reason, we decided to look at two-well tracer tests.

Two-Well Tracer Tests. The U.S. Geological Survey operates the Amargosa Tracer Site, a well field it developed southwest of the Nevada Test Site. Tests at the well field are carried out in a dolomite that is part of the lower carbonate aquifer—the principal path of ground water flowing in the eastern half of NTS. We obtained USGS permission to operate a two-well tracer test at the Amargosa site. Currently, we are preparing an application for submission to the Nuclear Regulatory Commission and the Nevada Bureau of Environmental Health for additional permissions.

The Amargosa site is predominantly a fracture flow system. Consequently, we are interested in comparing retardation factors measured in the field with those calculated from laboratory measurements on bulk rock. One of our hypotheses is that the fractures will be coated with minerals more sorptive than the bulk dolomite and, hence, will show greater retardation.

Bilby Cavity/Chimney Sampling. The first nuclear detonation below the water table at the Nevada Test Site occurred in 1963 and was code-named Bilby. A well (U3cn-PS2) was drilled and completed within the collapsed zone at and above the point of detonation. The USGS originally planned to pump from several vertical zones, which had been perforated to obtain infill data. But a partial collapse of the casing at the top of the perforated section prevented pumping the individual zones. In 1964, however, the USGS pumped samples from the entire 200-m section and analyzed some of them to determine whether ^{144}Ce, ^{137}Cs, ^{60}Co, ^{106}Ru, ^{125}Sb, and ^{3}H were present. During this time, ground water continued to fill the well.

We planned to use the pump that was already in the well, to collect samples for complete radiochemical analysis, including low level gamma-counting and a specific search for Pu. We also planned to test a field apparatus for concentrating water samples. Unfortunately, the pump no longer worked. But despite this setback, further effort seemed justified. We felt that a significant improvement in the NTS data base could be obtained through high-quality radiochemical analyses at the Bilby site. Also, no other NTS site location with water containing fission products, and possibly Pu, could be pumped for the purpose of testing a field apparatus for water concentration. Therefore, we developed a work plan, estimated the cost, worked out joint funding with the Weapons Test Program, and refurbished well U3cn-PS2 at the Bilby site.

We pumped 5000 gallons out of the well, from which we took eleven 1-gallon samples and one 55-gallon sample for low level analysis. We plan to analyze these samples in FY 1978. The well will be available for testing the field apparatus for water concentration when the apparatus is built.

Other NTS Locations. The opportunity to pump water contaminated by fission products and Pu may arise at other NTS locations. Two such locations, Cambric and Almendro, have been developed by the Weapons Test Program. Cambric has been pumped in the past and is currently blocked by packers. Almendro has been drilled but not perforated because of a slow infill of water. We plan to pump large-volume water samples from these locations when the opportunity presents itself, probably in FY 1978.

Wells have been completed at two other NTS nuclear test sites that have the potential for providing information on radionuclide migration: the Nash site in dolomite and the Bourbon site in limestone. Pumping at the well near the Nash site established the presence of tritium in the water. We took a large-volume sample to concentrate for the low level gamma-counting of nuclides other than tritium. We plan to take another large-volume sample at the Bourbon site when pumping is done there.

At both the Nash and Bourbon sites, no radionuclides other than tritium have been found in the water. Therefore, we plan to use the field-water concentration apparatus at these sites as soon as it is built.

Field Water-Concentration Apparatus

At present, large-volume water samples in 250 litre (55-gallon) drums are sent to LLL for concentration and analysis. We are planning to either buy or build a field distillation unit similar to that shown in Fig. 1. Such a device would concentrate up to 4000 litres (880 gallons) of NTS well water to about 2 kg of salts. This concentration would improve the sensitivity of our well-water analyses by several orders of magnitude, thereby broadening our understanding of underground radionuclide movement at NTS.

Feasibility of Work at Selected Sites

We evaluated nuclear test sites in media other than the standard alluvium and tuff of NTS: two in salt, three in granite, and three in basalt. Additional field studies at one salt site and one granite site are feasible and might produce data relevant to waste isolation. Further field studies at the remaining sites are less likely to be productive or economically worthwhile.

Basalt Sites. Although there have been some tests in basalt above the water table at NTS, the only nuclear tests in basalt below the water table have occurred at Amchitka Island, Alaska. Of the three tests at Amchitka Island, no postshot reentry was attempted for the first two (code-named Longshot and Milrow), but one was attempted for the third (the Cannikin test). Small-volume thief samples were obtained, but no pump tests were carried out. The island is essentially deactivated now and the cost of further sampling operations would be prohibitive.

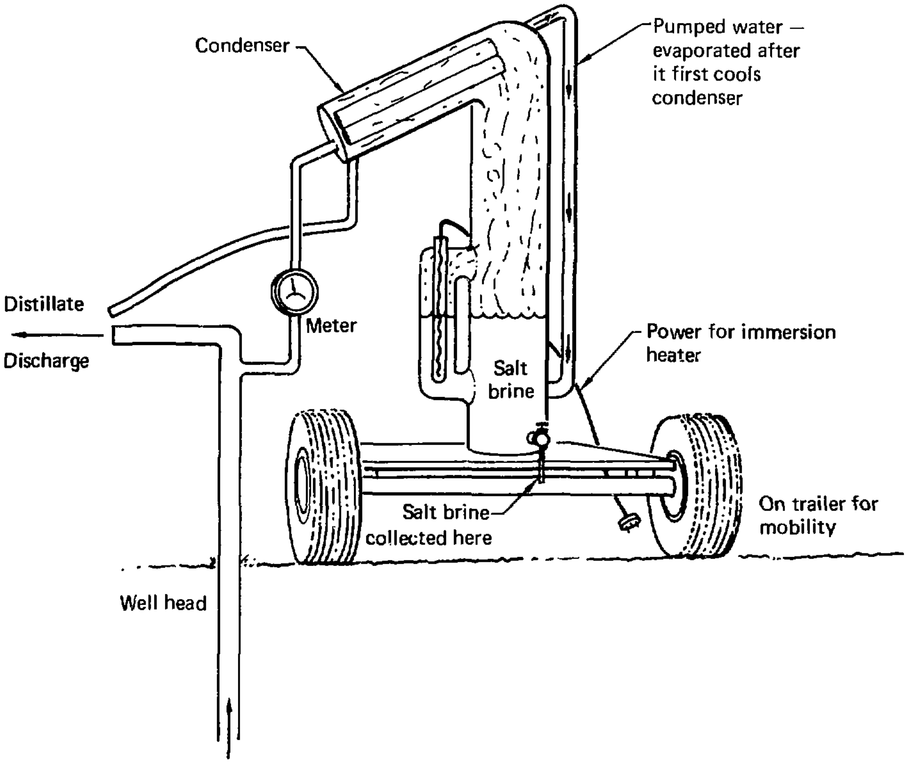

Fig. 1. Field distillation apparatus (sketch shown is a modified version of a Barnstead thermodrive still). Apparatus is capable of concentrating 4000 litres of water (1 to 2 kg of salts).

Granite Sites. Three U.S. nuclear explosions have occurred in granite. Two at NTS (Hard Hat and Pile Driver) were conducted above the regional and local water table in an unsaturated zone; as a result, no water samples can be collected at these sites.

The third test in granite (the Shoal event) was conducted below the water table in the Sand Springs granite, 48 km (30 miles) southeast of Fallon, Nevada. Burst depth was 367 m (1205 ft) below the land surface and 91 m (300 ft) below the pretest, water table altitude. Hydrologic studies before the test showed a low storage capacity in the rock, and the estimated time required for chimney infill was 10 years. Following infill, it was estimated that there would be a 9-m/yr (30-ft/yr) water migration to the southeast.

The Shoal site is a good place to study and document leaching and transport of radioactive materials deposited in granite below the water table. Measurements there could be correlated directly with crystalline rock repositories.

