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Spent Fuel Test-Climax: Technical Measurements, Interim Report, Fiscal Year 1981

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SPENT FUEL TEST-CLIMAX:
TECHNICAL MEASUREMENTS
INTERIM REPORT
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ABSTRACT

The Spent Fuel Test-Climax (SFT-C) is located 420 m below surface in the Climax granite stock on the Nevada Test Site. The test is being conducted for the U.S. Department of Energy (DOE) under the technical direction of the Lawrence Livermore National Laboratory. Eleven canisters of spent nuclear reactor fuel were emplaced, and six electrical simulators were energized from April to May 1980, initiating the 3- to 5-year-duration test.

The SFT-C operational objective of demonstrating the feasibility of packaging, transporting, storing, and retrieving highly radioactive fuel assemblies in a safe and reliable manner has been met.

Technical objectives of the test led to development of a technical measurements program, which is the subject of this report. Geotechnical, seismological, and test status data have been recorded on a continuing basis for the first 1-1/2 years of the test on more than 900 channels. Much of the acquired data are now available for analysis and are presented here. Highlights of activities this year include completion of site characterization field work, major modifications to the data acquisition and the management systems, and the addition of instrument evaluation as an explicit objective of the test.

CHAPTER 1

SUMMARY AND CONCLUSIONS

The Spent Fuel Test-Climax (SFT-C) is being conducted under the technical direction of the Lawrence Livermore National Laboratory for the U.S. Department of Energy. As part of the Nevada Nuclear Waste Storage Investigations, it is managed by the Nevada Operations Office of the DOE.

The SFT-C is located 420 m below surface in the Climax granite stock where facilities were constructed between June 1978 (when the test was funded) and April 1980 (when spent fuel emplacement began). Spent fuel emplacement between April 18 and May 28, 1980, and spent fuel exchanges in January and October 1981, met the operational objective of the test: demonstration of safe and reliable packaging, transport, storage, and retrieval of spent nuclear reactor fuel.

The technical measurements program is aimed at acquiring data about the ultimate qualification of granite as a repository medium, as well as the design and prediction of the response of such a repository in granite. Numerous technical objectives focus our activities on these stated aims.

Data has been recorded continuously on more than 900 channels during the first 1-1/2 years [fuel age: 2.5 to 4.0 years out of core (YOC)] of the test. Most data is acquired through a central data acquisition system (DAS). Periodic displacement measurements and radiation dosimetry data are acquired manually and processed independently of the DAS. Acoustic emissions data are also acquired independently.

This report is the second in a series of technical interim reports (Carlson et al. 1980). It summarizes the data acquired and presents some preliminary analyses and interpretations. For the sake of completeness, we also summarize key results published in topical reports throughout the fiscal year. Some important results that became available in fiscal 1982 while this report was in preparation are included.

1.1 SITE CHARACTERIZATION AND GEOLOGICAL INVESTIGATIONS

Site characterization and geological investigations completed this year include fracture mapping, core logging, geohydrology, and laboratory rock mechanics of granite. Our observations to date indicate:

- The typical mean fracture density is about 3/m in the canister drift. In addition, several major shear and fault zones pass through the facility.
- Logging of unoriented core provided sufficient data for siting geotechnical instruments.
- The top of the saturation zone is located about 975 m above MSL or about 145 m below the test level.
- A statistically significant degradation in uniaxial compressive strength (~20%) and Young's modulus (5%-10%) were observed following gamma irradiation of Climax stock granite at a dose of 13 MGy. Brazilian tensile strength was not affected by the same treatment.

1.2 THERMAL SOURCES

Thermal sources are monitored during the test to ascertain their input for thermal and thermomechanical calculations of SFT-C response. Results to date show that:

- Total thermal input to the SFT-C has been 562.8 MW·h during the first 1.5 years of the test. This is about 13% higher than that used in thermal calculations for the test.
- The input energy partition is 30.0% from the spent fuel, 17.1% from the electrical simulators, 49.6% from the guard heaters, and 3.3% from the facility lights.
- Electrical sources of heat, associated controllers, and instrumentation are displaying a high degree of reliability.

1.3 DATA ACQUISITION SYSTEM

Data acquisition system has undergone significant hardware and software modifications and continues to function with a high degree of reliability. The two most significant modifications are addition of an HP-IB Extender Switching Network that allows either computer to scan all channels in the event of hardware or software maintenance or failure, and incorporation of lease-line telephone service. System accuracy and reliability statistics indicate:

- The accuracy of dc voltage measurements has been within an envelope of $\pm 4 \mu\text{V}$.
- The accuracy of 4-wire resistance measurements has been within $\pm 0.0092 \%$.

1.4 NEAR- AND INTERMEDIATE-FIELD TEMPERATURE MEASUREMENTS

Near- and intermediate-field temperature measurements are made at nearly 500 locations throughout the facility. Measurements to date show:

1. Temperatures in the repository-model cell closely approximate those calculated to exist in this region.
2. Temperatures throughout the array indicate that the conductivity and diffusivity of the host rock are slightly higher than determined in the laboratory and in Heater Test No. 1. The highly jointed rock mass appears to be homogeneous regarding heat transfer.
3. The axial and radial distribution of heat flow from the spent fuel and electrical simulator canisters is somewhat different. These differences exist primarily because of the gamma contribution and helium backfill of the spent fuel canisters.
4. Agreement between data and calculational results of both the TRUMP and ADINAT heat-flow codes is quite good throughout the rock mass. Differences are generally within a few degrees.
5. The effects of changes in ventilation rate are readily seen at locations greater than $\sim 3 \text{ m}$ from the thermal sources.
6. Type-K thermocouples deployed throughout the facility are functioning reliably.

1.5 VENTILATION AND DEW-POINT MEASUREMENTS

Ventilation and dew-point measurements document the heat removed from the SFT-C by the ventilation system. To date we have seen that:

- The type-K thermocouples, lithium chloride dewpoint meters, and turbine flowmeter have displayed a satisfactory reliability.
- Total heat removed from the SFT-C was $\sim 75 \text{ MW}\cdot\text{h}$ 1-1/2 years into the test. Of this, 74% was removed as sensible heat and 26% was removed as latent heat of vaporization.

- About 31,000 L of water have been removed to date from the facility by the ventilation system. During the first 0.4 years, the evaporation rate averaged 3.3 L/h while construction water was being removed, and it has now decreased to ~1.8 L/h.
- Agreement between calculated and measured heat removal rates is poor. We are continuing to study this area.

1.6 RADIATION-DOSE-TO-GRANITE MEASUREMENTS

Radiation-dose-to-granite measurements have been performed using lithium fluoride TLD systems. Significant disagreement between the various peaks indicates a previously unreported temperature sensitivity of one or more of the peaks. We continue to investigate this phenomenon. We have also researched the feasibility of using granite whole-rock samples for self-dosimetry measurements. This technique looks as though it will be possible to use, but we need to study the problem further before we can apply it rigorously with acceptable accuracy.

1.7 MEASUREMENTS OF RADIATION DOSAGE TO MAN

Measurements of radiation dosage to man indicate that no whole-body dose above background was received during spent fuel handling and storage operations. Very low finger doses were recorded on technicians responsible for thermocouple installation on the emplaced canisters.

1.8 ROCK STRESS MEASUREMENTS

Rock stress measurements are unavailable for analysis because these units failed shortly after test initiation. The failures resulted from the vibrating wire having rusted. In some gauges, corrosion advanced to the point where the wire was damped mechanically against the coil. Before failure, the gauges exhibited a slow drift to higher period reading; then they behaved erratically. Although the onset of this erratic behavior is easy to detect, that of slow drifts is not. This, therefore, casts a shadow on all the readings.

Laboratory calibration of the IRAD vibrating-wire stressmeter has been completed for a variety of conditions. This calibration supported development of an algorithm to interpret the data acquired in a heated environment--an essential task in waste isolation research.

1.9 DISPLACEMENT MEASUREMENTS

Displacement measurements are made using borehole-rod, wire, and tape extensometers, three-component fracture monitors and a Whittemore gauge.

Investigations to date indicate that:

- Thermal corrections to instruments, though simple in concept, are often difficult to apply. Two principal factors in this difficulty are complex temperature distributions (particularly in air) and nonlinear, imprecisely known coefficients of thermal expansion.
- Agreement between calculated displacements and those measured with a tape extensometer and borehole extensometers are quite good in most regions. Observed variations are probably due to our imprecise knowledge of rock modulus and in situ stresses, small errors in temperatures used to calculate mesh displacements, and current unavailability of a joint model in our stress and displacement code.
- In many regions, displacements are due almost entirely to the thermal expansion of the rock, that is, only minor displacements are occurring along joints. Other regions exhibit larger displacements, presumably due to joint motion.
- Near-field vertical borehole extensometers were plagued by failures early in the test. The failures were the result of nonlinear changes in the resistance of the rectilinear potentiometers deployed as displacement transducers. The problem has been investigated and replacement transducers have been fielded to allow continuation of data acquisition on these instruments. Most displacement instruments continue to function reliably.

1.10 ACOUSTIC EMISSION AND MICROEARTHQUAKE ACTIVITY

An experiment has been designed and deployed to characterize acoustic emission and microearthquake activity related to thermal, radiation, and

mining effects at the SFT-C. We have developed an automated seismic processor to monitor and analyze data in field under conditions close to real time and applying techniques used in acoustic emission and earthquake seismology. The experiment has been designed to detect and analyze the occurrence of fractures with lengths from a few centimetres to a few metres. Preliminary findings are

1. The repository rock has average P- and S-wave velocities of 5.5 to 5.9 km/s and 3.2 to 3.6 km/s, respectively, for a Poisson's ratio of 0.20 to 0.25.
2. The rock mass is not homogeneous in velocity and attenuation properties for seismic waves at frequencies between 1 and 10 kHz. Ongoing observations of these properties may offer a means of mapping the propagation of fracture zones.
3. Discrete seismic events occurred within the mine structure in the absence of elevated temperatures. There were 1 to 3 events per week, which were discrete fractures with source dimensions of a few centimetres. These are believed to be responses to changes in stress induced by mining, drilling, and other construction activities.
4. After waste emplacement and heater activation, discrete seismic events were detected in the previously quiet canister drift--both in the concrete and in rock surrounding the canisters. The spectral characteristics of the seismic waves resulting from these events indicate source dimensions of the discrete fractures to be several centimetres. There is an indication that slip may be occurring on preexisting fractures due to thermal stresses.
5. Changes in P- to S-wave amplitudes indicate a possible drying out of the canister region. Areas beginning to cool, and which had earlier exhibited an S/P amplitude increase, now appear as though they are returning to preheated conditions.

1.11 DATA MANAGEMENT SYSTEM

The data management system has been further developed and expanded this year to accommodate changes in the DAS hardware and software, and to deal with irregularities in the acquired data. Features of the system include a binary read processor (BREAD), a data editing program (SFIX), a file merging program (MFAB), a reconversion program (REVERT), and a set of merging and sorting

programs (UFO and VFO). BREAD reads the tapes, converts from HP binary to CDC7600 ASCII format and screens acquired data. SFIX corrects certain specific data irregularities, which results in clean files of raw and field-converted data ready for further processing or analysis. BREAD and SFIX output statistics document the types of errors found and corrected in the raw data tape. MFAB corrects variations in file size and files overlaps in time. REVERT principally corrects geotechnical data for temperature effects. This program requires a data base of changes, modifications, and calibrations of all the instruments. That data base is still in the developmental stage. The merging and sorting programs have prepared nearly 900 individual files (one for each instrument operated at the SFT-C). This feature facilitates plotting each instrument or group of instruments over long time periods.

CHAPTER 2

INTRODUCTION

The National Waste Terminal Storage (NWTs) Program of the DOE sponsors research and development activities aimed at providing reliable long-term isolation of commercial nuclear reactor wastes in geologic repositories in a variety of host media. This large, multidisciplinary program plans the creation of an operational repository in the 1990s. There will be few opportunities early in the program for field tests involving actual reactor waste.

One such opportunity is being exploited at the Nevada Test Site (NTS). Two existing facilities at NTS are in use to test packaging, transport, storage, and retrieval of a limited number of actual spent-reactor-fuel assemblies.

The first of these, the engine maintenance, assembly, and disassembly (E-MAD) facility in southwestern NTS, has the capability to encapsulate spent fuel assemblies in canisters suitable for geologic storage. All of the remote-handling equipment and interim storage facilities needed to support a geologic storage test were established there in connection with the DOE's Commercial Waste and Spent Fuel Packaging Program.

The second facility (consisting of underground construction originally built in the 1960s for weapons effects testing) provides access to an intrusive granitic rock mass (the Climax stock) at a depth comparable to that being considered for geologic storage. This site (located in northeastern NTS about 80 km [50 mi] from the E-MAD facility) required relatively little rehabilitation to accommodate the SFT-C.

2.1 GENERAL OBJECTIVES OF THE SFT-C

The overall objective of the SFT-C is to evaluate the feasibility of safe and reliable short-term storage of spent reactor fuel assemblies at a plausible repository depth in a typical granitic rock, and to retrieve the fuel afterwards (Ramspott et al., 1979). An additional objective of the original concept was to evaluate the difference--if any--between the effects

of an actual radioactive waste source and an electrical simulator. To achieve these objectives the following specific design criteria were defined for the test:

1. Create a storage drift geometry reasonably similar to what might be expected for a spent fuel repository.
2. Deploy supplementary heaters of appropriate power levels and geometric position to simulate thermally induced effects within the storage drift and adjacent pillars that would occur within a large repository.
3. Facilitate handling of the fuel under test conditions (design of a prototype handling system for a repository is not an objective of this test) so that retrieval is possible at any time during the test.
4. Meet appropriate industrial and radiation safety standards.
5. Allow access during the test for technical operations and observation by appropriate governmental, scientific, and public interest groups.
6. Contain a sufficient number of electrically heated simulator canisters to compare the effects of spent fuel (radiation plus heat) with those of an electrical source (heat alone) of the same size, shape, and thermal output.

These criteria were sufficient to define the major aspects of the test, such as the three-drift geometry, the number of canisters used, the need for a data acquisition system that could also provide alarms, conservative radiation shielding, remote operation of handling equipment, and other necessary functions.

2.2 TECHNICAL AND SCIENTIFIC OBJECTIVES

The SFT-C is the first in situ exposure of a crystalline igneous rock to actual spent commercial-power-reactor fuel. Five technical objectives are the focus for research at the SFT-C:

1. Detailed characterization of the fuel, itself, both before and after the test (funded separately from the SFT-C).
2. Documentation of the thermal history of the canisters.
3. Comparison of close-in effects in granite of heat and radiation with the effects of heat alone.

4. Continuous monitoring of radioactive dose rates for personnel safety.
5. Continuous and automatic generation of alarms when any data are out of range.

Furthermore, since the test involves the largest scale heating of a hard rock medium to date for a test of this type, we have the opportunity to collect technical data addressing two subjects: the ultimate qualification of granite as a medium for deep geologic disposal of high-level reactor waste, and the design of future repositories in granite or other hard rock and the prediction of their response to reactor waste exposure. The following scientific objectives are also being pursued:

1. Documentation of displacements and stress changes in the rock comprising the pillars between the central and side drifts due to the mechanical disturbance of mining the central drift.
2. Comparison of that response to the results of existing computational modeling to assess the validity of those models in terms of mechanical effects alone.
3. Documentation of the temperature and radiation dose in the close-in heat zone to infer both the total power level of the spent fuel assemblies and the proportion of that power transported out of the canisters by nuclear radiation, as opposed to thermal processes.
4. Documentation of displacement and stress effects in the intermediate heat zone due to the thermal disturbance of the fuel and heaters.
5. Comparison of measured thermomechanical responses with computational modeling to assess the combined validity of those thermomechanical models.
6. Documentation of the amount of heat removed by ventilation.
7. Documentation of the thermal field (both close-in and intermediate) and comparison to calculational models.
8. Documentation of the relative effect of existing fractures on rock response by duplication of all mechanical measurements in regions which are either relatively unfractured or fractured, and by direct instrumentation of selected, prominent fractures.
9. Evaluation of displacement and stress instrumentation under simulated repository conditions. This objective was added during FY 81.

2.3 FACILITY GEOMETRY

We briefly describe the SFT-C facility to acquaint the reader with the physical dimensions of the test. A more detailed account of facility geometry and development is presented elsewhere (Patrick and Mayr, 1981).

Surface facilities at the SFT-C site include the preëxisting shaft, head frame, hoist house, and mine support buildings, together with the newly constructed access hole, exhaust fan/filter system, access-hole head frame and hoist house, control skid, data acquisition system trailer, and several office and support trailers (Fig. 2-1). The access hole is used exclusively for emplacement and retrieval of spent fuel assemblies and as the outlet for ventilation air of the SFT-C storage drifts. All other access to the underground facilities is through the shaft.

The layout of the underground installation is illustrated in Fig. 2-2. Parallel heater and canister storage drifts extend northwesterly from the railcar room, which, in turn, extends from an access drift excavated from

Figure 2-1. Surface area layout of Climax site, NTS (after Patrick and Mayr, 1981).

previously existing workings. A 3.7×3.7 -m (12×12 -ft) access drift enters the railcar storage room, which is $14.6 \times 6.0 \times 7.6$ m ($48 \times 20 \times 25$ ft) high. Beyond this room, the canister storage drift [which is 6 m (20.5 ft) high by 4.6 m (15 ft) wide] extends 64 m (210 ft) to the receiving area at the bottom of a 762-mm (30-in.) access hole with a 485-mm (19.1-in.)-i.d. casing. (The spent fuel canisters are lowered from the surface through this access hole.) From the access hole to the railcar storage room runs a set of tracks for the railcar. The spent fuel canisters are stored in a linear array of vertical holes located between the rails at a spacing of 3 m (10 ft).

There are 17 storage holes in the canister storage drift. Eleven of these are used for spent fuel and six for electrical simulators. An additional hole is located in the railcar room to store a dummy canister for training and equipment checkout. The holes themselves have a 609-mm (24-in.) diameter, a 457-mm (18-in.) casing, and a 6-m (20-ft) depth. Numerous small-diameter holes were drilled to contain thermal, stress, and displacement instrumentation.

The north and south heater drifts, which measure 3.4×3.4 m (11×11 ft), have been excavated on either side of and parallel to the

Figure 2-2. Spent Fuel Test layout in Climax granite (after Carlson *et al.*, 1980).

canister storage drift. Their center-to-center spacing of 9.8 m (32.3 ft) and 10.2 m (33.3 ft) from the storage drift results from adjusting the storage drift to center on the drilled access hole. This location was verified by mining the heater drifts. Tubular electrical resistance heaters (with a diameter of approximately 19 mm. or 3/4 in.) are placed in these heater drifts at 6-m (20-ft) intervals in small holes in the floor.