At the Shoal site, one drill hole (PS-1) penetrated the apex of the chimney and went out through the bottom of the cavity. This hole, if reentered, would provide water samples from the chimney/cavity region. Because the amount of the radioactive species deposited is known or can be calculated, it would be compared with the amount of radioactivity in the water. Although the radioactivity in the water is a result of a two-stage process of leaching and resorption, leaching could be estimated by using laboratory values to calculate resorption.

Because of the low permeability, low storage capacity, and low flow rate within the Shoal granite, measurements outside the chimney area do not appear practical. At present, we are still trying to verify the manner in which the postshot hole was plugged, so that we can write a proposal for reentry and sampling.

Salt Sites. Three nuclear tests have been conducted at two sites in salt. The first (code-named Gnome) was located about 48 km (30 miles) southeast of Carlsbad, New Mexico. It was a 3.1-kt explosion in December 1961, at a depth of 361 m (1184 ft) in the Salado bedded salt.

The second site, the Tatum salt dome near Hattiesburg, Mississippi, accommodated two tests. The first (code-named Salmon) was a 5.3-kt explosion in October 1964, at a depth of 828 m (2717 ft). The standing open cavity was reentered and used for the 0.4-kt Sterling nuclear explosion, which was a test of seismic decoupling.

Our conclusion is that the best opportunity for work useful to the Waste Isolation Safety Assessment Program exists at the Gnome site in New Mexico. Cleanup operations there are planned before deactivation, and it is possible that some of our work might be combined with them.

Definitive research on migration below the cavity would likely be very expensive. It would require a shaft and a mined drift under the base of the cavity to obtain unequivocal data. However, a sample of brine from the cavity could probably be obtained during the site cleanup operations, at which time the Nevada Operations Office of the Department of Energy (DOE-NV) plans to drill a reentry hole and pour nuclide-contaminated soil through it into the cavity. Before soil emplacement, it would be possible to set a bridge casing across the cavity to sample brine in its lower part. During previous operations, about 100,000 litres of water entered the cavity. This water should now be in approximate equilibrium with the cavity material, having dissolved about 36 metric tons of contaminated salt. It offers a unique opportunity to obtain field data on the availability of radionuclides to a brine solution.

In the cleanup operations before the Salmon site was deactivated, a slurry of contaminated mud was injected into the cavity, creating a completely unnatural environment because of the mud mineralogy. If we recovered brine samples from the cavity, we would find it difficult, if not impossible, to relate the samples' data to the natural mineralogy of the salt. Such sampling attempts, therefore, are technically infeasible, if the purpose is to obtain information relevant to waste isolation in salt formations.

Sorption Studies

Sorption is studied by three methods: static, column, and core. The core method is rarely used, but it most closely simulates intergranular flow under field conditions. Preliminary work at LLL[2] indicated the feasibility and utility of flowing a tracer through a core, compared with statically contacting powdered rock. The apparatus we are building for taking core measurements is designed to operate under confining pressures higher than those of the earlier experiments; also, control of temperature is possible. Thus, we can simulate *in situ* conditions. In addition, a considerable variety of rock material is available because of the small core size of the apparatus. Our objectives in using this apparatus are to:

1. Compare static and core methods of determining sorption ratios.
2. Investigate phenomena, such as dispersion and desorption, by injecting tracer pulses into a steady-state flow through the rock core.
3. Systematically investigate sorption as a function of time, pressure, temperature, and composition of the carrier liquid (including the effect of competing ions).
4. Take measurements relevant to specific field site locations at the Nevada Test Site.

High-Pressure Sorption Apparatus

We designed this apparatus (Fig. 2) in FY 1977. At the end of September, we had available: the high-pressure source and sample injection system, the sample mold, and the sample holder. The receiver design, however, was deferred until the pressure source, the sample holder, and the rock samples had been initially tested. The apparatus is designed for longitudinal driving (fluid inlet) pressures up to 3.4 MPa (500 psi) and radial confining pressures up to 34.8 MPa (6000 psi). Rock samples are each 13 or 26 mm in diameter and 26 mm in length; their sides are covered by cast plastic jackets, which also seal the sides to the end fittings and prevent leakage of the confining pressure fluid. We have specified brass and stainless steel for the prototype sample holder. These materials have mechanical properties that are quite adequate for the initial tests and their fabrication is quicker and cheaper than that of high-pressure steel.

The driving pressure of 3.4 MPa is determined by the nominal pressure rating of the radionuclide spike-injection valve. The other components have higher ratings: 68.0 MPa (10 kpsi) for the supply pump and 6.8 MPa (1 kpsi) for the supply line between the injection valve and high-pressure cell. The injection valve and supply line are both made of Teflon to minimize sorption effects. To increase the driving pressure, we must either operate the injection valve above its nominal rating at the cost of

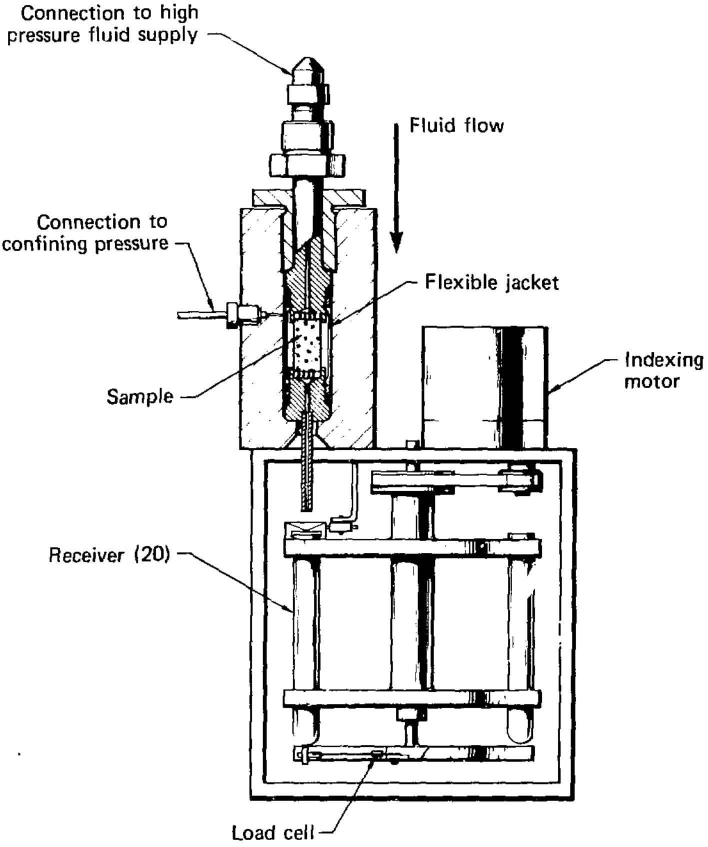

Fig. 2. High-pressure sorption apparatus.

shortened valve life, or we must switch to a stainless steel injection valve. The high-pressure sample chamber (brass) is rated for a maximum confining pressure of 40.8 MPa (6 kpsi), which corresponds to a depth of 1.7 km (5700 ft) in media of 2.4-Mg/m ^{3} density; therefore, it should be adequate for simulating reasonable waste-repository depths.

The adapters that hold the ends of the cylindrical samples have been designed in both 13- and 26-mm sizes, with the 13-mm size being used for initial pressure and jacket fabrication tests. The smaller size minimizes sample support problems, but the larger size tends to average out sample inhomogeneities. We plan to use the larger size wherever possible.

We have obtained large samples of well-characterized tuff, the Trailridge member of the Thirsty Canyon Tuff from a locality at Pahute Mesa (NTS). It is a partially welded, silicic, ash-flow tuff with moderate sorptive characteristics and permeability in the millidarcy range. The tuff is not strongly zeolitic. But we have found that very clay-rich or zeolitic tuffs are not strong mechanically (tend to disintegrate in the apparatus), or they are highly impermeable. We are obtaining other samples from known stratigraphic horizons.