CHAPTER 3
SITE CHARACTERIZATION AND GEOLOGIC INVESTIGATIONS

3.1 GEOLOGIC MAPPING

Mapping the discontinuities in the Climax stock proceeded in several phases, most of which were completed prior to this fiscal year, but which are presented here for the first time. The first phase of mapping reported in the technical literature was performed for nuclear weapons effects tests at various times. Mapping the Piledriver drifts was done specifically for the SFT-C (Maldonado, 1977).

A second phase of mapping was conducted during SFT-C excavation. This planning phase mapping was limited to the tail drift, portions of the instrumentation alcove, the south rib (wall) of the main access drift leading into the SFT-C complex, and major features in the heater drifts. Typically, the mapping was done by individual project engineering geologists. The intention of this second phase of mapping was threefold:

- To compare the orientations of features in the tail drift and the SFT-C area with features reported for the Piledriver drifts, and to confirm that fracture orientations interpreted from the core borings were basically correct.
- To define which geologic features needed to be mapped within the project and at what level of detail.
- To identify those features which would project into the area of the SFT-C and which might affect stability.

After the canister drift was excavated, a third phase of mapping was undertaken. This phase consisted of mapping the canister drift invert (floor) and ribs (walls). Field work was conducted by four teams of two people each. The teams generally consisted of a trained geologist or engineering geologist and an individual from one of several other backgrounds (i.e., an environmentalist, a mining engineer, computer modeler, or technician). During this exercise, joints, shear zones, and faults were traced to the extent possible across the canister drift invert. Mapping of the ribs here was performed in the same way it had been in the tail drift and electrical alcove (i.e., specifically as a tape line survey at the 5-ft elevation; features intersected by the tape line were recorded).

After the canister drift was mapped, the final phase of mapping was performed. This included detailed mapping of all ribs in the heater drifts and receiving room. Mapping was carried out both during construction and after much of it was finished, including the installation of wire mesh, cable trays, overhead conduits and lights, and ventilation/access control bulkheads. This mapping was typically conducted by one or two engineering geologists working individually. More specific descriptions of various segments of the mapping are provided in subsequent sections.

3.1.1 Tail Drift Mapping

The tail drift was mapped as the excavation proceeded to determine the frequency and orientation of jointing and faulting, to compare the attitudes of these features with those previously mapped in the Piledriver drift, and to generally estimate the type of features that would be intersected by construction in the SFT-C area. These features were described in terms of their orientation (determined by a Brunton compass) and general characteristics.

3.1.2 Main Access Drift Mapping

Mapping of the main access drift was performed similarly to that of the tail drift. The purpose was to obtain correlations with features mapped in the tail drift, where possible. This mapping was done concurrent with excavation. However, once mining of the heater drifts commenced, two faces were mined simultaneously, creating a heavy mucker traffic pattern in the access drift. This interfered with the mapping, so that it could only be done on the south rib.

3.1.3 Heater Drift Mapping

Mapping the heater drifts was done in three stages. As the heater drifts were being excavated, major features were identified (with particular attention given to shear zones). This first-stage mapping information was used to locate instrumentation, so that selected instruments would either intercept or avoid major joints and shear zones, as appropriate. Typically,

this stage of mapping was done on a project engineering map, utilizing a Brunton compass for joint orientations.

The second stage of mapping attempted in the heater drifts was similar in level of detail to that which had been done in the tail drift. However, this effort was quickly abandoned because of a pressing need to log core and to select instrument locations and extensometer anchor points.

The third stage of mapping conducted in the heater drifts was carried out after excavation of the heater and canister drifts was complete. The canister drift mapping had been completed in the interim as described below. Much of the heater drift construction had also been completed before this mapping was started. This included placement of decomposed granite on the invert; installation of permanent fan lines, lights, and overhead structures; and erection of wire mesh and steel-channel equipment supports along the ribs. The mapping was performed with a Brunton compass. Where metal objects were present, an apparent drift orientation was recorded and compared to actual drift orientation so that corrections could be made to joint orientations. The Brunton compass was sometimes used merely as a protractor in measuring the angle between the drift orientation and the joint strike. Mapping in the heater drifts was done at eye level, usually at the level of the steel channel. No continuous survey elevation control was available. Therefore, the elevation of mapping was not constant. Using a steel tape, the mapping parties marked the stationing on the ribs and steel channel. In curved sections, stationing had to be approximated. This method, however, introduced some inaccuracies, particularly on the inside of the curves.

3.1.4 Canister Drift Mapping

So that the SFT-C construction could proceed on schedule, it was necessary to map the canister drift as soon as excavation was completed. This mapping was accomplished in two 12-h shifts on a Saturday and Sunday by four crews consisting of a trained geologist working with another professional or technician. In the case of one crew, both crew members were trained in geotechnical engineering. The project engineering geologist provided overall supervision of these four crews by rotating between the crews to assure some consistency, coordinate the mapping effort, provide logistics, and obtain contractor support.

The invert and the ribs were washed prior to the beginning of mapping. This was attempted initially by washing the invert and then using a compressed air stream to blow the muck and excess water up grade (because of the ventilation air-flow direction) to the receiving room. Since this splattered muck on the ribs, the ribs would be washed down again, and the process repeated. This was attempted several times with some general improvement in the cleanliness of ribs and invert, but without sufficient improvement for mapping. Also, because no effort had been made to bar loose rock from the invert, each blowing cycle would loosen sizable slabs of rock, which then had to be removed by hand. Therefore, rather than blow out the excess water, it was decided to wash the ribs and invert and to pump out the excess water wherever possible. The remaining water was left sitting as puddles in the invert's low spots.

The invert had not been finished to a smooth grade, but was left in the rough, undulating condition that resulted from benching operations. The radiation shield pits were not excavated nor had the canister emplacement holes been drilled. However, blast holes had been drilled and plugged in the invert for later placement of explosives to excavate the pits. We surveyed the location of each canister-emplacement hole to provide stationing at 3-m (10-ft) intervals. A similar stationing was marked on the ribs, and a line of constant elevation was established to account for the 0.5% grade of the invert. This line began approximately 1.5 m (5 ft) above the invert in the railcar room and dropped gradually to approximately 1 m (3-1/2 ft) above the invert in the receiving room. This allowed usage of a horizontal plane for mapping the rib so that a plan view could be prepared showing features on the rib. This was especially critical because of the variability of invert elevation from point to point within the drift described previously.

As features were mapped, they were marked in the field with orange spray paint so that they could be seen easily during the fracture sketching and readily identified in the future. Any new cracks that formed or any existing cracks that had not been mapped could be distinguished by the absence of paint. Also, the paint facilitated photographic documentation. We had early on rejected a suggestion to do the mapping only from photographs, but we did decide to photograph the invert and the ribs to record the actual fractures mapped. Invert photographs were taken from the crown using a 35-mm camera mounted on a cable system. Rib photography was accomplished using a hand-held

35-mm camera. Because the cable was approximately 6 m (19 ft) above the invert, we felt that small, unmarked features would not be readily picked up by the camera. Therefore, photography was delayed until most of the features were painted. The photographic work was done by NTS staff photographers. Although some distortion occurred at the edges of the film, the invert photographs provided a direct overhead view of features. Photographs of the inverts and ribs are shown for the central portion of the canister drift in Figs. 3-1 to 3-3.

At the time of mapping, wire mesh had been placed over the ribs and crown to within approximately 1.8 m (6 ft) of the invert. However, sufficient portions of the rib were exposed to allow mapping directly on the rock rather than through wire mesh. The lighting conditions during the mapping of the canister drift were generally good. Several portable quartz-halogen lamps were placed in the drift and were moved about as needed to provide lighting on the areas being mapped by the individual crews. There were two to three of these lights available for each 15-m (50-ft) section mapped. Lighting was supplemented through the use of miner's cap lamps. These cap lamps were particularly useful, not only to augment the light from the quartz-halogen lamps, but also to allow highlighting and tracing of features on the crown and spring line from one rib to the other.

Features identified on the ribs by one mapping crew were not described by the adjacent mapping crew. Therefore, many continuous low-angle joints were sketched as a line segment by only one of the mapping parties. A record was usually made in the comment section of the field notes when those features were continuous. Where joints could be traced from one rib to another, they were so identified. Frequently, it was impossible to trace the joints more than 1 to 2 m. However, shear zones were traceable from one rib to another across the invert and appeared to be continuous between drifts.

Although each of the four crews attempted to map uniformly, the level of detail and possibly the accuracy of the mapping varied from crew to crew. This variability exists for several reasons, among which are the experience level and judgment of the mapper and the note taker, their attention to detail, and the location of the mapped section--particularly since the cleaning of the invert and ribs was done from the railcar room towards the receiving room. The section from Stations 3+50 to 4+00 had a significant number of standing puddles of water and, towards the receiving room, a fair amount of muck which masked the features.

Figure 3-1. Section of canister drift floor.

Figure 3-2. Section of north rib of canister drift.

Figure 3-3. Section of south rib of canister drift.

3.1.5 Discussion of Results

Time and personnel constraints required that several people do the mapping. The canister drift was mapped by four teams of two individuals each. The use of many people in structural geologic mapping minimizes the impact of individual bias on the overall fracture data set. However, it introduces the problem of varying levels of expertise and observational skills among the mappers. Table 3-1 shows mapping results from six different 15-m (50-ft) scanlines as recorded in the field notes. Each is taken from the north rib of one of the heater drifts or the canister drift. Therefore, all six are parallel in orientation. The six scanlines represent the work of six different individuals or teams of individuals.

Obviously, different mapping teams saw differing numbers of fractures within their given 15-m (50-ft) scanline. Several factors may account for this. The ribs mapped may have been dirtier at some locations than at others, the mapping teams may have differed in skill, or the fracturing actually present may differ from place to place within the SFT-C drifts. The first two

Table 3-1. Results of team mapping for six parallel 15-m (50-ft) scanlines.

Scanline/team	Fractures		Total
	No. dipping over 45°	No. dipping 45° or less	
1	46	18	64
2	20	28	48
3	47	28	75
4	37	31	68
5	22	24	46
6	20	19	39
Mean/scanline	32	24.7	56.7
Std dev	12	5.3	14.3
Coefficient of variation	40%	21%	25%

of these three factors are likely to be true. The third will be examined in subsequent data analysis. It is interesting to note, however, that the variation in observations of high-angle fractures (which are generally open) is about twice that of low-angle fractures. This may support the notion that fracturing, especially the more steeply dipping fractures, may vary within the project site. An alternate explanation for the greater uniformity in mapping low-angle joints is that the rather pervasive (although thin) alteration on them may have aided in identifying those features. A comparison of the mapped and photographed fractures indicates that nearly all features visible on photos were identified by the mapping parties.

Over 2500 fractures (including joints, shears, and faults) have been mapped in the drifts of the SFT-C. This was accomplished through the efforts of several individuals under a variety of constraints imposed by the project construction schedule and by the work environment. Fracture sketch maps from the field notes have been compiled and reported (cf. Fig. 3-4; after Wilder and Yow, 1981). Furthermore, there is a significant data base available, which will allow a greater range of analyses.

Figure 3-4. Fracture map of central area of canister drift (after Wilder and Yow, 1981).

3.2 TECHNIQUE AND RESULTS OF CORE LOGGING

3.2.1 Exploratory Core Logging

One inclined exploratory borehole and three nearly horizontal ones (UG-1-4) were drilled prior to excavation and construction of the SFT-C. These borehole were located as shown on Fig. 3-5. They were continuously cored for a total core length of 468 m (1575 ft). The core runs were tabulated and recoveries noted by Fenix and Scisson drilling inspectors. The cores were then boxed and shipped to the USGS library in Mercury, NV where they were logged by an LLNL engineering geologist. The core logging emphasized jointing and alteration. Prior investigators (Maldonado, 1977) found that the mineralogy of the quartz monzonite unit of the Climax stock was

Figure 3-5. Locations of exploratory boreholes (after Carlson *et al.*, 1980).

not highly variable, with the exception of alteration along jointing and in localized areas. Mineralogy was, therefore, described in the rock mass as a whole, but it was not reported in detail on each core log. Joints were described in terms of inclination from the core axis, intensity of jointing and alteration of the surrounding rock material, and any joint-filling materials. The rock quality designator (RQD) was also noted on the log sheets. A letter report (Emerson, 1978) on this core logging was transmitted to agencies involved in the SFT-C and will be included in a later report. In

Because the core was not oriented, interpretation of specific geologic features was impossible. The core logs were used to ascertain that no adverse conditions were expected within the area of the SFT-C. Generalized interpretations were based on projections between boreholes of zones of highly altered or intensely jointed (sheared) materials. These interpretations were made to alert project personnel to the types of features that could be anticipated and to give a general impression of what might be encountered in the project area. Therefore, the correlations are not rigorous.

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identified. On this basis a through-going feature was interpreted to project at N45-55°E, just beyond the canister drift and receiving room. This feature was interpreted as an intensely jointed and altered zone, potentially a shear zone (Fig. 3-7). A fault zone with clay gouge more than 0.3 m (12 to 16 in.) thick was later identified during drift mapping in this location. No

Figure 3-7. Vertical fence section including borings (vertical lines enclose segments of boring with similar bearing).

large gouge zones or similar features were noted in the core nor were there significant core losses. Subsequent examinations of the core and fault exposures within the drifts have led us to the conclusion that the character of the fault is so variable that it is unlikely this section of the UG-1 core would be identified as anything other than intensely jointed, highly altered, and possibly sheared zone.

In an attempt to correlate other features that might be encountered during the excavation, possible orientations were considered for those major features seen in the core. This was done by assuming the features would be one of the joint sets or faults reported by Maldonado and would, therefore, have similar attitudes. These orientations were compared with the inclination to the core axis of each of the features logged to see if they correlated with one of the possible orientations. We tried to correlate between boreholes using these potential attitudes. This was facilitated by use of a fence diagram showing the four boreholes. The major features were drawn at the assumed or potential orientations (Fig. 3-7). When features with these possible orientations projected to similar features in other boreholes with the same hypothetical orientations, a possible correlation was identified. Since this technique is not rigorous, it was used only for the more significant features. Features mapped after the drifts were excavated are shown in Fig. 3-8.

3.2.2 Mine-By Instrumentation Holes

All the holes for multiple-point borehole extensometers (MPBX) were cored 76 mm (NX) in diameter. The core was partially logged while still underground to assist selection of anchor locations for the extensometers. The orientation of the extensometers had been chosen based on computer models of the rock response during excavation. The final anchor locations were specified based on the core examination, so that the anchors would be located in competent rock areas. This logging was performed concurrent with the excavation and drilling operations to facilitate installation of extensometers prior to construction of the canister drift. Our logging technique was later limited to include only the zones where anchors were to be placed. Based on the core logging, sketches were made to show the specified anchor locations relative to geologic features. When core was logged for anchor locations only, the borehole as an entity was logged later in the USGS core library.

Figure 3-8. Vertical fence section including borings (vertical lines enclose segments of boring with similar bearing). Mapped geologic features shown for comparison.

The same logging criteria used on the exploratory boreholes was also utilized for the mine-by instrumentation holes. Core logging was performed by project engineering geologists, who were assisted by a graduate geology student. The core logging included scaled sketches of the features within the core.

3.2.3 Thermal-Phase Instrumentation Boreholes

Stressmeters were installed in 38-mm (EX)-diam boreholes, which were cored to provide smooth holes for instrument installation. However, because of the small diameter the core was prone to break into small pieces. This breakage was probably aggravated by the somewhat flexible, postmounted drill rig used during this stage of drilling. For this reason, no attempt was made to log this core. Sections were examined to try to locate sufficiently sound rock. However, the typical length of intact core recovered was less than 75 mm (3 in.). Therefore, the only features that could be successfully identified were alteration zones, which were avoided. Additional problems were encountered in the mechanism for removal of the EX core (namely the core would often get jumbled as it came out of the barrel).

Logging of heater holes from north and south heater drifts was performed by geology students who were summer employees. The logging was performed in the same fashion as outlined for the mine-by instrumentation holes, with the exception that all of the mapping was performed in the USGS core library. The results of the core logging on these vertical holes have been reported by Tewes (1982).

Vertical, 76-mm (NX)-diam boreholes for placement of thermal-phase MPBX systems were continuously cored as well. By the time this core was taken project engineering geologists had observed that the low-angle joints were of fairly consistent mean orientation. Therefore, we attempted a technique to orient this core in addition to the techniques described for other core logging. This involved drawing a reference line along the core after it had been pieced back together as much as possible. Features were then described not only by the inclination to the core axis, but also by the number of degrees of rotation of their dip direction from this reference line. Once the mean orientation for low-angle joints is obtained relative to this reference line, it should then be possible to orient all other joints (providing the core is continuous and can be pieced together).

3.2.4 Canister Emplacement Holes

Boreholes 76-mm (NX) in diameter were drilled near the edge, within the perimeter of each canister emplacement hole to provide a record core for evaluation in the future. These cores were not logged, but rather sent to the

USGS core library where they will be held until the completion of the project. At that time an additional 150-mm borehole will be drilled parallel to each canister emplacement hole (exactly opposite the record core borehole), so that it includes the borehole wall. The core from both sets of boreholes will be logged at the same time by the same personnel to allow in-depth comparison of the mineralogy and fracturing before and after exposure to radiation and/or heat during the heated phase of the SFT-C. The emplacement holes themselves were drilled by percussion methods and no core was obtained.

3.2.5 Practice Hole

A practice hole was drilled in the railcar room using the same unit employed to drill the canister emplacement holes. This hole provides for practice with the railcar operations. However, it also provided an area to test the feasibility of drilling a 150-mm core along the emplacement hole wall. After the practice hole was completed, a 150-mm borehole was drilled along the wall of the practice hole, and a 76-mm (NX) core was drilled 0.6 m from the practice hole centerline. These cores are being used to evaluate the damage produced by percussion-drilling the emplacement hole.

3.3 SPATIAL RELATIONSHIPS OF JOINTS TO INSTRUMENTS

We discuss only the location of instruments relative to geologic features here, since details of instrument selection and installation are presented elsewhere (Brough and Patrick, 1981).

3.3.1 Extensometers

After major features in the heater drifts had been mapped, we determined that the shear zones we had identified would probably control the rock mass response to excavating the canister drift. Therefore, two sections of instrumentation were specified, one where instrumentation within the pillar would essentially be in unsheared (although jointed) rock, and one other where instrumentation would be emplaced in rock containing shear zones (Carlson et al. 1980). The instrument locations were based on projections of these shear zones through the pillar areas. The actual MPBX anchor locations were based on analysis of the core recovered from those boreholes. The locations

were specified so they would not be close to a fracture (particularly an open one) or to a shear zone. If the installed location of anchors was slightly different from that specified, the anchors were set close to fracture zones. Joint and shear zone locations relative to anchor locations for mine-by extensometers, are shown in Figs. 3-9 and 3-10.