During FY 1977, we developed a collection system for use with both the high-pressure K_d system and the leaching system. Effluent from the latter systems is fed into bottles lined with polyethylene bags, measuring 4 × 2 × 12 inches. The bottles are then placed inside of a forced-air oven whose temperature is held at 85°C. Experiments have shown that it takes from 30 to 40 hours to complete the evaporation. Each bag is removed from the bottle and then rolled with the residual salts at the center of the roll. It is placed in a 1-in. steel die and pressed to a pellet shape at 20.6 MPa (3000 psi), while a heating jacket raises the temperature to 150°C. When this temperature is reached, the die is cooled rapidly and the pellet is removed.

The produced pellets are gamma-counted with a low level, Ge(Li) gamma-ray spectrometer. Experiments (Table 1) show that the precision of pelleting and counting is about 4%. Accuracy is about 5%. The precision of just the gamma-counting is roughly 0.4%.

Depending on the particular sample, selected pellets are then ignited in platinum beakers and radiochemically separated and purified for $^{239+240}$Pu and ^{238}Pu analysis. This process requires the addition of a ^{242}Pu-tracer, lengthy purification procedures, and electrodeposition with subsequent alpha-pulse height analysis. As of the end of FY 1977, we had not completed tests of this collection system, using Pu solutions.

Static Sorption Samples

We have obtained a suite of samples from a drill hole near the site of the Cambric experiment. The reasons for our interest in the Cambric site is that extensive measurements have been made in the cavity/chimney area[3] and pumping is continuing in a well located 91 m (300 ft) away. We are attempting to obtain laboratory data for use in interpreting these field measurements.

We selected our samples from a depth equal to that of the cavity/chimney zone below the water table. The samples have been analyzed by x-ray diffraction for their mineralogical content. Samples from depths of 287 to 308 m (940 to 1010 ft) have been crushed and then screened to recover particles in the 44- to 150-μm size. We plan to composite these particles into a large sample for static K_d studies.

We have already used the samples of water from well 5B in Frenchman Flat for other K_d studies. So, we have obtained a fresh supply of that water. We have also replenished our stocks of fission product tracers, including Sb, Ru, Y, Sr, Ce, and Co. We plan to start a series of static K_d measurements on Cambric material in early FY 1978.

Table 1. Precision and accuracy of gamma-counting pellets–plastic bag collection system.

Experiment	Precision (1σ from $\bar{x}$) %	Accuracy (compared to liquid standard) %
5 separate pellets	4	+5
Pellet #6 counted 6 times–same detector	0.4	+3
Pellet turned over and counted 6 times	0.2	-3
3 aliquots of ^{137}Cs tracer counted in STD liquid geometry	0.4	–

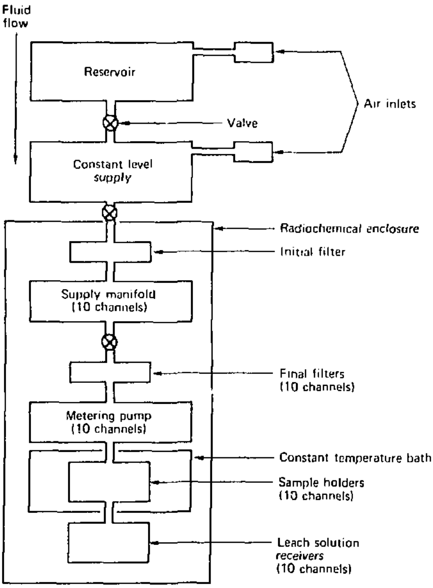

Fig. 3. Functional diagram, one-pass leaching system.

Leaching Studies

During FY 1977, as part of the RNM program, we designed, built, and tested a one-pass leaching system in which the solution contacts the solid only once (Figs. 3 and 4). Leaching experiments are commonly carried out either in closed vessels under

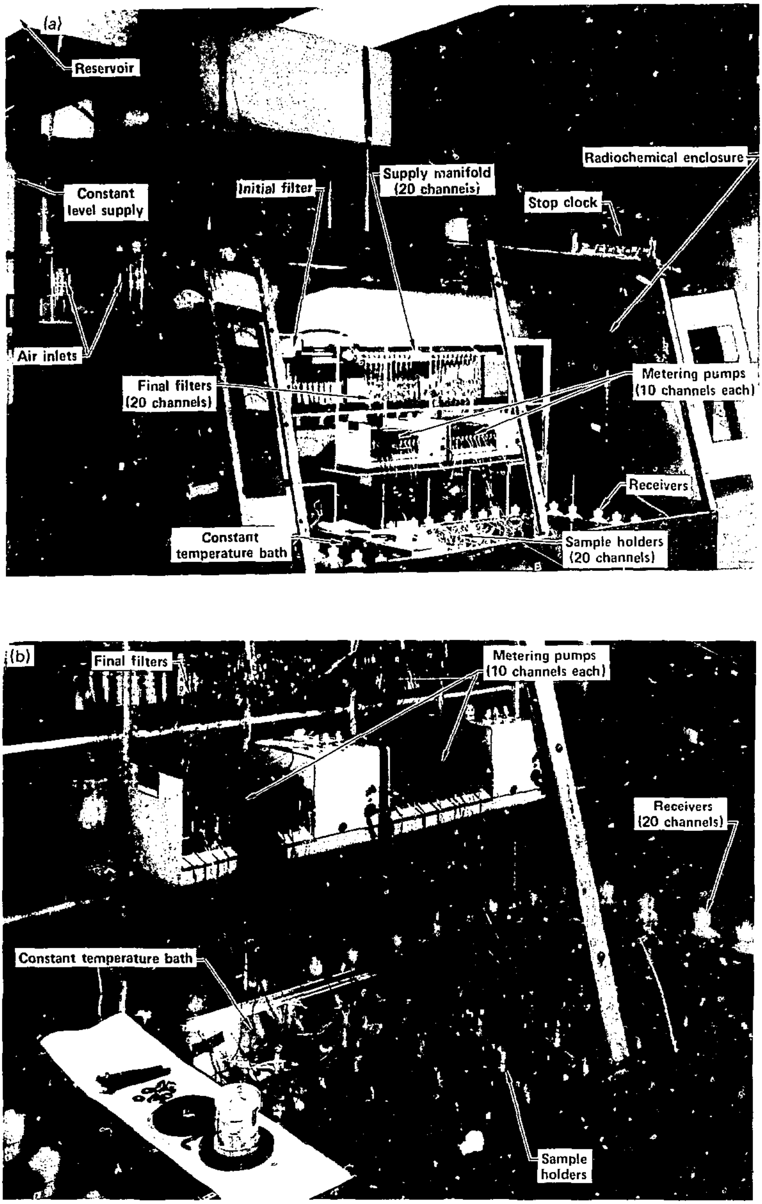

Fig. 4. One-pass leaching system. (a) General view. (b) Pumps, sample holders, and receivers.

static conditions, or in a recirculating system with continuous leachate removal (multiple pass). Under static conditions, the solid and liquid phases tend to equilibrate with each other. With our one-pass leaching system we hope to simulate a nonequilibrium situation, where new solution constantly contacts the solid, and where the maximum possible leach rate is attained. Also, this one-pass system will allow us to study resorption by the leached material, using tracers in the leach solution.

Our leaching system has 20 channels, which can be operated in 1 to 4 flow-rate groups. Each metering pump (10 channels each, Fig. 4b) is continuously variable in flow rate. Each channel can be operated in either a high- or low-flow position, giving a flow-rate range of 9 to 331 m/yr (Table 2). By comparison, the flow rate in the lower carbonate aquifer at the Yucca Flat test area (NTS) has been estimated to lie between 1.8 and 180 m/yr, and elsewhere between 18 and 410 m/yr.[1] Also, flow velocity beneath the Pahute Mesa test area is estimated at 2 to 76 m/yr.[1] In light of these various estimates, our equipment is designed for realistic NTS flow rates.