Location of the MPBX units for the thermal phase was based on three criteria. First, we wanted to compare the responses across a shear zone with those in the unsheared (although jointed) rock mass. Therefore, vertical extensometers (GxE series) were placed around CEH09 (which is intersected by a shear zone) and another set of extensometers was located around CEH03, where there are a minimum number of joints and no shear zones. Locations of the MPBX units are shown in Fig. 3-11. Second, extensometers were sited to observe the deformation across the low-angle joints. This required a vertical orientation of the MPBX. Third, we wanted to observe displacements at various

Figure 3-9. Anchor locations in relation to geology-station 2+83 (after Wilder and Patrick, 1980).

Figure 3-10. Anchor locations in relation to geology-station 3+45 (after Wilder and Patrick, 1980).

distances from the thermal sources and the pillars. The MPBX units were, therefore, spaced in the geometric configuration shown in Fig. 3-11. The anchors were chosen based on core logging to avoid fracture zones. Construction procedures were more closely controlled for thermal-phase extensometers than for mine-by MPBX units. Therefore, the anchors were located essentially as specified.

3.3.2 Tape Extensometers

Two sets of tape extensometer measurement stations were established during the mine-by experiment. Two through holes were drilled from the north heater drift to the south one to allow taping from their outer ribs. In addition, tape extensometer anchor points were placed on or close to mine-by extensometers and across each drift exactly opposite these anchors. They were also placed approximately 0.3 m above the collar of through holes and on the

Figure 3-11. Location of borehole extensometers with respect to main geologic features.

ribs opposite the through holes. The locations for these anchor points were chosen to be in sound rock (consistent with geometric constraints). The soundness of the rock was based on projections of joints or shears and on observations of the sounds emitted when the rock was hit with a geologist's hammer. This gave an indication of nearby fractures and loose rock on the rib. Loose rock was scaled off where practical.

During excavation, tape extensometer anchor points were installed within the canister drift behind the advancing face. However, flyrock destroyed or loosened the majority of these anchor points so that no attempt was made to analyze the data. These anchor points were chosen to be in sound rock in accordance with the procedures described above.

After the canister drift was completed and other instrumentation installed, additional tape extensometer anchor points were installed to provide redundancy for the CWE instruments described below. Their location was not chosen based on the geology, but rather on the location of the CWE instrumentation.

3.3.3 Convergence-Wire Extensometers

Convergence-wire extensometers (CWE)--designed to observe tunnel deformations--were located at frequent intervals in all three drifts. For the most part, they were placed in rock containing no shear zones. However, some of the wires were specifically located so that they would extend across shear zones. The location of these convergence-wire extensometers relative to shear zones is shown in Fig. 3-12. It is evident that many of these extensometers, although not in actual shear zones, do cross or bracket shear zones. The

Figure 3-12. Location of CWE and FMS units with respect to main geologic features.

locations were chosen so that the mounts for instruments were anchored in sound rock. Loose rock was removed prior to instrument installation. The mounting anchors extend back into the rock approximately 0.3 m (12 in.) Therefore, an assessment was made of nearby fractures and their orientations so that the anchors would not be mounted in shear zones.

3.3.4 Fracture Monitor Systems

Although most of the instrumentation was designed to detect motion integrated over several fractures, the motion of single fractures or of a single set of closely spaced fractures also needed to be monitored. This was done in seven locations using fracture monitor systems (FMS). The locations of FMS units relative to fault and shear zones are shown on Fig. 3-12. The locations were chosen based on a field assessment of which features would be most significant. This assessment was made after the canister drift mapping was completed. However, the assessment was based on visual inspection of the major fault and shear zones, rather than an evaluation of the mapping work per se. FMS units were founded in sound rock either side of the selected shear or fault zones. Figure 3-13 shows one of these fracture monitoring systems installed across the fault encountered in the receiving room.

3.3.5 Stressmeters

Three vibrating-wire stressmeters were installed to monitor the mine-by. Two stressmeters were located near MPBXs installed at station 2+83 in essentially unsheared rock. One gauge was near the rib and one was in the interior of the pillar. An attempt was made to keep the stressmeters out of shear zones (based on the projected locations of those zones). However, the core was too broken to allow the same kind of detailed analysis that was made for the MPBXs. The third stressmeter was chosen in a location near the rib, but where it would be on the other side of a shear zone projected to pass through the area (Fig. 3-14). This allowed the influence of the shear zone to be evaluated by comparing data from stressmeters near the rib on either side of the shear zone.

For the thermal phase, 18 stressmeters were installed. Three were located in each of the two vertical holes near the vertical extensometers to

Figure 3-13. Typical installation of FMS unit.

monitor stress changes near the thermal sources. In addition, two sets of three gauges were installed in each of two horizontal holes in the north pillar. Once again, core logging was impossible, so that projection of fractures from the ribs guided the selection of gauge locations.

3.3.6 Thermocouples

The location of thermocouples was constrained more by the location of instruments and by the geometric relationships necessary to monitor temperatures than by the geology. Furthermore, where thermocouples were placed in separate boreholes rather than on instruments, the boreholes were 38 mm (EX) in diameter. Because our experience using EX core for fracture analysis had been disappointing, we requested no core for the majority of the EX-thermocouple boreholes.

Figure 3-14. Location of vibrating-wire stressmeters with respect to main geologic features.

3.4 GEOHYDROLOGY OF THE SFT-C SITE

Previous investigators identified zones of perched water in and around the Climax stock (Fig. 3-15, Table 3-2). However, the zone of total saturation had not been identified. At the level of the SFT-C (approximately 1120 m above MSL), the stock is unsaturated [although local seeps occur where water-bearing fractures and faults intersect the underground openings (Fig. 3-16)]. Previously published data and recent water level measurements in an exploratory borehole indicate that the top of the zone of saturation exists at about 975 m above MSL in the Climax stock (Murray, 1981).

To the southeast, the Climax stock is in fault contact with Paleozoic carbonates. Water levels in the carbonates vary from 1100 to 1200 m above MSL

Figure 3-15. Vertical borehole locations in the Climax stock (after Murray, 1981).

in the northeast to 800 to 900 m above MSL in the southwest (Fig. 3-17). Since the stock is of low permeability (except where faults and shear zones are present) the water level was inferred to be somewhat higher in the stock than in the higher permeability carbonates.

An existing exploratory borehole (UG-02) was deepened to probe for the water level inferred from measurements in the carbonates. After extending the

Table 3-2. Vertical boreholes in the Climax stock and vicinity.^a

Borehole ^b	Ground surface elevation ^c (m)	Hole depth (m)	Water level ^c (m)	Comments
A	1674	362	1387	Perched water
B	1599	60	1549	Perched water
C	1621	298	1475	Perched water
D	1588	115	1486	Perched water
31	1559	366	1502	Perched water
32	1548	277	1418	Perched water
33	1571	301	--	Dry
34	1571	301	1363	Perched water
35	1519	246	1494	Perched water
37	1543	508	--	Dry
38	1536	610	--	May be dry
GZ-1	1590	549	--	Unknown
GZ-2	1550	549	--	Unknown

^a From Walker (1962) and Thordarson *et al.* (1966).

^b cf. Fig. 3-15.

^c Referenced to MSL.

borehole to 960 m above MSL, a series of water level measurements were made (Fig. 3-18, Table 3-3).

Once the water level in UG-02 stabilized, bailing tests were performed to determine the recovery characteristics of the water levels. Analysis of the bailer test data indicated a permeability of about 10^{-5} D. The rising trend of the hydrograph (~ 0.25 m/mo) is apparently due to recharge of the well through a pervasive fracture system. These data (together with the inferred water level of 800 to 1200 m above MSL) support definition of the local zone of saturation at about 975 m above MSL.

Figure 3-16. Location of seepage zones in the SFT-C (after Wilder and Patrick, 1980).

3.5 PHYSICAL PROPERTIES MEASUREMENTS

An extensive number of laboratory measurements of various physical properties of Climax stock quartz monzonite (CSQM) have been made at a range of hydrostatic pressure (P) and temperature (T) conditions that encompass the expected range of (P,T) conditions at the SFT-C. The measured properties are thermal conductivity (λ), thermal diffusivity (κ), thermal linear expansion (α), Young's modulus (E), and bulk modulus (K). Pressures ranged from 0.1 to 55 MPa and temperatures from 300 to 773 K. The results are shown in Figs. 3-19 to 3-24. Figures 3-19 to 3-21 are taken from Durham and Abey (1981) and Figs. 3-22 to 3-24 are from Heard and Page (1981). All results are consistent with the generally accepted model of a solid containing microfractures whose behavior is altered by the generation of new microfractures

Figure 3-17. Potentiometric levels surrounding the Climax stock in metres above MSL. Numbers in parentheses indicate measured water levels. Where two numbers are separated by a slash, the first refers to the Paleozoic rocks; the second is the water table in the Cenozoic rocks (after Murray, 1981).

Figure 3-18. Water-level hydrograph for exploratory borehole UG-02 (after Murray, 1981).

Table 3-3. Water levels in exploratory borehole UG-02.^a

Date	Time	Water level (m above MSL)	Comments
09/25/80	--	--	Drilling ended
10/14/80	1200	977.7	--
11/06/80	1200	974.5	--
11/19/81	1200	974.0	--
02/18/81	1017	974.6	--
02/18/81	1528	973.2	Bailer Test 1
03/04/81	1000	974.9	--
03/25/81	1035	974.9	--
03/25/81	1520	973.8	Bailer Test 2
03/27/81	1000	974.6	--
03/27/81	1137	973.1	Bailer Test 3
03/30/81	0900	974.3	--
04/01/81	1300	974.7	--
04/09/81	1300	975.1	--
05/07/81	1200	975.4	New probe on water level indicator

^a UG-02 is a 76-mm (3-in.)-diam cored borehole.

Figure 3-19. Thermal conductivity vs temperature at 50 MPa for CSQM Run 2, corrected and uncorrected. Dashed line is uncorrected data from Run 1. Error bar indicates precision of data from this study (after Durham and Abey, 1981).

with increasing temperature. [Heating tends to raise α and decrease λ , κ , E , and K as compared to the intrinsic (crack-free) behavior.] The application of increasing P tends to drive the rock towards the intrinsic behavior (because--by the model--cracks neither open as much nor form as easily under pressure). In other words, increasing P tends to decrease the extrinsic dependence on T . The general trends with P and T in these five properties are usually monotonic but are typically nonlinear. The one exception is $\alpha(T)$ shown in Fig. 3-24.

Figure 3-20. Thermal conductivity vs pressure at 313 K for CSQM Run 2, corrected (solid symbols). Also shown are the uncorrected data, open symbols (after Durham and Abey, 1981).

Figure 3-21. Thermal diffusivity vs temperature and pressure for CSQM Runs 1 and 2, uncorrected (after Durham and Abey, 1981).

Figure 3-22. Normalized Young's modulus (E/E_0) vs temperature for Climax quartz monzonite. The error bars represent 1 std dev of the 9-sample population, which averages $\pm 7\%$ at 19°C , ranging to $\pm 40\%$ at 350°C . Estimated std dev for E/E_0 of a uniform population is $\pm 10\%$ at 19°C , and $\pm 6\%$ at 350°C (after Page and Heard, 1981).

Figure 3-23. Normalized bulk modulus (K/K_0) vs temperature for Climax quartz monzonite. The error bar represents 1 std dev of the 9-sample population, which averages $\pm 50\%$. Estimated std dev for K/K_0 of a uniform population is $\pm 10\%$ at 19°C , ranging down to $\pm 6\%$ at 250°C (after Page and Heard, 1981).

Figure 3-24. Coefficient of thermal linear expansion at five pressures vs temperature for the Climax quartz monzonite. The error bars represent 1 std dev of the 9-sample population which averages $\pm 15\%$. Estimated std dev for α of a uniform population is $\pm 2\%$ (after Page and Heard, 1981).

We are furthermore determining water permeability in stressed intact and fractured CSQM at 273 K and pressures to 50 MPa. In these tests, the pore fluid pressure is maintained at 0.5 of the confining pressure (lithostatic). Other data measured are longitudinal and radial strains resulting from the axial stress (ranging up to 0.88 of the failure stress at pressure), fracture closure, compressional wave velocity, the attenuation of the first-arrival compressional wave, and electrical conductivity. Results are currently being analyzed.

3.6 RADIATION EFFECTS STUDIES

An investigation has been carried out to look for effects of gamma irradiation on the mechanical properties of CSQM (Durham, 1982). Earlier work by Page (1979, 1980) had shown that gamma irradiation affected the color and thermoluminescence (release of internal energy by emission of light during heating) of CSQM, suggesting their potential as dosimeters at the SFT-C. It was not known whether or not irradiation from the spent fuel canisters (primarily gamma rays) had any effect on rock properties of direct concern to the integrity of a repository (for instance, permeability and thermal conductivity). To ascertain the potential of gamma radiation for damaging a repository, rock samples were given a massive dose of gamma irradiation, which amounted to 13 MGy (1.3×10^9 rad), or six times the maximum dose expected to be absorbed by the rock at the SFT-C. The mechanical properties of the rock samples were then measured. Brazilian tensile and compressive tests were

performed on irradiated and unirradiated rock at room temperature and pressure. Under these conditions, it was presumed that any changes in mechanical properties could be directly related to changes in the arrangement of microfractures in the rock. If any change in permeability is to result from gamma irradiation, this change must also be reflected in the microcrack structure. Hence, the mechanical tests (which are easier to perform than permeability measurements) should flag whether or not gamma irradiation can potentially affect permeability. To the extent that gamma irradiation does not change the intrinsic thermal conductivity of the grains of the rock--the statements just made regarding permeability also apply to conductivity.

The test results (summarized in Table 3-4) showed that the irradiation treatment most likely (probability = ~0.995) did affect some of the mechanical properties. Ultimate compressional strength of irradiated rock dropped by 20%

Table 3-4. Effect of gamma irradiation on mechanical properties.

Physical property	Units	Irradiated ^a	Unirradiated ^b	Probability irradiated and unirradiated are different	
				t-test	Wilcoxon test
Tensile strength	MPa	11.9 ± 1.5 ^c	11.4 ± 1.8	<0.5	0.6
Ultimate strength (compression)	MPa	163.7 ± 35.2	204.4 ± 33.4	>0.99	0.995
E ₁ ≡ Young's modulus (σ < 20 MPa)	GPa	53.3 ± 16	52.1 ± 13.2	<0.5	<0.1
E ₂ ≡ Young's modulus (σ < 60 MPa)	GPa	66.3 ± 11.2	69.8 ± 8.5	0.5-0.8	0.7
ΔE ≡ E ₂ - E ₁	GPa	13.1 ± 6.3	17.7 ± 11.4	0.8	0.96
Poisson's ratio	--	0.202 ± 0.57	0.211 ± 0.067	<0.5	0.7

^a Sample sizes: tensile tests (n = 15); compressional tests (n = 14).

^b Sample sizes: tensile tests (n = 14); compressional tests (n = 12).

^c Mean ±1 std dev.

with respect to unirradiated rock, and Young's modulus under differential compressional stresses >20 MPa decreased from 5% to 10%. However, Young's modulus at lower stresses, and Poisson's ratio at all stresses, were not found to be affected by the irradiation. Tensile strength was also unaffected.

The implications of the test are that the gamma irradiation does not affect the elastic properties, but rather the inelastic properties of the rock. In particular, it has the effect of lowering the threshold of stress at which the rock passes from elastic to inelastic behavior. Based on the presumptions mentioned previously, the permeability and thermal conductivity should not be directly affected by gamma rays, and would be indirectly degraded (permeability rising, conductivity falling) only above the threshold stress. At atmospheric pressure this threshold stress lies somewhat above 20 MPa. Under lithostatic pressure this threshold probably rises in the way that mechanical strength of rocks typically rises with confining pressure.

It follows that radiation effects in a repository constructed in granite would be significant only in the presence of high differential stresses.

CHAPTER 4
THERMAL SOURCES

During the test period from 2.4 to 4.0 YOC, the total thermal energy input to the test array has been 562.8 MW·h. This total is the aggregate of four sources--the decay heat of the 11 spent fuel assemblies and 3 electrical loads. The partition of these sources is summarized in Table 4-1 and shown in Fig. 4-1.

4.1 PWR FUEL ASSEMBLIES

The thermal characteristics of the spent fuel assemblies are unchanged from those reported here last year (Carlson et al., 1980). The power level was 1564 W at initial installation of the first assembly into the storage test array and decayed to 870 W per assembly at 4.0 YOC. As shown in Fig. 4-1, the contribution of the spent fuel assemblies to the total thermal input to the test is 30% during the first 1.6 years and is steadily declining. Two exchanges of fuel canisters have been completed between the storage array and EMAD. The first exchange occurred from January 12-14, 1981, at which time fuel assembly S/N D09 was replaced with S/N D15 in storage hole CEH12. The second exchange occurred from October 26-28, 1981, when S/N D09 was returned to the array and S/N D06 was removed at storage hole CEH07. The D06 assembly is one of the three precharacterized units and contains one of the Materials

Table 4-1. Cumulative thermal input to 4.0 YOC.

Source	Cum power (MW·h)	Total (%)
PWR spent fuel assemblies (11)	169.0	30.0
Electrical simulators (6)	96.2	17.1
Guard heaters (20)	279.3	49.6
Facility lights	<u>18.3</u>	<u>3.3</u>
Total	562.8	100.0

Figure 4-1. Cumulative thermal input by source.

Interaction Test trains. Additional fuel exchanges are planned to occur at a frequency of about every nine months, with the next scheduled in late July 1982.

4.2 ELECTRICAL SIMULATORS

The six electrical simulators, located in alternate holes on either end of the test array, have operated with high reliability to date. No extended power outages have interrupted their output. Two difficulties developed with the partial duty cycle controllers. First, the rapid response I²T-type fuses, which were installed to protect the controllers from transient line voltage fluctuations, proved too sensitive and were abandoned in favor of conventional fuses. Second, the test location in a remote area of NTS resulted in substantial variation in the line voltage. The controllers are set to an adjustable duty cycle fraction and are not sensitive to voltage fluctuations. They are not configured to operate from a power-sensing feedback and the simulator power, therefore, reflects line voltage variation. The only significant simulator outage occurred in storage hole CEH17 due to a failed solid state rectifier. The outage lasted 12 days from 2.83 to 2.86 YOC (Fig. 4-2).

The contribution of the simulators to the total test input to date is 17.1%. The average simulator power is 4.4% higher than the spent fuel assemblies. As indicated in Fig. 4-3, this excess resulted from the simulators being set too high early in the tests. As a result of a

Figure 4-2. Electrical simulator controller failure.

Figure 4-3. PWR fuel assembly and electrical simulator power history.

subsequent reduction in the fuel assembly decay curve, the simulators were corrected and are now tracking the curve.

4.3 GUARD HEATERS

The 20 guard heaters were initially energized in June 1980 as indicated previously. In accordance with the previously planned schedule, the power level of these heaters was increased from 925 W to 1250 W each on December 16, 1980. The reliability of these heaters and their controllers has been generally satisfactory. A total of five failures have occurred over the past 18 months. The heater controller failure mode can best be demonstrated by Fig. 4-4 (SHW001). The power level fluctuation appears between the setpoint and a higher level, but not full power. To date, this failure has been observed on three of the six guard heater controllers.

Figure 4-4. Guard heater controller failure.

Data has reflected less than 1% downtime, all of which has been attributed to component failures in the heater controllers. No heater assemblies have failed or shown any indication of erratic performance.

The contribution of the guard heaters to the total test input to date is 49.6%. As the test proceeds, this percentage will increase, due to both the continuing decay of the fuel assemblies and the planned increase in guard heater power in March 1982.

4.4 FACILITY LIGHTING

The normal test configuration is with the lights off. However, when personnel are present in the test area, e.g., for tours, routine instrumentation maintenance or fuel assembly exchange operations, all lighting is turned on. This amounts to a load of about 18 kW, distributed as follows:

	<u>kW</u>
Canister storage drift	8.9
Railcar room	4.7
North heater drift	2.0
South heater drift	2.2

The contribution of the lighting load to the total test input to date is 3.3%, which corresponds to an average of 1.5 shifts/wk when the lights are on.

CHAPTER 5

DATA ACQUISITION SYSTEM

5.1 SYSTEM CONFIGURATION

5.1.1 Hardware

In its current configuration, the data acquisition system (DAS) meets or exceeds the original design criterion set forth in specification document LES-22179 Revision B. As shown in Fig. 5-1, the system is built around two Hewlett-Packard 21MX (HP 1000) disc-based computers. Each on-site unit has the following hardware:

1. HP-1000 Model 2113 E-Series mainframe for high-performance real-time systems applications with 320 K words of standard performance fault control memory, Fast FORTRAN Processor (FFP) firmware, and distributed system interface (DS1000) firmware.
2. HP-7906 20-megabyte cartridge disc unit.
3. Texas Instrument 733KSR printing system terminal.
4. HP-2645/8 user display terminal with dual mini-cartridge tape drive units.
5. HP-7970B 9-track, NRZI, 800-BPI, 45-IPS digital magnetic tape unit.
6. HP Distributed Systems Interface (direct link to other computer unit).
7. HP-IB (IEEE-488) instrument interface (bus 1) to HP-59309 digital master clock (with 1-y battery backup) and HP-3495 scanner.
8. HP-IB (IEEE-488) instrument interface (bus 2) with HP-37201A bus extenders (extends downhole bus from 20 to 1000 m) to HP-3455 6-1/2-digit, high-resolution digital voltmeter and HP-3495 80-channel scanners. At the present time, computer node-100 utilizes 6 scanners; node-200 utilizes 7 scanners. Both are expandable to 13 scanners totaling 1040 channels each.
9. Vadic telecommunications system with two modems, two data access arrangements (DAA), and two power supplies. The system operates at 1200 baud.

The two computers jointly share and are capable of independently controlling the modem switching network (MSN) and HP-IB (bus 2) extender switching network (ESN). Those networks utilize the HP-3495 scanner on HP-IB

Figure 5-1. SFT-DAS hardware configuration.

bus 1 and two LLNL custom-designed junction boxes, LEA-82-1638 and LEA-82-1600, respectively.

In addition to the above, the node 100 computer unit is augmented by the following hardware:

- HP-2608 132-column, 400-LPM line printer for medium speed printout.
- IRAD Stressmeter Datalogger with two 10-channel switch modules.

The node 200 computer unit is augmented by the following hardware:

- Two remote TV system status monitors.
- HP-9872 4-pen graphics plotter interfaced via HP-IB bus 1.
- HP-1310 large-screen, high-resolution graphics display interfaced via a HP-1350 graphics translator on HP-IB bus 1.

The three remote terminal stations also shown in Fig. 5-1 are configured as follows:

- The CP-40, NTS Radio Network Control Center operates with a Vadic modem and DAA, and HP-2635 printing terminal. The site, manned 24 h each day, functions as an alarm communications center.
- The LLNL station is located in a room adjacent to the project personnel at LLNL, Livermore, CA. The site operates with a Vadic modem and DAA, HP-2648 graphics display terminal with dual mini-cartridge tape drive units, and HP-7310 printer/plotter.
- The third station, located downhole in the instrumentation alcove, functions as a work station. It operates with a Vadic modem and DAA, and HP-2645 terminal with dual mini-cartridge tape drive units.

5.1.2 Software

The DAS software consists of both Hewlett-Packard standard and special software, and LLNL special applications software. FORTRAN IV is the industry-standard, high-level programming language used. The Hewlett-Packard software (currently updated to Revision 2126) includes:

1. RTE-IVB Real-Time Executive operating system software package.
2. DSI1000-IV Distributed Systems network communications software/firmware package.
3. IMAGE 1000 Data Base Management software package.
4. Graphics 1000 plotting support modules.
5. Graphics 1000-II (DGL) device independent graphics. This software package will eventually replace Graphics 1000.

6. FTN4X FORTRAN compiler.
7. Several standard drivers to interface with peripheral equipment.
8. Special high-speed driver to interface with the downhole scanners and digital voltmeter.
9. Special driver to interface with the IRAD stressmeter datalogger.
10. Special driver to interface with the Vadic multiple automatic calling system (MACS).

The LLNL applications software is organized into seven subsystems. These include:

1. ACQUISITION modules that control the accumulation of raw measurement data.
2. PROCESS modules that collate data measurements (raw data) and convert to engineering units (converted data), update data bases, and store data on digital magnetic tape for posterity and analysis by scientific personnel.
3. ALARM modules that determine out-of-limits measurements and alert personnel to potential hazards.
4. DISPLAY modules that output converted data to system status monitors and hardcopy devices.
5. DATA BASE modules that provide access to control and conversion parameters.
6. CALIBRATION programs that provide a method of obtaining instrumentation calibration parameters.
7. MISCELLANEOUS routines used to write data base reports and software documentation reports, provide system backup and maintenance, and perform a host of less significant functions.

5.2 OPERATION

In its normal mode of acquisition the DAS routinely collects and processes approximately 500 data points/h from 927 channels of instrumentation. Each channel typically represents one analog instrument. However, there are several critical devices recorded as two channels (one on each computer) for reliability. These redundant channels include the continuous air monitors, remote area radiation monitors, and a few system status monitors.

Each transducer is assigned a unique six-character alphanumeric designator ("license plate") for the life of the experiment. An instrument may, in time, be assigned any number of designators, thereby affording documentation of the modification and replacement of front-end transducers. This minimizes the likelihood of arriving at false conclusions based on instrument behavior produced by maintenance or repair.

Tables are maintained within the computers that define and relate data channels. At predetermined intervals ACQUISITION modules ingest a scan table containing the following information for each computer's devices:

- Channel logical state (ON or OFF).
- Scan time-interval at which each instrument is to be read.
- Time of last scan.
- Scanner channel to which the instrument is wired.
- Type of reading that must be taken (dc or ac voltage, or 2- or 4-wire resistance).
- Processing algorithm code (processor code).
- List of reference channels required by the processing algorithm.

A module then checks each channel to determine whether it should be scanned as ascertained via its logical state and comparisons made among the current clock time, time of last scan, and scan time-interval. If the conclusion is true the module: 1) builds a sequence of channels to scan based on the list of reference channels required by the processing algorithm; 2) requests that the scans be made; 3) receives the raw data values in response; and 4) dispatches those values to the appropriate processor as defined via the processing algorithm code. For example, consider rod extensometer GCE242. Rod extensometers typically require an excitation supply and from two to seven thermocouples for processing to engineering units. Thermocouples, in turn, require reference block temperature devices (RTDs). RTDs and excitation supplies are independent devices. For this example, GCE040 is the required excitation supply and CET020, CET021, and CET022 are the required thermocouples. All these thermocouples require RTD008. The sequence of channels to be scanned is RTD008, CET022, RTD008, CET021, RTD008, CET020, GCE040, and finally GCE242. An internal check is made to eliminate multiple scans of any one channel within a list. Hence, RTD008 is scanned only once. The time of last scan is updated for each channel scanned and the raw data values are dispatched to the appropriate conversion module to complete the processing.

The PROCESS routines accept data packets of channel designator, system acquisition time, and raw data from the ACQUISITION routine. They then retrieve conversion parameters from the conversion coefficient tables to process the data to engineering units. For those having reference channels, like the rod extensometer and thermocouples above, there is also access to the acquired database.

The data packet is expanded to include the engineering value and is then passed to a central acquired data processor. At that point the converted data is stored in the acquired database and also buffered for transmission to digital magnetic tape. Assuming acquisition of 500 data points/h, the data can be buffered for approximately 80 h in the event of tape drive failure.

The ALARM modules first see the data in the central acquired data processor. There each data point is compared to high- and low-alarm limits that are retrieved from the alarm coefficients tables. If the value is found to fall outside its expected limits the channel is further examined for recurring, contingent, redundant, and/or change-of-status alarms. After final determination of an alarm status, the alarm is logged for permanent record and alarm messages are constructed and buffered. Finally the messages are routed to any combination of four devices via direct connection or line modems. After receipt of the alarm has been acknowledged, the monitor (typically CP-40, NTS Radio Network Control Center and/or LLNL) follows a procedure that directs him to contact the project personnel in Livermore, CA who will respond to the alarm and take whatever action is appropriate.

5.3 PERFORMANCE

5.3.1 Measurement Accuracy

Although the DAS is capable of measurements over a broad range of scales, its scientific data most heavily depends on dc voltage readings in the millivolt range and on 4-wire resistance readings in the 125 Ω range. To assure long term accuracy, the digital voltmeters (DVMs) are recalibrated every 90 days and are operated at $\sim 23^{\circ}\text{C}$. In addition, several system standard references are measured periodically. These include a precision millivolt source (SSR002 and SSR005), two nominally 120 Ω precision resistances (SSR003 and SSR006) and several temperature references (SSR007,

SSR008, RTD200, TRT001, TRT012, and TRT013). The millivolt source is accurate to 1 μV ; the resistance values are stable to 0.00018 Ω .

Figure 5-2 illustrates the results obtained from the dc voltage and 4-wire resistance references. The readings provided by the DVMs are guaranteed to 1 μV and 0.0042 Ω with 90-day drifts not to exceed 4 μV and 0.005 Ω , respectively. Resolutions are specified at 1 μV and 0.001 Ω . Examination of those ~ 9000 data points/channel collected from 2.7 to 4.0 YOC shows that the system operates within design specifications. The voltage source is always measured in the envelope 0.996 to 1.004 mV. Minor perturbations are observed at DVM calibration exchanges (indicated by the upward arrows). The 4-wire resistance measurements are stable to $\pm 0.0092 \Omega$. However, several out-of-limits readings are identified on computer node 100. Closer examination of that data, coupled to that of the temperature references, reveal that the DVM suffered from noise problems after the 3.803 YOC exchange. The DVM was returned to the EG & G-Atlas instrumentation shop for repair and recalibration.

Three criteria are used to routinely evaluate the quality of data acquired on a real-time basis. First, the system is checked to ensure that data acquisition is progressing as expected. Second, the alarm log is checked to determine whether out-of-range data values are being recorded. The system standard references have very tight alarm limits that are exceeded in the event of DVM or other system problems. Third, data from a significant percentage of instruments are displayed or plotted to ascertain whether they fall within reasonable limits.

5.3.2 System Reliability

Figure 5-1 showed that there is a physical separation of ~ 650 m between the main portion of the DAS and the front end, containing the scanners and digital voltmeters. The factors necessitating separation were the impractically long cable runs of all low-level instrumentation signals to a system installed on the surface, and the inaccessibility for routine maintenance and repair of a system installed as a subsurface facility. The scanners and DVM are reliable devices that require little attention.

The single-point, mean-time-between-failure (MTBF) and downtime (duration of a failure rendering the system inoperable) figures established for each computer node are 30 days and at least 2 to 4 days, respectively. The

Figure 5-2. SFT-DAS system standard references.

relatively long downtime estimates are a function of both the remote siting of the experiment and the availability of qualified HP service personnel. The DAS has now been functional for three years and experience has shown performance to fall well within the previously stated Hewlett-Packard specification.

A performance statistic more pertinent to the scientific community than MTBF and downtime might be called the "functionally disabled index" (FDI). As interpreted here the FDI (typically expressed as a percentage), is a measure of a system's inability to acquire data as designed. This statistic can be applied to a device, a computer, or an entire data acquisition system for any interval of time.

Figure 5-3 shows the observed daily FDI for each computer node, and the DAS (calculated as the "AND" of the nodes) as a complete unit; it indicates the likelihood that a data point was recorded as expected. Major ticks on the horizontal axis represent the first day of each month; lesser ticks represent the 7th, 14th, 21st, or 28th day. The minor ticks signify Saturdays and Sundays. Statistical record keeping was initiated in April 1980. As evidenced by that figure, node 200 is reported to be more available for data acquisition than node 100. The primary reason for this observation is that software development and/or update is performed on node 100 and often requires that data acquisition be suspended during the testing phase. Once proven operational, the software is loaded onto the node 200 computer. It is obvious that considerably more development was done in 1980 than in 1981. (Figure 5-4 summarizes the daily data in Fig. 5-3 by calendar month.)

Other factors that influence the FDI include:

1. System generation (such as updates of the operating system).
2. Fuel handling operations--data channels of significant interest are scanned rapidly, many others are turned off.
3. Hardware maintenance and/or calibration.
4. Instrumentation maintenance and/or calibration.
5. Cartridge disc unit backup to digital magnetic tape.
6. Software failure.
7. Hardware failure.
8. Computer overburden.

As a general rule, all hardware purchased has performed as expected. There have been, however, a number of nonconformance dispositions related to

Jan. 1, 1980-Feb. 4, 1982

Figure 5-3. SFT-DAS daily FDI.

Figure 5-4. SFT-DAS monthly FDI.

software. The major problems revealed themselves during system integration and have been resolved; a few remain to be worked out.

Software problems with the LLNL-developed clock routines and the HP-procured operating system account for the loss of a large portion of pretest data and early time experimental data. As shown in Fig. 5-3, those problems were remedied by mid-June 1980.

The special high-speed driver used to interface the subsurface scanners and digital voltmeters was found to produce a number of bogus raw-data values. The problem was resolved to approximately one error in 4000 readings after Hewlett-Packard corrected the problem in August 1980. Consideration is still being given to replacing the interface with the standard driver. However, misinterpretation of the bogus data as real data is unlikely since bogus values are typically far outside the range of expected values and often

beyond the recording capability of the instrument, e.g., a 1-m reading on a linear potentiometer only 25 mm long.

As noted in the last report (Carlson et al. 1980), performance of the remote alarm terminals presented the most serious deficiency to the DAS since they hampered a response to actual or potential problems with the experiment. The difficulties at that time were both software and hardware/communications-line related and often resulted in erratic outages on computer node 100 through late 1981. Currently the only remaining problem is the quality of the communications path out of the central facility. Lease-line telecommunications service is scheduled to be completed to the CP-40 and LLNL remote stations by April 1, 1982, thus, eliminating the deficiency.

The IRAD datalogger interface to the DAS was not functional at last report due to software interrupt incompatibilities. The special driver is now operating, but is believed to be responsible for a recurring operating system conflict, resulting in erratic outages of computer node 100. The driver is being scrutinized for fault.

5.3.3 Enhancements and Modifications

Referring to Figs. 5-3 and 5-4, it has been shown that the functionally disabled index (FDI) for the total DAS is considerably lower than that observed for either of the two computer nodes. For that reason an extender switching network (ESN) has been designed and installed to provide remote computer access to the downhole scanners and digital voltmeters. In the wake of a computer failure, the alternate computer can now connect to the other computer's scanners and DVM, affording a communications path to the otherwise inaccessible instrumentation.

The network can also be activated intentionally by an operator. For both cases, however, the result is the same. Local data acquisition proceeds normally as defined above, but with the ESN remote computer override on. After completing that acquisition process, the ACQUISITION software disconnects the local computer's subsurface bus extender and connects that of the other computer. The latter computer's scan table--normally updated periodically on the local node--is then ingested by the ACQUISITION modules. The acquisition process again proceeds to completion, at which time the ESN is reconfigured for local data acquisition.

Installation of leased-line telecommunications service to the CP-40 and LLNL remote stations necessitated the design and implementation of a modem switching network (MSN). The unit is operated under control of either computer and eliminates the need for the Vadic Multiple Automatic Calling System (MACS). That system--in conjunction with the typically poor dial-up telephone service available at the experiment site--has been partially responsible for difficulties related to the remote-alarm capabilities of the DAS (as noted in Subsec. 5.3.2.)

As part of an effort to speed up the processing phase of data acquisition, the applications software has been modified to eliminate the IMAGE 1000 Data Base Management software package supplied by Hewlett-Packard. A much simpler system has been formulated and installed reducing program size by as much as 30%. The result is that processing now proceeds at better than twice its former rate.

CHAPTER 6

NEAR-FIELD HEAT TRANSFER MEASUREMENTS

6.1 MEASUREMENT SYSTEM

For ease of reporting, all temperature recording instruments, whether near-field or intermediate-field, will be discussed here.

6.1.1 Algorithm

The thermocouple conversion algorithm is derived from the National Bureau of Standards Monograph 125. A quartic calculation is performed after obtaining two measurements: reference temperature and TC electro-motive force (EMF). The thermocouple reference temperature is obtained by measuring the resistance temperature detector (RTD). The thermocouple EMF is measured as it appears at the reference isothermal block.

The reference RTD resistance temperature ($^{\circ}\text{C}$) is converted by polynomial expansion. At this point, a comparison is made with an expected range of values to assure validity. If the value is greater than 15°C , but not more than 40°C , the conversion continues. The reference temperature is numerically converted to the EMF value that would be generated if it were a thermocouple. The reference EMF value is then added to the measured TC EMF. The result is a numerical value equal to the thermocouple temperature referenced to 0°C . This value is compared with a table containing four temperature points where the final polynomial crossovers occur. Once a range is selected, the conversion coefficients are applied in a polynomial quartic equation.