The one-pass leaching system allows variation in (and control of) flow rate, temperature, leaching solution composition, and solid particle size. The range of operating conditions is given in Table 2.

In theory, each channel could receive a different leaching solution, although we will start with a single solution for all channels. As many as three solutions may be studied simultaneously, which we will attempt later.

Details of the sample holder are shown in Fig. 5. The purpose of the side filler plug is to allow the solid sample to be introduced after assembly and pressure testing.

Table 2. Characteristics of one-pass leaching system (maximum of 10 types of solution for each metering pump).

Flow rates:		
	Low speed	**High speed**
Volume, cm^3/day:	13 – 158	26 – 460
Linear, m/yr:	9 – 114	18 – 331
Sample holder filter:		
Diameter	25.4 mm	
Pore size	1 μm	
Operating temperature:	20 – 85° C	
Volume of powder:	2.1 cm^3, maximum	

During FY 1978, we will use the system to leach melt-glass samples from nuclear events selected for age, quality of samples available, and variety of rock types. This work will be sponsored by the RNM program. We also plan to construct a second system to leach simulated, doped, reprocessed reactor waste as part of WISAP Task-3 activities.

The most important advantages of this one-pass leaching system are:

- Control of resorption effects.

- Provision for a large number of simultaneous experiments.

- Ability to handle concentrated Cl$^-$ leaching solutions if necessary.

References

1. I. Y. Borg, R. Stone, H. B. Levy, and L. D. Ramspott, *Information Pertinent to the Migration of Radionuclides in Ground Water at the Nevada Test Site, Part 1: Review and Analysis of Existing Information*, Lawrence Livermore Laboratory, Livermore, California, UCRL-52078 (1976).
2. J. D. Tewhey, *Preliminary Results of Experimental Work in the Radionuclide Migration Program: The Sorptive Character of Tuffaceous Rocks in a Static versus Dynamic Mode of Testing*, Lawrence Livermore Laboratory, Livermore, California, UCID-17064 (1976).
3. D. C. Hoffman, R. Stone, and W. W. Dudley, Jr., *Radioactivity in the Underground Environment of the Cambric Nuclear Explosion at the Nevada Test Site*, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, LA-6877-MS (1977).

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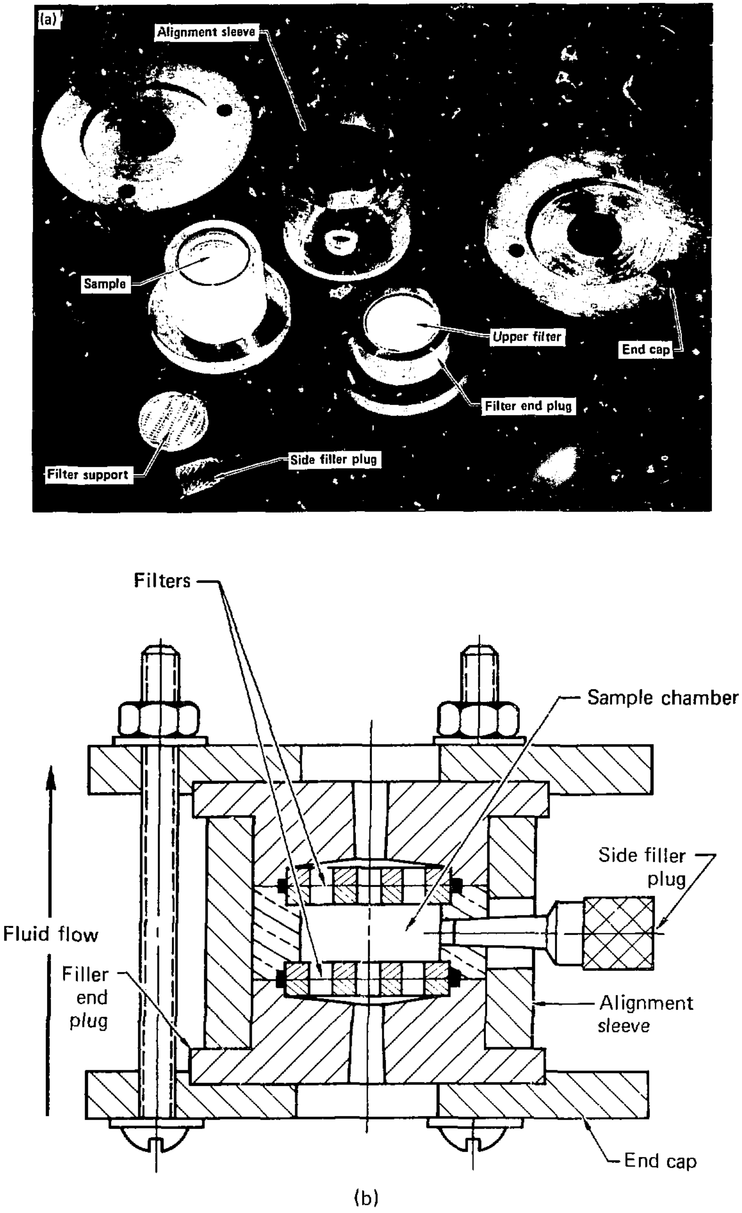

Fig. 5. Sample holder, one-pass leaching system. (a) Assembly. (b) Cross section.

3. TERMINAL STORAGE R&D — STUDIES OF NTS ROCKS (CLIMAX GRANITE)

CONTENTS

Summary

In the last five months of FY 1977—the period during which LLL was funded to initiate the first *in situ* heater test in crystalline rock—we essentially completed the preparations for fielding the test. Supporting field construction ended and all mechanical and electronic systems were ready for final installation. (Note that in the first two weeks of October the installations were completed, and we activated the first heater on October 14.) LLL's expenditures for these activities totaled 21 man-months; the total cost was $705,000.

The planned field tests, designed to determine the *in situ* thermal properties of Climax granite, will take place during FY 1978.

Introduction

LLL first became involved in waste isolation-related activities in granite at the Nevada Test Site at the request of ERDA's Nevada Operations Office (now DOE-NV) in mid-1976. We were asked to help in preparing a proposal, for ERDA-HQ, to conduct a generic demonstration of the storage of a high-level waste canister in the Climax stock, an intrusive granite formation. This proposal was completed in late FY 1976. No further significant activity occurred until mid-April 1977. At that time, we were asked to contribute to a planning meeting for significantly broadening the OWI-sponsored activity at the Nevada Test Site. The work described in this section was first proposed then, and it was authorized in May.

Our work activities during FY 1977 fell into two categories: site and laboratory. Except for the last two weeks of the year, these activities, while closely coordinated, occurred independently of each other. As a result, we describe them separately in this section.

Scope of Work

LLL was initially tasked to start preparations for conducting a series of experimental tests to simulate waste isolation *in situ* in the Climax granite stock of the Nevada Test Site. The target date for the first test was the end of FY 1977. We designed the first test to obtain realistic values of the *in situ* thermal properties of a granite typical of those found in the basin and range province. We have proposed that subsequent tests include the granite's mechanical response to sustained heat loads, and other technical issues related to waste isolation.

Site Description

The Climax granite stock is located close to the northeast corner of the Nevada Test Site, in Nye County, Nevada. It is near the site of a small tungsten mine, called the Climax Mine in the 1940's. During the 1960's, the Atomic Energy Commission and the Department of Defense jointly sponsored two nuclear-weapon effects tests in the granite stock: Hard Hat and Pile Driver. The first test was a 5-kt explosion at a depth of 250 m; the second was 60 kt at 425 m below the surface. In both tests, extensive underground structures were monitored for their response to the explosions. The required excavation, structure installation, and monitoring instruments were supported by a vertical shaft (2 × 3 m). The experimental site for the first heater test is near the bottom of this shaft. It is located in a small alcove that we excavated in an existing drift (Fig. 6).