6.1.2 Error Analysis

A principal source of error is addressed by analyzing the system calibration results. Basically, the calibration consists of measurements of each thermocouple at three temperatures: 0° , 50° , and 150°C . Some TCs were calibrated only at 0° and 50°C , or at 0° and 150°C . A Rosemont Model 911A1 ice bath is used for the 0°C measurement; a Kaye Model HTR150 temperature reference is used for the 50°C measurement; and a ProceDyne Model TH050 dry bath is used for the 150°C measurement. The reference ice

bath for the cold junction is a Kaye Model K140-4. The actual temperature of the three baths is measured with precision platinum resistance thermometers. The worst case error of the calibration system is $\pm 0.11^{\circ}\text{C}$, while the typical error is estimated to be $\pm 0.07^{\circ}\text{C}$. All thermocouples calibrated fell within the special limits of errors ($\pm 1.1^{\circ}\text{C}$).

Figures 6-1 to 6-3 show the distribution of errors detected in the thermocouples when calibrated at 0° , 50° , and 150°C . A decision was made not to include individual thermocouple offsets in the conversion algorithm because of the small magnitude of these errors, particularly at the lower temperatures present within the rock mass.

6.1.3 Reliability

To date, two thermocouples were damaged beyond repair during installation, and three other thermocouples were destroyed while removing

Figure 6-1. Distribution of error for 0° calibration.

Figure 6-2. Distribution of error for 50° calibration.

Figure 6-3. Distribution of error for 150° calibration.

Table 6-1. Original calibrations March-April 1979.

No. of TC calibrated	Calibration temp ($^{\circ}\text{C}$)	Error ($^{\circ}\text{C}$)		
		Mean	Std dev	Max
404	0	0.020	0.059	-0.414
179	50	-0.016	0.059	0.227
394	150	0.250	0.367	1.232

stressmeters. Two other occurrences have required investigation. These thermocouples were repaired and are back in service with minimal down-time. There has never been a nonrepairable in-service thermocouple failure.

6.1.4 Recalibration

Nearly all thermocouples were calibrated in place to arrive at an instrument calibration that encompassed all system errors. Only a limited number of TCs (those located on vertical rod extensometers) were not calibrated in the field. This omission was required because these TCs were grouted in place (Brough and Patrick, 1981).

The results of the laboratory and field calibrations are listed in Table 6-1.

A similar calibration was performed on six thermocouples during a fuel exchange in January 1981, about 10 months after the first field calibration and fuel emplacement. These thermocouples were at about 140°C for the 10 months and were in a nuclear radiation field in excess of 10,000 R/h. The results of that calibration are listed in Table 6-2.

During fuel exchange No. 2 in October 1981 (about 19 months after the initial calibrations) a different set of thermocouples were calibrated. These thermocouples were removed from the circumference of the fuel assembly in CEHO7. The results of that calibration are listed in Table 6-3.

Table 6-2. Calibrations made during first fuel exchange (January 1981).

No. of TC calibrated	Calibration temp ($^{\circ}\text{C}$)	Error ($^{\circ}\text{C}$)		
		Mean	Std dev	Max
6	0	0.096	0.050	0.177
6	150	-0.290	0.085	0.411

6.2 UNIFORMITY OF HEAT DEPOSITION

Heat deposited in the rock as a result of radioactive decay of the spent fuel results in a smoothly varying temperature vs time curve (Fig. 6-4). Thermal output of the electrical simulators varies somewhat as a function of time while following the same basic decay curve as the spent fuel (Fig. 6-5). It is interesting to observe that the effects from variations in the source (as indicated by the canister temperature) are markedly reduced 360 mm into the rock.

Temperatures 360 mm into the rock are compared in Table 6-4. The means and standard deviations of temperatures measured at the top, middle, and bottom of the thermal sources are shown for 4.0 YOC (about 1.5 years after emplacement). Several interesting observations may be made from this table. First, in the worst case, temperature variations at any axial location do not exceed about 10% to 12% of the average temperature rise. Second, electrical

Table 6-3. Calibrations made during second fuel exchange (October 1981).

No. of TC calibrated	Calibration temp ($^{\circ}\text{C}$)	Error ($^{\circ}\text{C}$)		
		Mean	Std dev	Max
6	0	0.046	0.031	0.076
6	150	-0.640	0.381	1.139

Figure 6-4. Measured and calculated temperature histories at various radial locations at the axial midplane of CEH07.

simulators are somewhat more variable than spent fuel. Third, as expected, the temperature uniformity in the repository model cell is exceptionally good, standard deviations being 5 to 9 times smaller than for the total array. Fourth, there are some basic differences in the temperature distributions associated with spent fuel and electrical simulators 360 mm into the rock. For spent fuel, the top position is coolest, the bottom is about 1.1°C warmer, and the middle is about 5.5°C warmer than the top. For the simulators, the bottom is coolest, the top is about 2.0°C warmer, and the middle is about 5.0°C warmer than the bottom.

The fourth observation indicates a difference in the heat transfer mechanisms in and around the canisters. Since the spent fuel canisters are helium-filled and the simulators are air-filled, the variations are at least partially a reflection of differences in the thermodynamic properties of the

Figure 6-5. Measured and calculated temperature histories at various radial locations at the axial midplane of CEH06.

Table 6-4. Measured temperatures at selected axial locations 360 mm into the rock at 4.0 YOC.

Axial position	Mean and std dev ^a of temp (°C)			
	Total array	Spent fuel	Simulators	Repository cell
Top	54.85 (2.42)	54.69 (2.20)	55.15 (2.99)	55.71 (0.28)
Middle	59.44 (3.12)	60.19 (2.75)	58.08 (3.53)	61.62 (0.53)
Bottom	54.87 (3.26)	55.81 (2.82)	53.15 (3.56)	57.18 (0.69)

^a Standard deviation in parentheses.

gases. Both the conductive and convective components of heat transfer are controlled by these properties.

6.3 COMPARISON OF DATA WITH CALCULATIONAL RESULTS

6.3.1 As-Built Calculations

A recently completed study produced a set of calculational results that are compared here with data acquired during the first 1.5 years of the test (Montan and Patrick, 1981). In the near-field, full three-dimensional calculations were performed using the best-available thermal properties (Table 6-5) and emplacement geometry (Fig. 6-6). The calculations become two-dimensional in the intermediate field.

Calculations are keyed off the mean emplacement data (May 6, 1980) and mean power level on that date (1530 W/assembly at 2.46 YOC). As was noted previously, the simulators are air-filled and the spent fuel canisters are helium-filled. The calculations treat both as helium-filled. An additional difference is that the simulators were energized at 1580 W (in accordance with preliminary assessments of the spent fuel power level). Guard heater power histories were also included in the calculations.

Conduction, convection, thermal radiation, and ventilation were treated, as appropriate, in the as-built calculations. A new "partial flow" model was

Table 6-5. Thermal properties used in SFT-C as-built calculations.

Component material	Conductivity (W/m K)	Density (Mg/m ³)	Heat capacity (J/kg °K)	Emittance
Rock	3.11	2650	930	0.8
Air	0.03	1	1000	--
Canister (stainless steel)	--	--	--	0.4
Hole liner (mild steel)	--	--	--	0.8
Zircalloy cladding	--	--	--	0.4
Helium filling	$4 \times 10^{-4} / T^a$	--	--	--

^aT = absolute temperature in degrees Kelvin.

Figure 6-6. Detail of spent fuel storage configuration (Westinghouse Advanced Energy Systems, Pittsburgh, PA--drawing number 615339-1B).

employed to model the nominal $2.6\text{-m}^3/\text{s}$ flow rate through the facility. Quantitative discussions of thermal sources and sinks are presented in Chapters 4 and 8, respectively.

6.3.2 Comparisons at Selected Axial and Radial Positions

Figures 6-7 to 6-9 present data and calculational results associated with the center spent-fuel canister of the 17-position array. The data are from three planes: top (0.3 m below the top of the active source); middle (at the source centerline); and bottom (0.3 m above the bottom of the active source). There are six thermocouples in each plane: two at 180° opposed azimuthal positions on the canister, two at 90° opposed azimuthal positions on the liner, one 200 mm into the rock, and one 360 mm into the rock. A calculated rock wall temperature history is shown, but no data is taken at that radial

Figure 6-7. Measured and calculated temperature histories at various radial locations at the top of CEH09.

Figure 6-8. Measured and calculated temperature histories at various radial locations at the axial midplane of CEH09.

position. Details of thermocouple installation and locations are reported elsewhere (Brough and Patrick, 1982).

In general, Figs. 6-7 to 6-9 show that calculational results agree quite well with data, particularly at the midplane. However, three notable differences between measurements and calculations are evident. First, a marked asymmetry is evident in the two canister thermocouples opposed from each other 180° at the top of the assembly (Fig. 6-7). This effect is absent at other axial positions and is currently inexplicable in terms of thermal transport. Second, the quality of agreement is poorer on the liner than at other radial positions. Since agreement is better both on the canister and in the rock, the source of discrepancy lies somewhere between. We believe that the discrepancy is a result of using handbook rather than measured values for the emissivity of canister, liner, and rock components. Third, there is a general trend of measured temperatures decreasing at a

Figure 6-9. Measured and calculated temperature histories at various radial locations at the bottom of CEH09.

slightly greater rate than calculated temperatures. Thus, heat transfer is slightly more effective than calculated. This suggests that the conductivity and diffusivity of the rock are slightly higher than used in the calculations.

Table 6-6 allows us to extend these comparisons to include the total array and various subsets of the array. This table displays the means and standard deviations of differences between measured and calculated temperatures. Positive numbers indicate measured temperatures higher than calculated temperatures. Measured temperatures are consistently higher than calculated at the top of the canister and liner, while they vary from slightly lower to slightly higher at this position 360 mm into the rock. On the other hand, measured temperatures are consistently lower than calculated at all radial positions at the middle and bottom. These mean differences are greater for the simulators than for the spent fuel.

Table 6-6. Differences between measured and calculated temperatures at selected axial locations along thermal sources at 4.0 °C.

Radial position	Axial position	Mean and std dev ^a of differences (°C)			
		Total array	Spent fuel	Simulators	Repository cell
Canister	Top	11.02 (5.25)	7.64 (2.31)	17.23 (2.49)	7.93 (0.76)
Canister	Middle	-4.82 (4.13)	-2.56 (2.24)	-8.96 (3.60)	-1.46 (1.65)
Canister	Bottom	-15.80 (7.48)	-10.93 (3.10)	-24.75 (3.42)	-9.44 (1.66)
Liner	Top	4.60 (3.35)	2.92 (2.28)	7.69 (2.81)	3.51 (0.97)
Liner	Middle	-9.10 (2.91)	-8.09 (2.26)	-10.78 (3.28)	-7.40 (0.94)
Liner	Bottom	-15.69 (4.99)	-13.30 (3.87)	-20.07 (3.74)	-12.78 (0.83)
360 mm in rock	Top	-0.29 (2.34)	-0.51 (2.09)	0.11 (2.92)	0.32 (0.32)
360 mm in rock	Middle	-4.68 (2.99)	-3.99 (2.62)	-5.95 (3.46)	-2.75 (0.52)
360 mm in rock	Bottom	-7.06 (3.21)	-6.14 (2.77)	-8.74 (3.53)	-4.83 (0.68)

^a Standard deviation in parentheses.

We are currently studying the agreement between calculations and measurements of three sources of the observed variations. First, the models for convection in the narrow annular spaces between the fuel assembly canister, liner, and rock wall may be inaccurate. As discussed previously, known differences exist because of both helium and air being used for canister fill gases. This difference probably accounts for the large difference between spent fuel and simulator canisters (Table 6-6). Additional errors may exist due to other inaccuracies in modeling convection. Second, the actual quantity of heat removed by the ventilation system is about 64% of that calculated to be removed (Chapter 8). This reduction from the calculated heat removal would cause the surface above the canisters to lose heat less readily, causing the temperatures to be somewhat higher than calculated. This effect is probably small because the rock mass is expected to transport most of the generated heat away from the canisters. Third, a substantial amount of water (some 30.5 tonnes) has been removed from the test facility to date. Although much of this water was the product of seeps into the drift, accumulation of water in several boreholes has also been documented. Water

has also been observed to condense and puddle on the floor of the emplacement hole pits (Fig. 6-6). Vaporization and transport of this water would decrease temperatures at the hole bottoms and increase temperatures at the top. Since water is free to migrate out of the holes, the eventual overall effect should be to decrease temperatures in the vicinity of the holes due to removal of the latent heat of vaporization.

6.3.3 Comparisons at Selected Times

The previous comparisons were made at a spent fuel age of 4.0 YOC (1.5 years into the test). Table 6-7 compares results at 2.6 and 4.0 YOC at the midplane of the thermal sources. Although measured temperatures are lower than calculated at 4.0 YOC for all locations, this is not true earlier in the test. In some locations the measured temperatures are higher than calculated at 2.6 YOC. Even where measured temperatures are not higher than calculated, they do not differ by as much at 2.6 years as they do at 4.0 YOC. Once again, this supports the notion that heat is being transferred more effectively than calculated.

Table 6-7. Differences between measured and calculated temperatures at the midplane of thermal sources at 2.6 and 4.0 YOC.

Radial position	Years out of core	Mean and std dev ^a of differences (°C)			
		Total array	Spent fuel	Simulators	Repository cell
Canister	2.6	-0.14 (2.66)	0.84 (2.37)	-1.93 (2.32)	1.64 (2.31)
Canister	4.0	-4.82 (4.13)	-2.56 (2.24)	-8.96 (3.60)	-1.46 (1.65)
Liner	2.6	-5.05 (2.10)	-5.07 (2.11)	-5.01 (2.27)	-4.72 (0.52)
Liner	4.0	-9.10 (2.91)	-8.09 (2.26)	-10.78 (3.28)	-7.40 (0.94)
360 mm in rock	2.6	-0.22 (4.23)	-0.67 (2.31)	-1.86 (6.46)	1.93 (1.66)
360 mm in rock	4.0	-4.68 (2.99)	-3.99 (2.62)	-5.95 (3.46)	-2.75 (0.52)

^a Standard deviation in parentheses.

6.4 MISCELLANEOUS PERTURBATIONS TO THE THERMAL FIELD

There have been several events that have introduced minor perturbations in the near-field thermal regime. These include fuel exchanges, changes in ventilation rates, power drops in simulators, and water in annular spaces.

Two spent fuel exchanges have been executed to date. The first occurred in CEH12 at about 3.15 YOC (Fig. 6-10) and the second occurred in CEH07 at about 3.94 YOC (Fig. 6-4). It is interesting to note the rapid thermal response following both removal and replacement. Also of interest, and important to the quality of the simulation, is the similarity between the initial and replacement canisters. The only notable differences are the apparently greater front-to-back asymmetry in power of the initial CEH12 canister (Fig. 6-10) and the replacement CEH07 canister (Fig. 6-4). A close examination of Fig. 6-4 also reveals a slight perturbation at 3.15 years.

Figure 6-10. Measured and calculated temperature histories at various radial locations at the axial midplane of CEH12.

This represents a slight cooling, which resulted from removal of the pit plug to exchange radiation dosimeters during the fuel exchange at CEH12.

The effect of changes in ventilation rate (Chapters 4 and 8) is almost imperceptible at the canisters. Figure 6-7 exhibits slight increases in temperature in the intervals from 3.3 to 3.5 and 3.6 to 3.9 YOC when the ventilation rate was decreased.

As discussed previously, the slightly erratic simulator power output in general has little effect on temperatures even a few millimetres into the emplacement hole wall. An exception to this general observation is seen in Fig. 6-11. The decrease in temperature observed at about 2.85 YOC is a direct result of the major decrease in power output of the adjacent simulator (Fig. 6-12). Notice that since the perturbation was external to CEH16, the temperature change is as pronounced in the nearby rock as it is on the

Figure 6-11. Measured and calculated temperature histories at various radial locations at the axial midplane of CEH16.

Figure 6-12. Measured and calculated temperature histories at various radial locations at the axial midplane of CEH17.

canister. This is the only effect seen at CEH16 despite several additional, albeit minor, fluctuations in CEH17.

Construction records indicate that only one emplacement hole (CEH01) contained a significant quantity of water in the annular space between the liner and the emplacement hole wall. With about 2.4 m of water in the hole, the water level was slightly lower than the midplane of the canister at the time of emplacement. Figure 6-13 displays the measured temperatures at the bottom thermocouple positions of CEH01. It is clear that the liner temperature was suppressed for the first half-year of the test. The liner temperature then increased 3.0 to 3.1 YOC and has been smoothly decreasing since then. The canister temperature on the other hand increased, briefly remained almost constant at the boiling point of water (at the test elevation), and then turned sharply downward at about the time the liner temperature began increasing. Although the pretest construction records

Figure 6-13. Measured and calculated temperature histories at various radial locations at the bottom of CEH01.

reported water only in the liner/rock-wall annular space, the observed temperature data indicate that water was also in the canister/liner annular space. Hence, the limitation of the canister temperature to the boiling point of water. Examination of the canister and liner during the next fuel exchange (August 1982) is expected to confirm this explanation.

CHAPTER 7

INTERMEDIATE- AND FAR-FIELD HEAT TRANSFER MEASUREMENTS

7.1 ALGORITHM, ERROR ANALYSIS, AND INSTRUMENT RELIABILITY

These topics are discussed in Sec. 6.1. To date, no recalibration of thermocouples in the intermediate or far fields has occurred. Thermocouple resistance is measured periodically. Any significant change in the characteristics of the thermocouple will be detected as a change in resistance. At this time no recalibration is planned until the end of the test.

7.2 COMPARISON OF DATA WITH CALCULATIONS

7.2.1 As-Built Calculations

Two codes were used to calculate heat transfer in and around the SFT-C complex. The principal set of calculations was performed using the TRUMP finite difference code (Montan and Patrick, 1981). The basic geometry, materials properties, ventilation, and power data for these calculations are provided in Chapter 6 of this report.

Heat transfer calculations were also performed using ADINAT, the ADINA-compatible finite-element heat transfer code. The nodal temperature histories obtained with ADINAT calculations generated the thermal stresses for the thermomechanical stress and displacement calculations (Butkovich, 1981). The basic data input to ADINAT is the same as that used in TRUMP (noted in Chapter 6). An exception is the development and use of "effective" material properties for the air in the SFT-C drifts. The use of effective, rather than actual, properties is necessitated by the lack of internal thermal radiation and ventilation capabilities in ADINAT. We devised a method for determining the effective properties by running sets of ADINAT and TRUMP calculations and sequentially modifying the ADINAT input until the two calculational results agreed (Butkovich and Montan, 1980). The resulting effective properties derived from this process are given in Table 7-1. Thermal radiation is simulated by a material of high-conductivity and low heat capacity. Ventilation is simulated by connecting the center node of each drift to an

Table 7-1. Values of drift material properties derived to simulate radiation and ventilation with ADINAT.