The medium at the experimental site is a quartz monzonite. Its basic grain size is about 2 mm, with scattered feldspar crystals up to 0.1 m long. Average fracture frequency is about three fractures per metre, although the experimental area has few gross fractures. The *in situ* stress environment near the test area was measured by Lucius Pitkin, Inc., at 95 bars (maximum) and 12 bars (minimum). These measurements indicate that significant stress variations, caused by the excavated drifts, extend about one metre into the rock. The ambient rock temperature at the midplane level of the experimental array is 23°C.

Site Activities

Immediately after the May authorization to proceed with our proposed tests in the Climax stock, we inspected the site's surface and underground facilities thoroughly. We found that new shaft furnishings were needed, particularly replacements for the ladders and landings in the manway compartment and for the utility piping. Also, a new hoisting cable was required. We completed the necessary rehabilitation by mid-August. Original plans had included the cleanup of an existing alcove in the shop drift for the experimental site. But we found it to be more expedient to excavate a new alcove (3 × 4 m) and use that instead.

We drilled an array of small-diameter vertical holes in the floor of the alcove and drift for housing the heaters and thermocouples (Fig. 7). The array consisted of 13 AX (48-mm diam) holes, 2 NX (76-diam) holes, and 2 NX/AX stepped holes, all drilled with diamond core bits and using water as a circulating medium. Many continuous 1.5-m, unfractured core lengths were recovered (recovery totaled 98% of footage drilled). The holes, in orthogonal pattern, orient approximately parallel and perpendicular to the major fracture system in the immediate vicinity of the site. The two heater holes are located near the ends of the array. Thermocouple holes range from approximately 0.2 to 5 m from the heater holes. The 5-m hole is at the intersection of the two orthogonal lines. Two holes, each 0.5 m from the heater, are 12 m deep. The rest are 9 m deep.

After drilling, we surveyed the holes optically, using a right-angle prism theodolite and movable light-source target, to develop three-dimensional coordinates for locating each thermocouple and heater. We verified that the instrumentation would fit properly in the holes by running a mandrel, of similar size, to hole bottom.

All test controls and recording systems are located on the surface. Locating them underground proved prohibitive, because of the estimated $1000/day cost to keep access to the drift site open for personnel during the run of the experimental program. Multiconductor shielded cables, in the shaftway, will transmit the control commands and data between the 425-m level and the surface systems, via 100 data circuits and 13 control circuits. The cables are encased in a 6-in. conduit for physical protection and to afford additional shielding against 60-Hz ac power lines.

In late September, the construction activities were complete and the site was ready for installation of the experimental apparatus. We moved the mechanical support and recording/office trailers to the site, secured them, and powered them up at the end of the fiscal year.

Laboratory Activities

Activities at LLL, to prepare for the first field test, concentrated on several interrelated subtasks from May to September. These included:

- Conceptual design of the experimental program.
- One- and two-dimensional calculations of anticipated thermal profiles.
- Design, prototype fabrication, and evaluation and procurement of the mechanical assemblies.
- Design, specification, and assembly and checkout of the electronic recording and control systems.
- Planning of data reduction and analysis procedures.
- Laboratory measurements of thermal properties on core samples.
- Block-scale heater tests on Climax granite blocks.

Conceptual Design

Our developed test concept includes two heaters. This duality provides us with a redundant field system [illegible]ing us to duplicate a test if an early

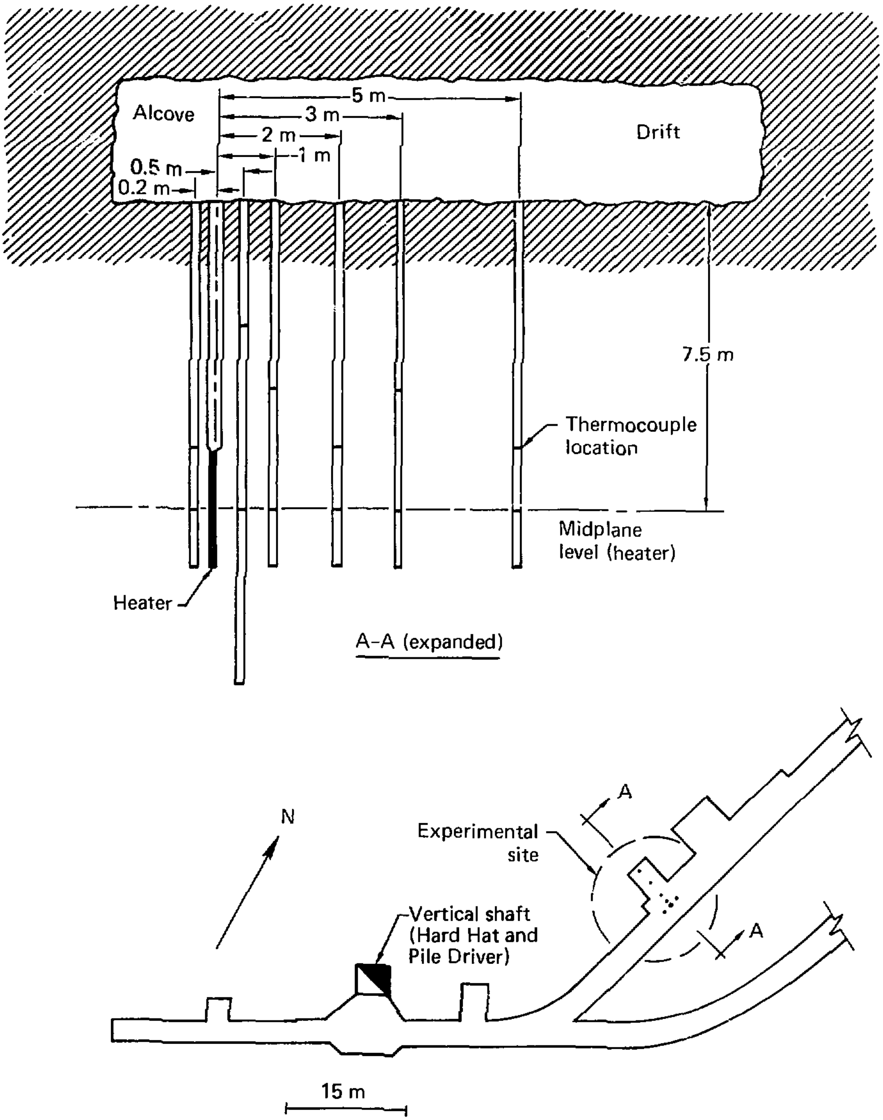

Fig. 6. *Plot plan and vertical cross section of underground experimental site for first heater tests* (Climax granite stock, northeast corner of Nevada Test Site, Nye County, Nevada).