Properties	Values
Thermal conductivity:	
Spent fuel drift	70 W/m ² •K
Heater drift	40 W/m ² •K
Vol. heat capacity	8 × 10 ⁴ J/m ³ K
Convection coefficient (H)	
<u>ΔT (K)</u>	<u>H (W/m²•K)</u>
0	0
0.272	4.5
0.445	5.0
0.903	5.5
1.878	6.0
4.074	6.5
9.427	7.0
24.042	7.5

external constant-temperature node through a heat transfer (convection) coefficient.

Figures 7-1 to 7-6 display TRUMP results at the two heavily-instrumented sections (2+83 and 3+45) for times of 3.0, 3.5, and 4.0 YOC where the average emplacement age was about 2.5 YOC. Contours of calculated temperatures are superposed on measured temperatures. Figures 7-7 to 7-10 display ADINAT results at the same locations and times of 3.5 and 4.0 YOC. Here we show contours of calculated temperature rises superposed on measured temperature rises. The presentation of temperature rises results from using a code that utilizes temperature changes for stress analyses.

Several observations may be made. First, the smooth continuous contours indicate that heat transfer away from the drifts is fairly uniform. Second, the finer, calculational mesh and three-dimensional near-field model used for TRUMP calculations results in better resolution in the very-near field where gradients are steep. Third, the level of agreement between calculated and

Figure 7-1. Comparison of measured temperatures with TRUMP-calculated temperature contours at 3.0 YOC at station 2+83 (first solid contour at 24°C; contour interval at 2°C).

measured temperatures is within a few degrees for both TRUMP and ADINAT. This implies that heat transfer and related thermomechanical analyses are basically correct.

7.2.2 Comparison at Selected Locations and Times

As noted above, the basic agreement between calculated and measured temperatures is quite good. A more thorough analysis reveals some interesting differences between the calculations and measurements.

The most significant difference is the apparently more efficient transfer of heat by conduction away from the drifts and heat sources. At 3.0 YOC, agreement near the heat sources is within 1° to 2°C (Figs. 7-1 and 7-4). Agreement progressively deteriorates until, at 4.0 YOC we see differences of 3° to 5°C less than calculated (Figs. 7-3 and 7-6). Although this is a

Figure 7-2. Comparison of measured temperatures with TRUMP-calculated temperature contours at 3.5 YOC at station 2+83 (first solid contour at 24°C; contour interval at 2°C).

fairly minor difference, it becomes more significant when we consider that more heat is actually being added to the facility (Chapter 4) and the ventilation is less effective than calculated (Chapters 4 and 8). Taking these facts into consideration, the measured temperatures should be higher, not lower, than calculated.

Another means of tracking the heat flow is to compare measured temperatures near selected contours as time progresses. Such a comparison for the 26°C contour (Figs. 7-1 to 7-6) shows that, while measured temperatures are slightly lower than calculated for early times, they are slightly higher than calculated for later times.

These observations support those presented in Chapter 6 of this report. The need to slightly adjust the conductivity and diffusivity of the rock is

Figure 7-3. Comparison of measured temperatures with TRUMP-calculated temperature contours at 4.0 YOC at station 2+83 (first solid contour at 24°C; contour interval at 2°C).

evident. The results of near-field temperature measurements will be used to develop more exact thermal properties for use in later calculations.

Another significant observation is the apparent lack of influence that variations in geology have on heat transfer. Numerous fractures and several clay-filled shear zones penetrate the facility (Wilder and Yow, 1981). Despite spacial variations in the intensity, orientation, and characteristics of fractures, there is no evidence of a related spacial variation in temperatures. This observation supports treating the rock mass as homogeneous for the purposes of heat transfer calculations. Implicit in this recommendation is the determination of thermal properties for a volume of sufficient size that the assumption of homogeneity is valid.

Figure 7-4. Comparison of measured temperatures with TRUMP-calculated temperature contours at 3.0 YOC at station 3+45 (first solid contour at 24°C; contour interval at 2°C).

7.3 VENTILATION EFFECTS

As discussed in Chapter 6 changes in ventilation rate are barely perceptible in the near field. Figure 7-11 confirms this for a location approximately 2.5 m radially from the heat sources and 3.4 m below the floor of the canister drift. The effects of changes in the ventilation rate are even more evident in the pillars between the canister and heater drifts (Fig. 7-12). Cycles of decreased ventilation rate are observed as increases in the slope during the time intervals 3.3 to 3.5 and 3.6 to 3.9 YOC.

Figure 7-5. Comparison of measured temperatures with TRUMP-calculated temperature contours at 3.5 YOC at station 3+45 (first solid contour at 24°C; contour interval at 2°C).

Figure 7-6. Comparison of measured temperatures with TRUMP-calculated temperature contours at 4.0 YOC at station 3+45 (first solid contour at 24°C; contour interval at 2°C).

Figure 7-7. Comparison of measured temperature rises with ADINAT-calculated temperature-rise contours at 3.5 YOC at station 2+83.

Figure 7-8. Comparison of measured temperature rises with ADINAT-calculated temperature-rise contours at 4.0 YOC at station 2+83.

Figure 7-9. Comparison of measured temperature rises with ADINAT-calculated temperature-rise contours at 3.5 YOC station 3+45.

Figure 7-10. Comparison of measured temperature rises with ADINAT-calculated temperature-rise contours at 4.0 YOC at station 3+45.

Figure 7-11. Temperature history at a rod extensometer anchor beneath the canister drift floor.

Figure 7-12. Temperature history at a rod extensometer anchor in the north pillar.

CHAPTER 8

VENTILATION SYSTEM MEASUREMENTS

Since the storage phase of the test was initiated, we have continuously monitored the key parameters of the ventilation system in addition to the power levels of all thermal sources. The purpose of these measurements is to compare the actual test performance with a computational model simulating removal by the low-volume ventilation system of a time-dependent fraction of the total thermal energy input.

This calculational scheme is our initial attempt at modeling the effects of low-volume ventilation on the near-field thermal region in a simulated repository geometry. Details of this model are presented in Montan and Patrick (1981).

The ventilation system employed in the SFT-C test array is an open circuit with inlet air drawn down the personnel access shaft, pulled through the test area, and exhausted up the canister access hole by surface-mounted exhaust fans. The distribution of the total air volume to the three drifts of the test array is accomplished by louvre-dampers located in the bulkheads in each drift. The design of this distribution is based on the cross-sectional area ratios of the three drifts and is approximately 1/4 the total volume through each of the heater drifts and 1/2 through the canister storage drift.

8.1 INSTRUMENTATION

The ventilation system parameters are monitored with three types of instruments. The dry bulb temperatures are measured with the same type-K sheathed thermocouples employed throughout the test. The inlet air temperature is monitored at the entrance to the railcar storage room near the center of the access drift. The primary exhaust air temperature monitor is located 2 m below the bottom of the shielding collar of the access hole in the canister receiving room. Additional air temperature monitors are distributed along the length of all three drifts.

Two dew-point meters of the lithium-chloride-cell-type are employed. The inlet air dew-point meter is colocated with the inlet air temperature monitor, and the exhaust meter is mounted on the access hole shielding collar.

A turbine flowmeter positioned in the surface exhaust ductwork 4-m downstream from a flow-straightening spool measures the ventilation air-flow

rate. The flowmeter is periodically checked against pitot-tube traverses of the duct.

Additional details on these instruments appear in Brough and Patrick (1981).

8.1.1 Additional Instrumentation

Several months following the start of the test, qualitative observations using smoke generator tubes indicated that the flow regime in the canister storage drift was quite complex and included several large convective cells. To obtain some quantitative data, five sets of thermistor arrays were fielded (four sets in the canister drift and one in the north heater drift) to obtain vertical and horizontal temperature profiles at several stations under varying air-flow rates.

These measurements confirmed the complex nature of the air-temperature distribution as a function of location and ventilation rate. This complex thermal regime may be described with reference to the temperature at the center of each of the four arrays. The top thermistor recorded temperatures from 0.6°C warmer to 1.1°C cooler, the bottom thermistor from 0.2°C warmer to 1.0°C cooler, the left rib thermistor from 0.2°C warmer to 1.1°C cooler, and the right rib thermistor from 0.3°C warmer to 0.9°C cooler than the center thermistor at the four stations spaced along the canister drift. Furthermore, these observed spatial variations in temperature changed significantly with changes in ventilation rate. Changes were primarily seen as reductions in stratification subsequent to reductions in ventilation rate.

8.1.2 Instrument Reliability

The ventilation instruments have been satisfactorily reliable. The exhaust temperature and dew-point meter could not be positioned correctly until the fuel handling operations were completed. Their relocation at 2.55 years can be seen in Fig. 8-1 as a change in slope.

The turbine flowmeter electronics experienced a failure after about 1.3 years of operation and the instrument was off line for about 20 days until replacements could be obtained.

Figure 8-1. Cumulative thermal energy removed by ventilation.

8.2 VENTILATION MEASUREMENTS

In this section, we discuss the data from the ventilation measurements. Rather than present the data directly, we have elected to compress about 200,000 data points into a few figures depicting 10-day averages and cumulative totals of the input power from all sources and heat removed by the ventilation system.

8.2.1 Input Power

The details of the various input power sources are discussed in Chapter 4. The upper trace in Fig. 8-2 shows the power input over time and is annotated with significant activities in the test area, which have caused the

Figure 8-2. Power input and removal history annotated for significant events.

average input power level to change. The cumulative total input power is shown as the upper trace in Fig. 8-3 which is taken from Fig. 4-1.

8.2.2 Heat Removed from Test Area

The heat removed from the test area by the ventilation system is of two types. The lower trace of Fig. 8-1 represents the energy deposited in the air by all transfer mechanisms as sensible heat that simply raises the exhaust air temperature. This represents about 74% of the total heat removed. Due to the location of the lighting system (directly in the air stream), most of the energy emanated from the lights is rapidly removed from the area. Thus, although these transients in the air temperature make the local conditions somewhat unpleasant, they have little effect on the long-term thermal regime.

The upper trace of Fig. 8-1 represents the addition of the other heat removal mechanism. This energy is deposited as latent heat of vaporization of water and makes up the remaining 26% of the total heat removed. While the

test facility is located ~150 m above the regional water table, the granite contains some water in its matrix porosity and there is some seepage through major fractures into the area. In addition, a substantial amount of water was lost to the formation during the test construction activities, primarily drilling. This latent heat plot is also shown in Fig. 8-4. Three distinct features are apparent in this illustration. First, the step at 2.55 to 2.60 years is related to the repositioning of the outlet dew-point meter following completion of fuel handling operations. Secondly, there is a distinct change in slope at 2.8 years. This is interpreted as a "drying out" by evaporation of the construction water in the first 0.4 years of the test. This initial portion of the curve represents ~12,000 L of water or an evaporation rate of 3.3 L/h. The nearly constant slope from 2.8 to 4.0 YOC represents the steady evaporation of seepage and pore water and constitutes ~19,000 L or an evaporation rate of 1.8 L/h. Thirdly, there is a somewhat reduced water removal rate during the winter months (~3 to 3.2 YOC), which we will continue to monitor to establish some correlation with annual precipitation cycles.

The lower trace of Fig. 8-2 clearly indicates the effect varying the ventilation air-flow rate has on the heat removal rate. On two occasions during the spring and summer of 1981, the total test ventilation rate was reduced from 2.6 to 1.3 m³/s for ~60 days each.

8.3 COMPARISON WITH CALCULATIONS

In comparing the ventilation system performance with the TRUMP calculations (Montan and Patrick, 1981), the most notable conclusion is graphically shown in Fig. 8-5. Briefly stated, the agreement between measurement and calculation is between poor and nonexistent. The calculation yields a time-dependent increasing fraction of the input power being removed by the ventilation, with that fraction being about 40% at 4.0 years. The measurements, on the other hand, indicate that, while the heat removal rate is directly proportional to the air-flow rate, it is otherwise essentially constant and averages about 15%. The initial spike in Fig. 8-5 is an artifact of the lights.

The disagreement between the modeled and measured input power (Fig. 8-3) is explained by the computational model having an insufficient number of guard heaters. This is due to end effects, the overpowering of the

electrical simulators early in the test (see Sec. 4.2), and neglecting the area lighting load. Clearly, the ventilation aspect of our thermal modeling effort is deficient and we will be working on this problem during the coming year.

Figure 8-3. Comparison of calculated and actual percentage of input energy removed by ventilation.

Figure 8-4. History of cumulative thermal energy removed by vaporization of water.

Figure 8-5. Comparison of calculated and actual cumulative thermal energy input and removal.

CHAPTER 9

RADIATION MEASUREMENTS

9.1 RADIATION DOSE TO GRANITE

Dosimeters have been emplaced in 5 of the 17 canister emplacement holes to measure the radiation dose to the granite (Carlson *et al.*, 1980). This work is being performed by EG & G-Goleta Operations. Dosimeters are located at the borehole wall in stainless-steel tubes within four holes containing spent fuel assemblies and one hole containing an electrical simulator (Table 9-1). Furthermore, dosimeters are located at radii 508 and 660 mm from canister centerline in CEH03. Emplacement was made in the hole with the electrical simulator to study the effects of thermal annealing on the dosimeters. These units were exposed to 4×10^6 , 3×10^7 , and 3×10^8 rad prior to emplacement.

The 7 dosimeter assemblies contain 25 gamma dosimeter subassemblies and 5 neutron subassemblies. Optical grade ^7LiF was selected for gamma dosimetry, based on its response above 10^8 rad and its insensitivity to fading at temperatures above 50°C (Quam and Devore, 1981). The companion neutron dosimeters consist of Co foils and the Ni present in the 303-type stainless-steel parts of the subassembly. These are used to compensate for the neutron sensitivity of the gamma dosimeters.

Calibration of the gamma dosimeters was performed over a range of exposure rates (1 to 85×10^3 rad- $\text{H}_2\text{O}/\text{min}$), using a ^{60}Co source at the Sandia Gamma Irradiation Facility, Albuquerque, NM. All exposures were in air with the LiF chips suspended in stainless-steel holders similar to those used in the field. Each exposure position was measured with a tissue-equivalent, three-terminal ionization chamber whose calibration is directly traceable to the NBS.

Total exposures from 5×10^3 to 5×10^8 rad- H_2O were obtained from this calibration. These exposures resulted in the data shown in Fig. 9-1. Since the curves overlap for the various peaks, it is possible to obtain multiple-exposure values from the field measurements. Rad- H_2O and rad-LiF are treated as interchangeable here, with an expected error of less than $\pm 4\%$.

Fade studies were performed in the laboratory to examine this characteristic of the dosimeters. Two chips each with exposures of 5×10^4 , 2×10^6 , 5×10^7 , and 5×10^8 rad-LiF were baked for 205 days at 50° ,

Table 9-1. Dosimeter location in the field installation.

Canister emplacement No. ^a	Vertical distance of dosimeters from centerline (m)	LiF No.	Co foil No.
01 (wall)	+1.22	14	--
	0	15	5,6
	-1.22	16	--
03 (wall)	+1.83	7	--
	+1.22	8	--
	+0.61	9	--
	0	10	3,4
	-0.61	11	--
	-1.22	12	--
	-1.83	13	--
03 (20 cm)	+1.22	84	--
	0	5	1,2
	-1.22	6	--
03 (36 cm)	+1.22	20	--
	0	21	7,8
	-1.22	22	--
04 (wall, heater)	+1.22	1	--
	0	2	9,10
	-1.22	3	--
07 (wall)	+1.22	17	--
	0	18	--
	-1.22	19	--
11 (wall)	+1.22	23	--
	0	24	--
	-1.22	25	--

^a Data in parentheses denote radial locations of dosimeters relative to borehole wall.

100°C, and 150°C. An additional group of chips was held at room temperature during this time and two unirradiated chips were used as controls. Readings were taken 10 days into the test and monthly thereafter.

No fading occurred in the dosimeters held at room temperature. The 100°C exposure resulted in fading of 10% to 40%, depending on exposure level (Fig. 9-2). Data at 50°C show a much smaller effect. The peak temperature the dosimeters will be subjected to in the field is about 85°C. Fade

Figure 9-1. Calibration curves for ^7LiF chips, ^{60}Co source (after Quam and Devore, 1981).

equations have been developed for correcting data for temperature, T (Table 9-2).

Dosimeters of ^7LiF , rather than natural Li , were selected to minimize neutron sensitivity. We have observed poor agreement between various absorbance peaks, which is tentatively believed due to greater-than-anticipated neutron effects. Available neutron sensitivity data are insufficient to explain the observed disagreements (Quam and Devore, 1981). Additional neutron measurements are now planned to study the observed effects.

The dosimeters were recovered during the January 1981 spent fuel exchange after exposure times of 229 to 269 days. Table 9-3 displays data from each gamma dosimeter and for each peak. Given the high quality of the calibration results, one would expect that the various peaks would provide similar exposure values. This is not the case. Agreement is better at the positions in the rock (CEH03 at 20 cm and 36 cm) than at the hole wall and where no exposure was acquired in the field (CEH04).

Figure 9-2. Fade data for ^7LiF chips (after Quam and Devore, 1981).

Table 9-2. Fade equations for various peaks (Quam and Devore, 1981).

Peak (nm)	Fade equation
247	$\text{Fade} = 3.473 T^{-0.370}$
374	$\text{Fade} = 0.878 + 0.00593T - 0.0000605T^2$
443	$\text{Fade} = 0.892 + 0.00517T - 0.0000632T^2$
IL500A @ 5×10^7 rad	$\text{Fade} = 0.152 + 0.0246T - 0.0000109T^2$
IL500A @ 5×10^8 rad	$\text{Fade} = 1.12 - 0.00529T + 0.0000428T^2$

Another set of data will soon be available from the October 1981 spent fuel exchange. Neutron flux measurements were also made at that time. The combined results of these measurements will be available in mid-1982.

9.2 RADIATION SELF-DOSIMETRY IN GRANITE

We have performed a preliminary study of the feasibility of using thermoluminescence (TL) for the self-dosimetry of the rock surrounding the canister emplacement holes at the SFT-C (Carlson, 1981). Post-test samples at various radial positions from the spent fuel could thus be analyzed to augment the previously described dose measurements and radiation transport calculations.

9.2.1 Laboratory Procedures

Samples of Climax granite were obtained from two 48-mm (NX)-diam cores taken from the pillar regions of the SFT-C. The geometry and size of individual samples were determined by the configuration of the radiation cell and the dose. Low-dose samples (below 10^4 rad) were 48 mm diam $\times$ 5 mm thick, intermediate-dose samples (10^4 to 10^5 rad) were 10 mm diam $\times$ 20 to 30 mm long, and high-dose samples (greater than 2×10^5 rads) were 48 mm diam $\times$ 10 mm thick. Irradiation was performed in one of two ^{60}Co cells, depending on the dose required. Pulverized samples were also prepared and later irradiated to examine the effect of postirradiation crushing on TL.