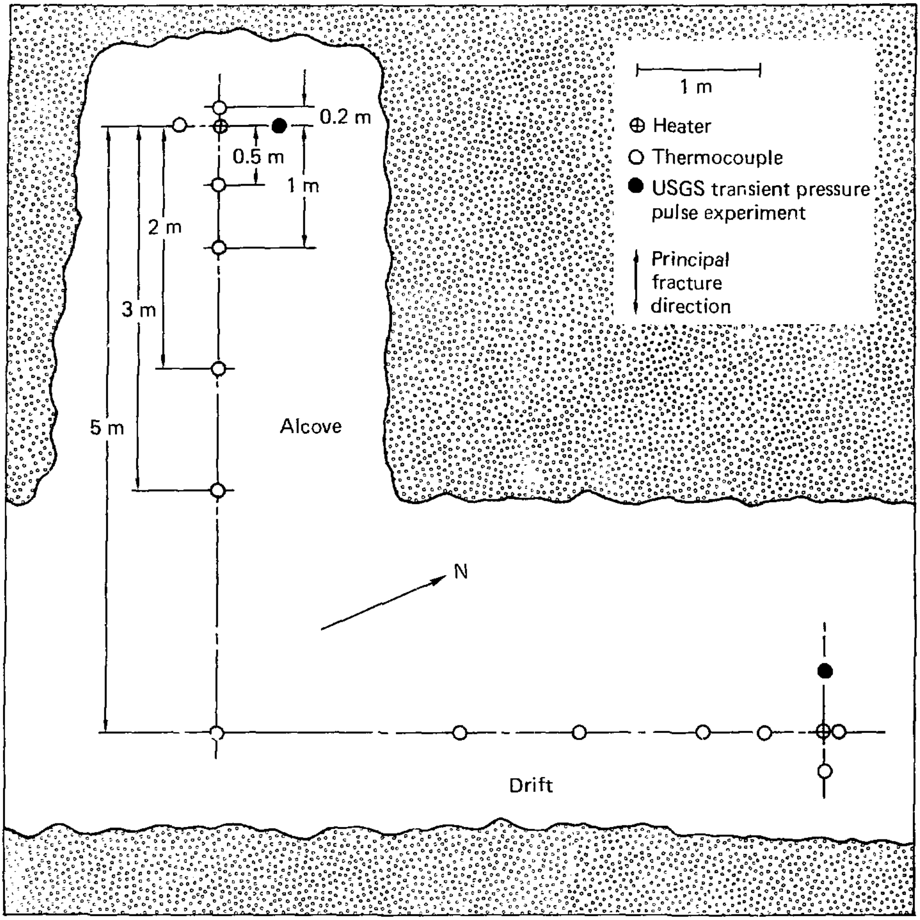

Fig. 7. Plan view of heater test #1 layout, 1400-ft level (Pile Driver level) (note that location dimensions for drift holes are the same as those for alcove holes).

rock failure should preclude the recovery of a heater. Also, the concept will permit us to investigate the anisotropic effects associated with the fracture orientation. In addition, it assumes a flexibility to operate a continuous constant-power mode and cyclic-pulse mode simultaneously. The heaters are specified to have high length/diameter ratios, to achieve high rock temperatures in the radial dimension in a relatively short time frame. Such ratios also allow us to use finite line source, two-dimensional, transient, thermal calculations in the instrumented region. We selected a heater power dissipation of up to 5 kW in a 3-m length to simulate full-scale, waste canister, thermal effects in the region outside a 1-m radius.

The size of the thermocouple array was limited by the capacity of available data recording systems. The resulting total of 60 data channels is adequate for the experiment. Data transmission techniques and power/control locations were decided upon, to permit the mechanical and electronic activities at LLL and in the field to proceed. We also prepared a draft experimental plan.

Thermal Profile Calculations

We performed one-dimensional scoping calculations, using reported granite thermal properties, to guide us in our detailed layout and to establish placement accuracy and precision requirements for various experimental elements.

We used two-dimensional calculations to give us detailed predictions on the dimensionless time/temperature relationships at each planned thermocouple location. These predictions were then utilized to evaluate the efficacy of the mechanical design of the thermocouple emplacement hardware. The relationships indicated by these calculations will also guide us in developing the experiment's operational procedures relative to defining power-duty cycle planning for pulse tests.

Mechanical Assembly Development

This development falls into three categories: heaters, thermocouples, and installation/extraction fixtures.

Because of lead-time considerations, we specified the heaters directly from the vendor's catalog, calling for minor modifications to permit mounting in the drilled holes. The heaters are standard cartridge-type immersion units. They are encapsulated in 16-mm diameter, Inconel cladding, with a centralizing flange at the bottom and a landing/adapter flange at the top, both made of stainless steel. An adapting fixture, with double J-slots, is used for either emplacing or removing the units. Electrical terminals are encapsulated in epoxy. Four thermocouples, fastened to the heater's exterior, monitor performance.

The thermocouples are grouped four to an assembly, designed specifically for our experiment. Each thermocouple, 1.6 mm in diameter, is made of Chromel-Alumel (type K) and is sheathed in stainless steel. Active junctions are silver-soldered into copper pins. A stainless steel space frame, enclosing the thermocouples, is equipped with Inconel springs that force the copper pins into contact with the granite sides of each hole. The contact resistance is reduced by a thermal-conducting cement. We have tested prototypes of this assembly in a mock-up environment at LLL, using a large concrete block that was cast for this purpose. Actual thermal properties of the block were derived from our analysis of these tests, under pulse testing conditions extending for about two weeks.

The field experiment thermocouples were then fabricated and shipped to the site for final assembly and installation. A 60-channel, thermally-isolated, reference junction block, mounted in the drift, provides the interface between the mechanical thermocouple installations and the electronic recording system.

Installation fixtures, made of modular tubing, provide the means for activating the thermocouple contacts remotely. Also, they permit all extraneous metal components to be removed from the upper six metres of each hole, after the assemblies are installed.

Electronic Control/Recording

The electronic systems control and record the heater power levels remotely; also, they record the thermocouple data remotely. They are designed to operate unattended with periodic inspection and reloading.

Two redundant, 60-channel data loggers provide a back-up capability if the system should malfunction. They record the power level and thermocouple data at selected time intervals on magnetic tape, with paper tape back-up. The loggers are controlled by an automatic reset-time, code generator and scan frequency selector.

Data Reduction/Analysis

The magnetic-tape data records from the site will be reduced and analyzed semi-weekly at LLL. We are developing the software for reading and reducing the data, utilizing LLL's interactive computer system. Type-curve fitting techniques, using the previously mentioned dimensionless time/temperature relationships, will be used for preliminary analysis work. For the subsequent detailed analysis, we will apply modeling techniques that use two-dimensional finite difference codes such as TRUMP. These modeling techniques will allow us to determine the temperature-dependent thermal conductivity and diffusivity; also, they will permit us to examine discontinuity effects, such as those caused by water saturation in fracture systems or by changes in fracture conductivity produced by stress changes.

Thermal Property Measurements

We have measured the thermal properties of Climax granite samples at high temperatures. We were unable to apply a controlled confining stress to the samples during tests, because facilities for doing so are not yet available. Thermal conductivity and diffusivity were determined at ambient and elevated temperatures. We met some difficulties at very high temperatures, but we measured realistic values at 25 to 200°C; additional work is underway in this area. We also heated some samples to 800°C and analyzed the off-gas constituents; no corrosive products were identified in significant quantities.

Granite Block Tests

We have conducted two block-scale granite tests, using material from the vicinity of the field experiment. An initial test with a 1-ft^3 block, at power levels of up to 4 W/mm (four times the power level planned for the field test), assured us that decrepitation of the heater hole wall will not be a serious problem. For our second test, we cast an 8-ft^3 granite test block into a 60-ft^3, bentonite, grout-filled form. We then instrumented it with a heater and thermocouples, to evaluate the effect of heating/cooling cycles and pulse testing techniques during both transient and near-steady-state conditions. We plan to continue these activities during the initial heating cycle of the field experiment, to provide guidance in developing the field test sequence.

L. B. Ballou

4. PHYSICAL/CHEMICAL FACTORS—WATER TRANSPORT IN DEEP SILICATE ROCKS

CONTENTS

Introduction

The goal of this study, which began in June 1976, is to assess the suitability of rocks other than salt to serve as safe, long-term containment materials for solidified, high-level radioactive wastes. We have set ourselves three objectives in meeting this goal:

- Develop working hypotheses and a theoretical basis, to account for the complete absence of circulating ground water in deeply buried rocks.
- Test these hypotheses in the laboratory and in the field.
- Synthesize the laboratory and field test data, to develop a predictive capability for long-term containment.

Our study focuses on igneous intrusive rocks, or high-grade crystalline metamorphic rocks.

Scope of Work

To predict the long-term behavior of certain igneous and metamorphic rocks, we will measure several physical properties of samples in the laboratory at simulated, deep *in situ* conditions and then correlate them with detailed field observations. This will allow us to predict the response, both in space and time, of a mined cavity in these rocks, based on only minimal exploratory data.