Table 9-3. Gamma dosimeter data^a (after Quam and DeVore, 1981).

Canister emplacement hole No. ^b	Vertical distance from midplane (m)	Exposure (rad-LiF)			
		Beckman 5270		IL500A	
		247 nm (peak)	374 nm (peak)	443 nm (peak)	547 nm (peak)
01 (wall)	+1.22		3.1×10^7	7.3×10^6	$2.1 \pm 1.10 \times 10^7$
	0		3.6×10^7	8.3×10^6	$1.9 \pm 1.00 \times 10^7$
	-1.22		3.2×10^7	6.2×10^6	$2.2 \pm 1.10 \times 10^7$
03 (wall)	+1.83		1.7×10^7	3.8×10^6	$9.7 \pm 4.80 \times 10^6$
	+1.22		3.4×10^7	8.6×10^6	$2.4 \pm 1.20 \times 10^7$
	+0.61		3.5×10^7	9.5×10^6	$2.5 \pm 1.20 \times 10^7$
	0		3.8×10^7	1.0×10^7	$2.5 \pm 1.20 \times 10^7$
	-0.61		3.8×10^7	1.1×10^7	$2.6 \pm 1.30 \times 10^7$
	-1.22		3.9×10^7	>3 A.U.	$3.1 \pm 1.60 \times 10^7$
	-1.83		2.0×10^7	4.4×10^6	$1.3 \pm 0.66 \times 10^7$
03 (20 cm)	+1.22	$5.1 \pm 1.2 \times 10^5$		$5.1 \pm 0.2 \times 10^5$	
	0	$4.4 \pm 1.1 \times 10^5$		$4.3 \pm 0.2 \times 10^5$	
	-1.22	$4.3 \pm 1.0 \times 10^5$		$4.3 \pm 0.2 \times 10^5$	
03 (36 cm)	+1.22	$9.9 \pm 2.3 \times 10^4$		$7.8 \pm 1.0 \times 10^4$	
	0	$1.2 \pm 0.3 \times 10^5$		$7.7 \pm 0.5 \times 10^4$	
	-1.22	$1.3 \pm 0.3 \times 10^5$		$8.7 \pm 0.9 \times 10^4$	
04 (heater wall)	+1.22		8.7×10^6	8.0×10^6	$8.2 \pm 4.20 \times 10^6$
	0		5.2×10^7	>3 A.U.	$1.4 \pm 0.15 \times 10^8$
	-1.22		>3 A.U.	>3 A.U.	$3.5 \pm 0.38 \times 10^8$
07 (wall)	+1.22		3.2×10^7	7.9×10^6	$2.4 \pm 1.10 \times 10^7$
	0		3.3×10^7	8.4×10^6	$2.2 \pm 1.30 \times 10^7$
	-1.22		3.9×10^7	1.1×10^7	$2.7 \pm 1.10 \times 10^7$
11 (wall)	+1.22		3.1×10^7	7.4×10^6	$2.1 \pm 1.10 \times 10^7$
	0		3.3×10^7	8.1×10^6	$2.0 \pm 1.00 \times 10^7$
	-1.22		3.0×10^7	7.1×10^6	$2.0 \pm 1.00 \times 10^7$

^a Note: 1. Data without errors indicated have errors of 3% to 4% at 2 σ . Other indicated errors are at 2 σ .

2. Data have been corrected for temperature-induced fade.

3. >3 A.U. indicates density exceeded measuring range of spectrophotometer.

4. CEH4 had preirradiated chips with exposures of 8.5×10^6 , 5.6×10^7 , and 2.9×10^8 .

^b Data in parentheses denote radial locations of dosimeters relative to borehole wall.

Most samples examined for TL were whole rock, but some quartz separates were prepared to determine the influence of sample heterogeneity on TL response. Quartz separates were prepared by optical sorting subsequent to staining.

Irradiated samples were pulverized, if they were not pulverized before irradiation, and were then sieved into various size fractions to examine size effects on TL. Selected samples were annealed at $\sim 100^{\circ}\text{C}$ (slightly in excess of the peak rock temperature at the SFT-C), while others were stored several months before reading. The prepared samples were read on a Harshaw TL Reader.

9.2.2 Results to Date

This preliminary study provided several results that support the concept of using whole-rock TL for the self-dosimetry of granite at the SFT-C. Additional testing will be necessary to allow the granite to be used with an acceptable degree of accuracy.

Remnant TL of minerals (caused by their exposure to natural radiation in the stock) is below the level of detection for the apparatus used. Thus, remnant TL should not influence the readings.

Total dose was seen to affect both the intensity of TL and the shape of the glow curve. Lower doses affect the lower temperature portions of the glow curves. As dose increases, the lower temperature regions first saturate and then actually decrease somewhat while higher temperature peaks increase.

The thermal history of the sample after irradiation and before reading has, as expected, an effect on TL. Exposure of a sample at a given temperature effectively erases the TL response below that temperature in a matter of seconds. Exposure to lower temperatures for longer periods of time can erase TL response at temperatures well above those to which the sample is exposed. The effect of simultaneous heating and irradiation was not studied here, but is essential to utilizing the TL technique on SFT-C rock. Further study is needed in this area.

The influence of mechanical treatment is believed to be at least partially the result of annealing due to the heat generated during crushing. At doses of 10^4 rad, all peaks are reduced; while at doses of 10^9 rad, only the 140°C peak is substantially reduced by grinding after irradiation.

The samples etched in hydrofluoric acid (to aid in the separation of quartz) were found to read 3% to 19% higher than the samples which were not etched.

Sieve size substantially affected the TL response of the samples. Although little effect was seen in the high-temperature intervals, for the lower-temperature intervals, finely crushed samples read 29% to 114% lower than their more coarsely crushed counterparts. This may very well be due to annealing caused by the heat produced during crushing.

9.3 RELIABILITY AND AVAILABILITY OF RAM/CAM SYSTEM

The Remote Area Monitors (RAMs) and the Continuous Air Monitors (CAMs) have an outstanding record of reliability.

The beta-gamma detection system (RAM) has run without a failure. The instruments are periodically calibrated using the internal calibration mode. Prior to a fuel exchange, external calibration sources are also used. The in-place calibration using a ^{60}Co and/or a ^{226}Ra source has shown that the instruments are performing as expected.

The tritium-krypton detection system (CAM) has performed reasonably well. Because redundant systems are operating, there has never been a time when the experiment has been without a monitor system. A problem arose in one system (in the form of a thermally sensitive connection), that took a number of weeks to identify, but which was then quickly repaired.

9.4 SUMMARY OF RADIATION LEVELS ENCOUNTERED DURING HANDLING AND STORAGE PHASES

9.4.1 April-May 1980 Fuel Emplacement

During the initial fuel handling phases, personnel working in close proximity to the spent fuel were issued pocket dosimeters and key individuals were issued neutron dosimeters. The two technicians charged with installation of thermocouples along the circumference of the fuel assembly were also issued hand and forehead TLD (thermoluminescent dosimeters). The highest reading on a pocket dosimeter was 50 mR. This amount constituted the radiation level for the entire emplacement operation (i.e., one 1 dry run and 11 emplacements of

Table 9-4. Area dosimeter results April-May 1980.

Location	Gamma dose (mR/emplacment)	Neutron dose (mRem/emplacment)
West canister drift	1	9
East canister drift	1	2
Electronics alcove	--	--
Other downhole locations	0-1	--
Hoist house	0.05	--
Headframe-top	0.02	2
Observer point	--	Not read out

fuel assemblies for ~40 days). Because of the low gamma doses recorded by area dosimeters, it is doubtful that actual exposures were as high as indicated by the pocket dosimeters. All doses on the neutron dosimeters were below detection thresholds. The TLDs had a total dose of <20 mR per emplacement.

Area dosimeters were placed at various locations for differing lengths of time. TLDs sensitive to beta and gamma radiation were placed underground before operations and showed a beta-gamma background of zero.

Exposures recorded by dosimeters during handling operations were low and no danger from radioactivity is anticipated during normal operation as Table 9-4 indicates.

9.4.2 January and October 1981 Fuel Exchanges

Fuel exchange exercises revealed no unexpected exposures. The personnel dosimeters, with a minimum detectable gamma and neutron exposure of 30 mRem, indicated zero for all personnel.

9.4.3 Surface Transport Vehicle Surveys

Radiological surveys are performed several times per fuel handling operation on the surface transport vehicle (STV).

The radiological survey performed during the most recent fuel exchange (October 1981) is reported here to put the radiation exposure levels into perspective.

Empty STV:

No radioactive contamination above background level
 $<10 \text{ dpm}/100 \text{ cm}^2$ (α), $<100 \text{ dpm}/100 \text{ cm}^2$ ($\beta + \gamma$), and radiation survey was background ($<0.05 \text{ mR/h } \beta + \gamma$).

Loaded STV (top cover open, cask in erect position):

Max of $200 \text{ mR/h } (\gamma)$ on contact and 3.5 mRem/h (n) on contact.
These radiation levels were due to the machined clearance between the cask and shield plug/element assembly.

Loaded STV (traveling position):

No radioactive contamination above $10 \text{ dpm}/100 \text{ cm}^2$ (α) and $100 \text{ dpm}/100 \text{ cm}^2$ ($\beta + \gamma$) and maximum radiation level of $15 \text{ mR/h } (\gamma)$ and 60 mRem/h (n) on contact with the cask at the trunnion pins.

CHAPTER 10

ROCK STRESS MEASUREMENTS

10.1 SUMMARY OF CALIBRATION STUDIES

IRAD Gage, Inc. was contracted to perform laboratory calibration studies of the vibrating-wire stressmeter in Climax granite at elevated temperatures (Dutta, Hatfield, and Runstadler, 1981). A test program was developed to study nine important factors which influence stressmeter response: test block size, stressmeter stiffness, gauge reproducibility and hysteresis, gauge preload, initial stress field, platen geometry, platen orientation, elevated temperature, and rock anisotropy. Many of these tests were conducted under uniaxial, biaxial, and triaxial loading conditions. The results of these studies were used to develop the algorithm described in Sec. 10.2 and to aid in data interpretation.

Aluminum, Barre granite, and lucite were used to study the effect of sample size. Sample width was constant at 250 mm and the aspect ratio was varied from 1.0 to 1.5 or 2.0. For the three materials tested the influence was 7.3%, 3.1%, and 1.1%, respectively.

Stressmeter stiffness studies revealed that the LLNL gauge which was electroless-nickel-plated, had a stiffness of $1.29 \times 10^7 \pm 1\%$ N/cm, while the standard VBS-1HT had a stiffness of $1.24 \times 10^7 \pm 3\%$ N/cm.

Gauge reproducibility was investigated under two conditions, single setting with multiple-load cycles and multiple setting with a single-load cycle. A zero shift is noted between the first and second cycles for all materials tested (Fig. 10-1). This zero shift (expressed as a percentage of the maximum stress change in the wire) is 18.3%, 17.5%, and 7.06% for Climax granite, Barre granite, and aluminum, respectively. This is probably a result of the stressmeter "bedding in" on the first cycle since, for later cycles, the effect is almost nonexistent (Fig. 10-2).

Gauge preload effects are present at low preload values, but the sensitivity of the gauge is nearly constant above some threshold value. A change in readout of about 175 units or more results in a constant sensitivity in the Climax granite.

The influence of initial stress field on gauge response is negligible.

Tests in lucite and aluminum indicated that the hard rock (HR) platen results in markedly smaller (in fact, negligible) variations in the

Figure 10-1. Stress hysteresis in Climax granite after Dutta *et al.*, 1981)

sensitivity factor as a function of stress than when soft rock and modified soft rock (SR and MSR) platens are used.

Theory shows that the ratio of gauge sensitivity to loading parallel to the wire compared to loading perpendicular to the wire is -3.00. Test results indicated that the actual ratio varies from -2.84 to -3.28, depending on stress level.

The influence of temperature is probably the most critical aspect of gauge response as it relates to the SFT-C. The measured thermal offset of a set gauge, expressed as wire stress, is seen in Fig. 10-3. Changes in stressmeter sensitivity with increasing temperature are negligible under uniaxial loading (Fig. 10-4) and somewhat greater under biaxial loading (Fig. 10-5) and triaxial loading (Fig. 10-6).

Tests in three slabs of Climax granite revealed that fairly significant anisotropy exists (11% to 27%) for different stressmeter orientations. This

Figure 10-2. Reproducibility of standard VBS-1HT stressmeter for 2nd-4th load cycle (after Dutta *et al.*, 1981).

Figure 10-3. Change in wire stress of a set stressmeter in Climax granite under elevated temperature (after Dutta *et al.*, 1981)

Figure 10-4. High-temperature stressmeter sensitivity under uniaxial loading (after Dutta *et al.*, 1981).

Figure 10-5. High-temperature stressmeter sensitivity under biaxial loading (after Dutta *et al.*, 1981).

Figure 10-6. High-temperature stressmeter sensitivity under triaxial loading. End load = 615 psi (4.24 kPa); after Dutta *et al.* (1981).

may be the result of preferential orientation of healed geologic fractures and feldspar phenocrysts in the rock slabs.

10.2 ALGORITHM AND ERROR ANALYSIS

10.2.1 Vibrating-Wire Stressmeter Algorithm

The calibration study described in Sec. 10.1 suggests that temperature change (Δt), has no effect on gauge sensitivity for changes in uniaxial stress. Changes in temperature merely cause an offset in the initial gauge reading (T_1) by an amount

$$T'_1 - T_1 = 1.55 \Delta t .$$

The algorithm in REVERT is as follows:

$$\text{CONV} = (1.7842 \times 10^{14}) A \left[\frac{1}{T_1'^2} - \frac{1}{T_2^2} \right] ,$$

where

CONV is the stress in pascals.

T_2 is the gauge reading.

$T'_1 = T_1 + 1.55 \Delta t$ is the initial set reading, offset by the temperature change.

A is 1.6, 1.8, or 2.0 depending on whether the initial set preload remained stable, dropped slightly (5% to 10%), or dropped by more than 10%.

The values of A, T_1 , and the temperature t_1 when T_1 was recorded are kept in a data base of instrument characteristics. The temperature of the gauge at the time for which a data conversion is desired is retrieved from the data base of gauge readings (see Chapter 13).

As an example of the impact of this correction on the data, Fig. 10-7 shows the temperature-vs-time at CSG012 (a radial gauge 1.17 m from hole CEH03). Figure 10-8 then shows the gauge reading-vs-time in pascals with and without temperature correction. It can be seen that the major component of the uncorrected curve is the temperature effect. The temperature-corrected

Figure 10-7. Temperature history at stressmeter CSG012.

stress change is quite small until about 2.85 YOC. The sudden increase in readings at this time is most probably the onset of gauge failure, discussed later in this chapter.

10.2.2 Error Analysis

The primary sources of error with the vibrating-wire stressmeter (VWSM) are variations in the rock-gauge contact and heterogeneity of the rock itself. Except for those gauges that failed due to internal corrosion, the variation between gauges is small, and gauge precision and stability are excellent (0.1% to 1.0%, depending on use).

At the present state of knowledge, the sensitivity of the gauge to rock stress changes at a particular location cannot be predicted with confidence to better than ~25%. This estimate is based on previously discussed calibration data that show sensitivity variations of this magnitude for the same gauge set

Figure 10-8. Raw and temperature-corrected data from stressmeter CSG012.

in three Climax granite blocks in each of two orientations, 90° apart. As noted earlier, these variations may be due to the presence of feldspar phenocrysts and healed geologic fractures. This is supported by measurements with multiple settings in the same block and the same orientation, which show imperceptible variations in sensitivity for Climax or Barre granite.

10.2.3 Gauge Location

In view of the preceding information, gauge location is obviously an important variable. The SFT-C gauge locations were chosen to avoid fractures, but their locations are not documented in respect to rock grain structure during the initial installation (March 1980). Using the 38-mm (EX) core, it proved impossible to identify and locate fractures. Furthermore, locations could be selected only in a gross sense by projection of features from the

canister drift (Chapter 3). In June 1981, nine of the gauges were replaced due to gauge failure and, at that time, locations accurate from 20 to 30 mm were chosen by borescope. An additional concern during replacement was the necessity of avoiding locations not totally cleansed of the plastic foam used as a sealant on the initial installation.

10.3 COMPARISON OF MEASURED AND CALCULATED STRESS CHANGES

As will be discussed in the following section, the vibrating-wire stressmeters installed at the SFT-C failed within a few months after emplacement. Because of the nature of the failures, it is difficult to discern when the stressmeter data became invalid (although some failures are obvious). Rather than publish potentially erroneous data, we have elected to delay presentation of acquired data until we better understand the timing of the failures. Data from replaced stressmeters will be reported later as it becomes available.

10.4 STRESSMETER FAILURE, MODIFICATION, AND REPLACEMENT

10.4.1 History of Failures

Two versions of the IRAD vibrating-wire stressmeter were available at the time of the initial procurement: the standard gauge and a high-temperature version (VBS-1HT). The high-temperature version was identical in construction to the standard gauge except that it used higher temperature materials for potting compounds, O-ring seals, and cable insulation. Furthermore, the body was heat-treated to higher temperature before assembly. LLNL requested a nickel-plated version of the VBS-1HT, which has also been called the "UCL³ gauge" (Brough and Patrick, 1981).

Since their installation in March 1980, 13 of the 18 gauges have failed. The cause has been identified as internal rusting, especially of the wire itself. IRAD has redesigned the gauge, providing a welded hermetic seal in place of the O-ring seal previously used. Nine gauges of the new design were reinstalled in place of failed units from June 16-17, 1981. All of these new units appear to be functioning normally to date (Patrick, Carlson, and Rector, 1981).

10.4.2 Evaluation of Failures

The onset of failure was observed as erratic signal output. Gauges functioning normally produced smooth curves whereas those which were failing produced erratic curves (Fig. 10-9).

On contacting the manufacturer, it was recommended that an attempt be made to read the gauges with an MB-6 readout device, which allowed tuning of the excitation signal to the gauge being read, and provided test points for observing the signals on an oscilloscope. The instrument was shipped to LLNL by IRAD on a loan basis and measurements were made. These measurements, along with oscilloscope pictures, led us to conclude that the gauge wires had decreased in Q (i.e., increased mechanical damping) so that the wire vibrations died out too quickly for the data logger to obtain a reading.

A spare gauge (Serial #02) was suspended in hole CSG02 without clamping as an environmental test. The subsequent response of this gauge was similar to that of previously observed failures. In spite of the fact that the gauge had zero imposed stress, it showed an initial drop in reading followed by a gradual, but pronounced increase until failure.

The stressmeters were removed from the two vertical holes (6 units) and one end of one horizontal hole (3 units). Other units were left in place to avoid damaging units that were still functioning (Patrick, Carlson, and Rector, 1981).