The properties we plan to measure, using fractured and unfractured rocks, include permeability, acoustic velocity, electrical conductivity, principal stresses, and principal strains when these rocks are loaded over a range of durations. The detailed field data that we will require (both surface and *in situ*) include fracture intensity and spacing, and as many of the above properties as are available. We hope then to develop simple models for estimating the permeability and mechanical stability of the rocks, based on the mechanisms of fracture closure that we determine from the combined laboratory and field results. The results from these models will help us to estimate the suitability of the rocks for solid waste disposal at a specific site, based on limited geologic information.

Activities Prior to FY 1977

In the four months before FY 1977 began, we designed and fabricated the high-pressure components of the apparatus for measuring the physical properties of the rock samples. Also, we designed and built most of the electronic components for controlling the apparatus during sample loading/unloading and for recording the ensuing data.

Our geological field work in this short period consisted of gathering structural and physical property data from several regions *in situ*. We selected two types of rock for our laboratory studies: White Lake gneissic granite (White Lake, Ontario) and Westerly granite (Westerly, Rhode Island).

Also, during the four months, we familiarized ourselves with the U.S. Waste Disposal Program. We met with personnel from the Office of Waste Isolation (OWI) to find out how we could help them meet their goals, within the limits of our study. In addition, we talked with Canadian scientists who are working on problems virtually the same as ours. From these talks, we were able to gain much valuable insight.

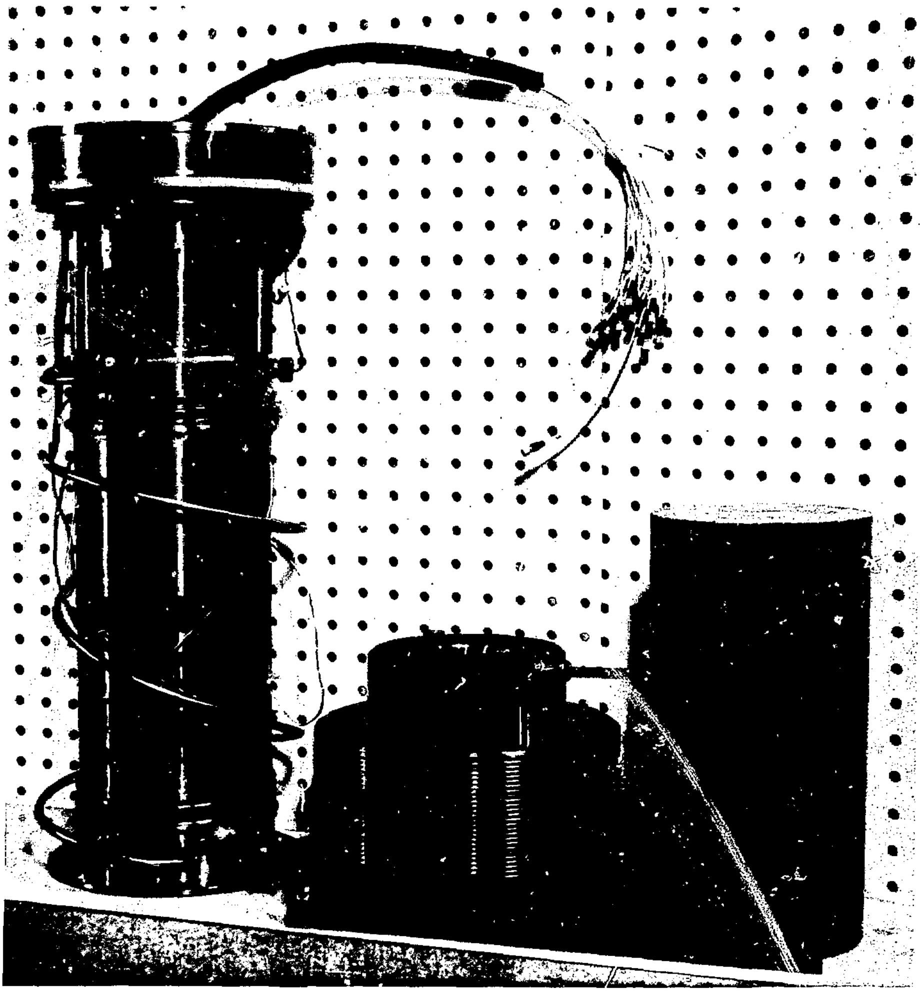

Fig. 8. Test sample geometry for high-pressure testing apparatus. At left, assembled test sample (steel dummy) for measuring k, V_p, ρ, σ, ϵ. Center, closure nut holding test assembly in pressure vessel. At right, test sample (14 by 29 cm) of White Lake gneissic granite.

Activities in FY 1977

We selected four more rocks for laboratory testing, based on available (or planned) field and physical property measurements: Montello granite (Wisconsin), Creighton gabbro (Sudbury, Ontario), Pile Driver granodiorite (Nevada Test Site), and the Stripa granite (Sweden). These four now complete our selected list of six different formations for use in evaluating the behavior of crystalline igneous/metamorphic rocks. We have received rock material from all but two formations: NTS and Sweden. Two to four test samples are being taken from each of the four rocks we have on hand, and either they have been cored and ground or they are in various stages of preparation.

We have completed the high-pressure testing apparatus (Fig. 8) for measuring permeability (k),

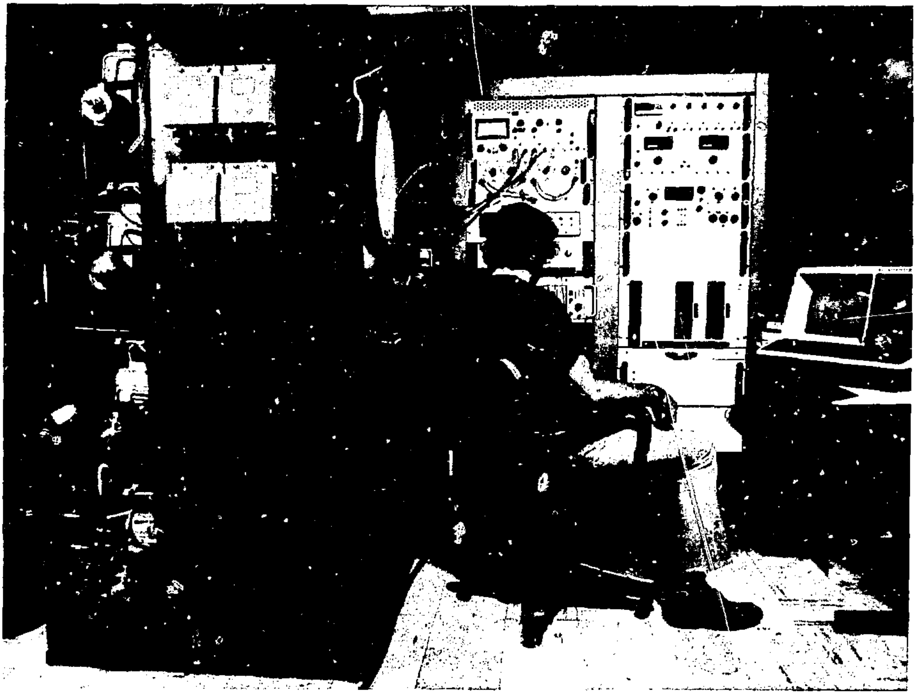

Fig. 9. Complete high-pressure testing apparatus, showing (from left to right) pressure vessel, pressure control and k measurement cabinets, pressure control panel, electronics for measuring k, V_p, ρ, σ, and ϵ. At far right, LSI 11 minicomputer and associated electronics for the experiment's data and control display.

acoustic velocity (V_p), and electrical conductivity (ρ) as functions of the three principal stresses (σ) and strains (ϵ). All ancillary oil and water systems for use in generating and measuring fluid pressures are assembled and may be operated manually. All electronic systems to measure k, V_p, ρ, σ, and ϵ, are complete for use in the manual data-acquisition mode. Electronic components, to provide automated data acquisition for the V_p and ρ measurements, are expected in the next several months. Figures 8 and 9 illustrate the test sample geometry and the overall apparatus, respectively. Calibration of the entire system is now about half-completed. Also, the programmable capability for controlling the total experiment and for controlling the automated data-acquisition system is complete. Both control systems are being debugged. During this calibration and debugging phase, we have made preliminary measurements of V_p and ρ (at 0.1 MPa pressure) on Westerly granite and White Lake gneissic granite.

Three reports were issued in FY 1977. Two deal with experimental aspects of the present project. The third predicts the time- and temperature-dependent closure of cavities in salt at depth. Figure 10 shows the results of this prediction for cavities, at several depths, at the West German repository facility at Asse. Abstracts of the three reports are given in Appendices A, B, and C.

H. C. Heard

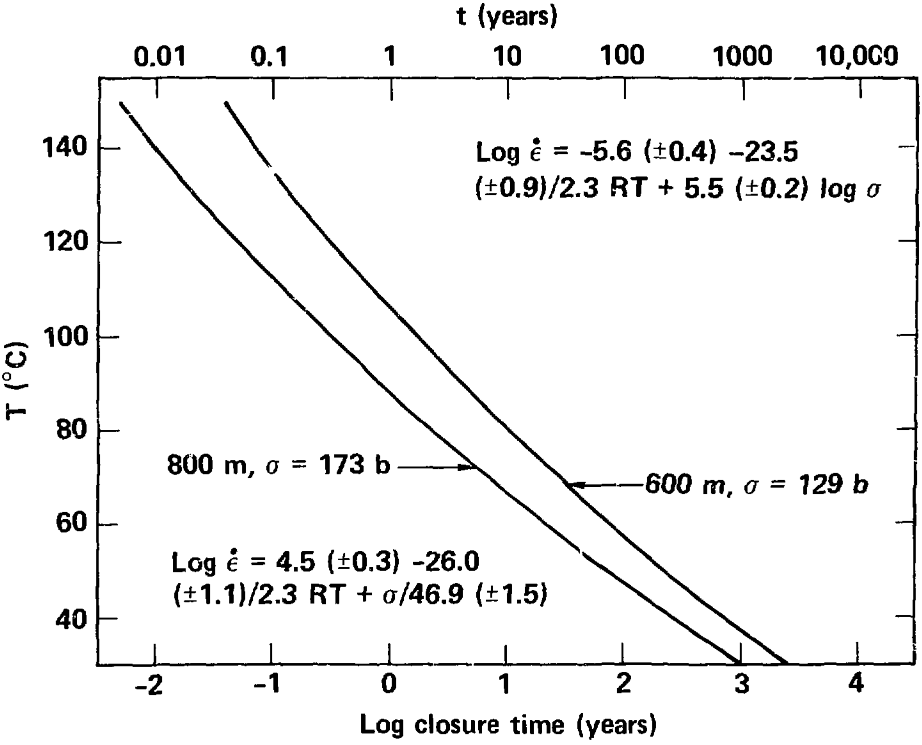

Fig. 10. Plot of temperature vs closure time for complete closure of any salt cavity at depth. Two illustrative examples are shown: at right, cavity at depth = 600 m, using low-stress flow law for polycrystalline salt; at left, cavity at depth = 800 m, using high-stress flow law for salt. Based on results of Heard, H. C., *Am. Geophys. Union Mono.* 16, pp. 191-209 (1972).

APPENDIX A

COMPRESSIBLE FLUID FLOW THROUGH ROCKS OF VARIABLE PERMEABILITY

ABSTRACT*

The effectiveness of coarse-grained igneous rocks as shelters for burying radioactive waste can be assessed by determining the rock permeabilities at their *in situ* pressures and stresses. We use analytical and numerical methods to solve differential equations of one-dimensional fluid flow through rocks with permeabilities from 10^4 to 1 nD. In these calculations, we use upstream and downstream reservoir volumes of 5, 50, and 500 cm ^{3}. The optimal size combinations of the two reservoirs are determined for measurements of permeability, stress, strain, acoustic velocity, and electrical conductivity on low-porosity coarse-grained igneous rocks.

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*W. Lin, *Compressible Fluid Flow Through Rocks of Variable Permeability*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52304 (1977).

APPENDIX B

SURFACE METHODS FOR DETERMINING THE ELECTRICAL CONDUCTIVITY OF CORE SAMPLES

ABSTRACT*

An electrode configuration is described for measuring the electrical conductivity of a core sample that does not rec[illegible] to the end of the sample. The methods [illegible] relatively insensitive to the shape of the sample, eliminating the need for machining. Validation of the measurement technique is provided by comparing results obtained from this method with actual measurements perpendicular and parallel to the core axis on granite samples. The seed idea for a new data inversion method is discussed, which could provide a three-dimensional picture of the low frequency conductivity profile throughout a sample (i.e., an impedance camera).

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*R. J. Lytle, A. G. Duba, and J. L. Willows, *Surface Methods for Determining the Electrical Conductivity of Core Samples*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52211 (1977).

APPENDIX C

PREDICTION OF THE CLOSURE BEHAVIOR OF TERMINAL RADIOACTIVE WASTE STORAGE VAULTS IN SALT BODIES AT DEPTH

ABSTRACT*

The flow law governing steady-state behavior of polycrystalline salt has been determined on artificial aggregates deformed in the laboratory at temperatures ranging from 23° to 400°C, stresses from 500 to 16 bars, and strain rates of 10^{-1} to 10^{-8} s^{-1}. At stresses greater than about 150 bars, the deformation mechanism responsible for steady-state flow is dislocation glide (slip). All data are well fit by $\log \dot{\epsilon} = 4.5(\pm 0.3) - 26.0(\pm 1.1)/2.3\ RT + \sigma/46.9(\pm 1.5)$ where $\dot{\epsilon}$ is the steady-state strain rate (s^{-1}), R is the gas constant, T is temperature (K), and σ is stress (bars). The stated uncertainties are reported at the one standard deviation level. At all lower stresses, the data are well correlated to $\log \dot{\epsilon} = -5.6(\pm 0.4) - 23(\pm 0.9)/2.3\ RT + 5.5(\pm 0.2) \log \sigma$, where the operative mechanism is dislocation glide and climb (polygonization). These results have been correlated with observations of flow in naturally occurring salt bodies (e.g., Zechstein salt, North Germany). Prediction of the steady-state flow behavior of natural salt on the basis of these laboratory measurements on artificial salt aggregates yields results which agree well within the uncertainties of the above flow equations. For example, steady-state room closure rates of 7-9 × 10^{-12} s^{-1} are observed at the 700-m level of the Asse #2 mine (Wolfenbüttel, North Germany), where temperatures are 30°C and lithostatic stresses are about 150 bars. When this range of strain rates and temperature for the Asse #2 mine are used together with the observed steady-state flow equation for slip in order to calculate the closure stress, the resulting values are 145 to 153 bars, depending upon the initial values of rate.

On the basis of these laboratory-determined flow laws, closure rates for openings in natural salt in this region are both stress- and temperature-dependent; thus, the duration of operation of vaults used for terminal radioactive waste storage may be accurately predicted. For example, at an ambient temperature of 30°C with no emplaced wastes, vaults at 600 to 800 m will remain open for 2500 to 1000 years, depending on depth. With emplacement of hot wastes, if the surrounding temperatures in the salt rise to 50°C at those depths, vault closure occurs at 220 to 70 years. At 100°C, closure could occur over durations as short as 1.6 to 0.3 years.

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*H. C. Heard, *Prediction of the Closure Behavior of Terminal Radioactive Waste Storage Vaults in Salt Bodies at Depth*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-79946 Abstract (1977). Also, invited lectures: Rockstore Conference, Stockholm, Sweden (1977) and Kavernen-Bao Betriebs, Hanover, W. Germany (1977).

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