The gauges were returned to LLNL and the seal plug of one gauge was removed to allow inspection of the interior. The wire itself is coated with red crystals which under x-ray analysis appear to be goethite, an iron oxide (Fig. 10-10). The gauges were later taken to the IRAD plant in Lebanon, NH, where two of them were sawn apart. The cut was made near the sensing wire to allow close inspection, but not so close as to disturb the wire or any coatings it had acquired. The wires of both these gauges were also rusted. A test was made of the O-ring seals in the two ends of each of the sawn apart gauges with pressurized air. One gauge showed a small air leak through the magnetic core region of one end plug, the other gauge showed a small air leak between the O-ring and the epoxy plug opposite the magnetic core plug. Inspection of the suspect plug showed a small amount of mold flashing at the bottom of the O-ring groove at the apparent site of the leak. Normally these mold marks are removed with a fine file before assembly, but this unit

Figure 10-9. Plots of data from selected gauges (after Patrick, Carlson, and Rector, 1981) CW = clockwise; CCW = counterclockwise.

Figure 10-10. Interior of failed VWSM (after Patrick, Carlson, and Rector, 1981).

apparently got through the manufacturer's inspection by mistake. Our current understanding of the problem is that:

1. Moisture enters at least some gauges through faulty O-ring seals or faulty potting of the magnet core assembly.
2. Since the gauges were not flushed with dry nitrogen or other gas at assembly, the possibility remains that sufficient moisture in the form of humid air is introduced into the gauge at assembly to ultimately perturb the gauge reading by wire rusting.

The LLNL specification of nickel plating inside the gauge body may have exacerbated the problem by removing rustable surface within the gauge, which otherwise might have acted as a "getter" for whatever water was present. This would probably be significant only for item 2, where a limited amount of moisture is available.

10.4.3 Remedial Actions

Under independent funding, IRAD subsequently designed and tested a hermetically sealed version of the gauge. In the new version, sealing is accomplished by thin, stainless-steel cups welded to the gauge body around the perimeter of the hole at the ends of the gauge (Fig. 10-11). Since the welding is done by electron beam, the interior of the gauge is a hard vacuum, eliminating any moisture entry at assembly.

Nine of the new gauges were installed at the SFT-C June 16-17, 1981. The location and orientation of each gauge was precisely selected to avoid rough spots, fractures, and residual foam on the wall contact areas. A borescope was used to select the appropriate locations. Locations and initial readings of the gauges are given in Table 10-1. The change in reading during first 24 h is due to the gauges achieving thermal equilibrium with the rock. To date, all these gauges appear to be functioning normally.

Figure 10-11. Use of thin, stainless cups in new gauge (after Patrick, Carlson, and Rector, 1981).

Table 10-1. Gauge data for June 1981 installation.

Gauge	Serial No.	IRAD channel	Depth ^a (m)	Orient.	Gauge reading				Next day
					Zero	Tool set	Tool removed	$\Delta(\%)$	
NSG241	RD135	7	2.65(N)	60°CW	2061	2500	2480	5	2465
NSG242	9	8	2.80(N)	Vert	2268	2500	2514	-6	2496
NSG243	RD116	9	2.95(N)	60°CCW	2041	2246	2208	19	2200
CSG211	RD125	13	3.50	60°CCW	1947	2186	2146	17	2154
CSG212	RD122	14	3.65	_ Rail	2037	2275	2245	13	2299
CSG213	RD130	15	3.80	60°C	1998	2222	2163	26	2188
CSG221	RD132	16	3.45	60°CCW	2065	2307	2343	-15	2395
CSG222	RD133	17	3.60	_ Rail	2085	2331	2312	8	2368
CSG223	RD124	18	3.75	60°CW	1815	2050	2029	9	2059

^a Hole NSG04 (containing gauges NSG241-243) is 5.702 m long.
(N) = depth from north drift.

CHAPTER 11

DISPLACEMENT MEASUREMENTS

This chapter describes the status and interpretation of rock displacement measurements at the Spent Fuel Test--Climax (SFT-C). An overview, including illustrations of the types of instruments in place and their locations was presented by Carlson et al. (1980). Chapter 3 of this report describes the relation of instrument locations to the geology of the SFT-C. This chapter is divided into three sections. Section 11.1 covers corrections of displacement data for thermal effects and also describes other factors affecting the data, including instrument removal and replacement, railcar movement, ventilation rate changes, and operator effects. Section 11.2 describes the available results from the measurements and compares them with displacement calculations. Section 11.3 summarizes instrument failure, repair, and modification.

11.1 DATA CORRECTIONS

11.1.1 Thermally Induced Measurement Errors

During the heated phase of the SFT-C, thermal expansion of various instrument components used to monitor displacements causes a significant amount of data errors. Several types of instruments monitor rock displacements caused by heating of the test facility. These include the GxE series, MBI series borehole rod extensometers, the convergence wire extensometers (CWE and THE devices), the fracture monitor systems (FMS), the tape extensometer (TX), and the Whittemore gauge. The latter two instruments are read manually, while the other instruments are read remotely by the computer-based data acquisition system (Chapter 5).

11.1.1.1 Thermal Correction of Remotely Read Instruments. As instrument temperatures rise above a preheated-phase baseline, the various instrument components expand in accordance with their individual coefficients of thermal expansion. Thermal expansion of some components results in an apparent convergence, while the expansion of others results in an apparent divergence (as sensed by the transducer in the remotely read instruments). Correction of

data read by the instrument can be accomplished by an equation of the following form:

$$D_A = D_M + \sum_{i=1}^m L_i C_i (\Delta T_i)$$

where

D_A = actual displacement,

D_M = measured or apparent displacement,

ΔT_i = average instrument component temperature less baseline temperature,

m = number of components included in correction (varies from 4 to 11, depending on instrument type),

L_i = length of component i ,

C_i = coefficient of linear thermal expansion for component i .

The expansion of many of the components as temperature increases results in an apparent convergence of the potentiometer, which is monitored in the remotely read systems. Assuming that convergence is negative, the proper correction is the algebraical addition of the calculated thermal correction to the measured displacement. However, some components produce an apparent divergence or extension after expansion, and their calculated corrections are, therefore, subtracted from the measured displacement. This is done in the equation by assigning negative values to the appropriate component lengths in the data base.

As can be seen, correction of displacement data for thermal effects requires input of temperatures and calculation of a suitable ΔT . Although algorithms with which the available quantities of data can be corrected have not yet been implemented, procedures have been developed for calculation of appropriate ΔT values for all remotely read systems with the exception of the CWE, THE, and FMS devices. These instruments are subject to a complex air temperature regime within the drifts, and require special temperature measurements, which are currently being acquired. Calculation of ΔT values for the GxE and MBI rod extensometers is based on temperatures obtained from thermocouples located at or near each extensometer anchor, and requires breaking the correction equation into segments for each interval between

adjacent instrument anchors. Values of ΔT for the FMS systems can be approximated from nearby temperature-sensing devices, but more accurate values will be obtained from thermocouples recently installed directly on each FMS. The tape extensometer and Whittemore gauge corrections are carried out based on readings performed in the field. These corrections are described in sub-subsects. 11.1.1.2 and 11.1.1.3. Chapters 6 through 8 of this report describe the thermal regimes to which the various instrument systems are subjected.

Other input required for thermal corrections includes instrument component lengths and material expansion coefficients. Component lengths have been determined from instrument design and assembly drawings, and--where appropriate--from dimensional measurements performed in the field. These lengths are fully documented in the project quality assurance files and not presented here. Coefficients of linear thermal expansion for instrument components were obtained from several sources. These included the instrument manufacturer (when possible), handbooks and reference works, and material specifications in the form of engineering standard references (ESRs). A file of ESRs is maintained at LLNL, which includes many of the materials used in fabrication of the CWE, FMS, and THE systems. Coefficients provided by manufacturers are assumed to be subject to relatively little variation. Those available from ESR files are also considered reliable. However, the coefficients obtained from handbooks and references may be expected to vary somewhat from those of the actual material used. This variation is typically on the order of 1% or 2%, and its effect is illustrated in the discussion of tape extensometer measurement corrections.

An error analysis for each type of device used to monitor displacement in the SFT-C will be documented in future reports. Table 11-1 illustrates the magnitude of correction required in selected instruments to compensate for a ΔT of 1.0°C .

11.1.1.2 Tape Extensometer Thermal Corrections. Manual measurements are regularly made in the SFT-C as a check on the remotely read convergence measurements. The manual readings are obtained with a Model 51855 Tape Extensometer, manufactured by the Slope Indicator Company of Seattle, WA. Although we have not yet fully implemented data correction for thermal effects for many of the remotely read instruments, we have been correcting tape extensometer (TX) data for some time. As a result, this section explains

Table 11-1. Typical magnitudes of thermal expansion corrections required by a ΔT of 1.0°C .

Device and location	Distance over which measurement is made (m) ^a	Typical correction if $\Delta T = 1.0^{\circ}\text{C}$ (μm)
CWE in heater drift	3.3	55.7
CWE in canister drift (horizontal)	5.2	84.3
CWE in canister drift (vertical)	6.0	100.5
TX in heater drift	3.3	39.4
TX in canister drift (horizontal)	5.2	59.6
TX in canister drift (vertical)	6.0	71.8
GxE in canister drift (shallow anchor)	2.0	0.2
GxE in canister drift (deep anchor)	13.2	2.3
MBI in heater drift (shallow anchor)	1.8	18.4
MBI in heater drift (deep anchor)	13.9	160.7
FMS in canister drift (FMS011)	0.4	3.8
FMS in canister drift (FMS012)	0	1.1
FMS in canister drift (FMS013)	0	0.5

^aNote: This distance spans the given drift for CWE and TX measurements, from the drift perimeter to the given anchor for GxE and MBI measurements, and across the indicated amount of rock for the FMS measurements.

these corrections in some detail. Because this particular instrument uses English units of length, our discussion mentions these rather than the metric units.

Several potential sources of variation in the readings have been identified during use of the tape extensometer and during analysis of the data. Three of the primary sources identified include the effects of thermal expansion, differences between steel tapes used with the instrument, and operator influence. The latter two sources are discussed in following sections. One source that has been identified, but remains unresolved is the temperature distribution along the tape. Instrument temperature is currently being measured at only one point on the steel tape per reading, although the

air temperature profile within the drifts is known to vary, as pointed out in Chapter 8.

The effects of thermal expansion of the instrument components are calculated for each measurement and the lengths recorded are then corrected for the variations in temperature. Length readings from the canister and heater drifts are corrected from the temperature measured on the tape to a baseline temperature of 22°C . This baseline temperature value reflects typical ambient air temperatures recorded in the drifts prior to spent fuel emplacement. The corrections are made by measuring the temperature at a single point on the tape, using that temperature as representative of all instrument components to adjust the lengths back to the reference temperature. The temperature recorded is within the middle third of the tape for horizontal readings, and from a point about eye-level for vertical readings.

The tape extensometer consists of an aluminum instrument body, a stainless-steel tensioning screw, proving ring and dial indicators, stainless-steel sockets, and a carbon-steel surveyor's tape. The materials of each component, their lengths and coefficients of thermal expansion are listed in Table 11-2. The coefficients were obtained from various reference works; some variation was found from reference to reference. The values for stainless steel and aluminum may, thus, be minutely in error.

The coefficient for the steel tape was supplied by the tape manufacturer; its variation is, therefore, assumed to be much less. Because of the potential for variation in coefficients, it should be realized that a 1% error in the expansion coefficient for all of the components would result in a maximum error of 1% in the thermal correction to be applied to a given reading. The error in correction could be less than the maximum since some of the coefficient errors may differ in sign, partially cancelling each other out.

Although the increment of measurement used by the instrument is 0.001 in., the lengths of the aluminum instrument body, tensioning assembly (see footnote to Table 11-2), and stainless-steel sockets are not measured this closely since they are small and do not enter into displacement calculations except for thermal corrections. Table 11-3 presents the effects of a 0.05-in. variation in these lengths on displacement measurements. Effects of errors in the values of the thermal expansion coefficient and in component lengths (other than the steel tape) are small. If the temperature difference is 10.0°C (near the maximum expected temperature rise) rather

Table 11-2. Coefficients of linear thermal expansion for tape extensometer components.

Material, component, and component length	Coefficient of linear thermal expansion (per °C)	Change in length for $\Delta T = 1.0^{\circ}\text{C}$ (in.)
Aluminum instrument body (5.40 in.)	23.5×10^{-6}	127.0×10^{-6}
Stainless-steel sockets (4.20 in.)	17.3×10^{-6}	72.7×10^{-6}
Stainless-steel tensioning assembly ^a (12.35 in. minus dial reading)	17.3×10^{-6}	214.0×10^{-6}
Steel tape (8.5 in. plus tape reading)	11.6×10^{-6}	98.6×10^{-6} for 8.50 in. of tape

^a Includes dial indicator, tension screw, and proving ring assembly.

than 1.0°C , the errors in these thermal corrections are still on the order of 2% or less of the 0.001-in. measurement increment.

Only temperature, tape, and dial readings are field-recorded. These are used to calculate a distance between two anchor points. Since this is not the true distance between the points, we compare it with previous distance values to discern convergence or divergence between the two points. No other lengths

Table 11-3. Effect of 0.05-in. error in instrument component length on displacement measurement corrections.

Component	Error in 10^{-6} in. ($\Delta T = 1^{\circ}\text{C}$)	Error as % of 0.001-in. increment
Aluminum body	1.18	0.12
Stainless-steel socket	0.87	0.09
Stainless-steel tensioning assembly	0.87	0.09

enter into data correction calculations except for temperature correction purposes.

11.1.1.3 Whittemore Gauge Thermal Corrections. Soon after emplacement of spent fuel, cracks were observed to be forming in the concrete floor around each canister emplacement hole of the canister drift. Conical reference seats were, therefore, anchored in the floor to allow measurement of crack deformations with a Whittemore gauge. The Whittemore gauge, commercially available from Soiltest, Inc. of Evanston, IL is accompanied by an INVAR reference bar mounted with two of the reference seats. The reference bar is kept with the instrument and is, therefore, assumed to be at the same temperature as the instrument. Data reduction involves comparing a reading taken from the bar (used as a standard) with readings from the anchor points in the floor. The instrument readings are in this way automatically corrected for temperature as part of the data reduction procedure, without need of direct measurement of instrument temperatures.

11.1.2 Effects of Removal and Replacement on CWE/THE Systems

Fuel exchange activities require the removal of 12 CWE and 2 THE instruments prior to operations and their replacement after completion. Although these instruments were designed in anticipation of this requirement, some offset inevitably occurs in the data.

Table 11-4 demonstrates the offsets created by this type of instrument disturbance. The average error is $-29\text{ }\mu\text{m}$, and extreme values range from $+167$ to $-282\text{ }\mu\text{m}$ in the CWE units and from $+285$ to $-688\text{ }\mu\text{m}$ in the THE units. This analysis assumes that no actual displacement occurred during the brief (~ 1 wk) period when the instruments were removed.

11.1.3 Effects of Railcar Movement

As displacement data become available from various instrument systems, they are reviewed for effects caused by sources other than thermal expansion or rock movement. One potential source of offsets or discontinuities in the data that has been considered is the movement of the railcar. Apart from removal and replacement effects described in subsec. 11.1.2, vibrations and increased loads caused by movement of the railcar conceivably could trigger

Table 11-4. Errors produced by instrument removal and replacement.

Instrument	Fuel emplacement (μm)			Fuel exchange (μm)	
	Cycle 1	Cycle 2	Cycle 3	January 81	October 81
CWE061	-118	8	-282	- 30	112
062	-23	-46	-122	-234	119
071	92	N/A	N/A	29	-55
072	74	-54	102	-46	105
081	16	-87	-147	159	96
082	1	167	37	-151	95
091	-169	-109	-238	19	29
092	93	-36	45	5	-50
101	-98	-82	-174	53	-37
104	N/A	N/A	N/A	-48	34
111	-95	-82	-39	-22	-57
112	15	52	-86	-33	-180
THE002	N/A	N/A	N/A	-64	285
THE003	N/A	N/A	N/A	171	-688

the small slip-stick rock deformations detectable by some of the instrument systems.

The railcar moved several times during changeout of spent fuel canisters in January and October of 1981. Thermally corrected TX and Whittemore gauge data and uncorrected FMS data were scrutinized for effects attributable to use of the railcar. In no cases were there changes in data values, which could have resulted from the transient loadings of railcar activity. Although the TX and Whittemore gauge data did change during the time periods of interest, the changes were all well within the range of those stemming from instrument operator effects.

11.1.4 Effects of Changes in Ventilation Rate

The thermal regime of the SFT-C has been described in Chapters 6 through 8. Chapter 8 in particular described the ventilation system and its

effects. Because of the removal of large amounts of heat from the SFT-C facility by the ventilation system, variations in ventilation rate cause corresponding variations in the temperatures of many of the instruments measuring rock displacement. This is particularly significant for those instrument components exposed to airflow within the drifts.

The ventilation system air flowrate, temperature, and humidity are monitored frequently, as are the remotely read displacement instruments. Planned decreases in the ventilation rate result in a noticeable rise in air temperature. The temperatures of the affected instruments are measured to enable thermal correction of the displacement data. The effects of ventilation rate changes should, therefore, be obvious in the uncorrected data, but not in the corrected data. Although no plots have been constructed containing both uncorrected and corrected data for--say--the tape extensometer, deviations apparently caused by ventilation rate have been noted in plots of uncorrected data as a function of time. Some of these will be pointed out in Sec. 11.2 of this chapter.

11.1.5 Operator Variability and Other Sources of Error

As was presented by Yow and Wilder (1981), measurements made with the tape extensometer are carried out by more than one individual. Rock displacement data from this device are subject to an average variation of ± 0.05 mm, based on the ability of a given operator to repeat his own measurements. Enough readings have been made to allow the influence of various individuals on the data to be compared. Measurements including different operators are subject to ± 0.10 -mm average variation. This variation is small in proportion to the total magnitude of the displacements measured with this device. The horizontal measurements in the heater drifts would constitute an exception, since these have recorded extremely small displacements. The effects of operator variability in the Whittemore gauge data have not yet been fully analyzed, but a preliminary inspection of the data indicates that effects are also small in comparison to the magnitude of displacement data from this instrument.

11.1.6 Adjustments in Tape Extensometer Data

Two sets of adjustments are routinely made to the tape extensometer data during data reduction procedures. The first set corrects the data for

replacement of the steel tape, which took place in November 1980 (Yow and Wilder, 1981). The second set of adjustments is applied to 15 of the 32 tape measurement stations to account for problems with tape anchor points in early measurements. These problems, for the most part, consisted of loose anchors and resulted in displacements being erroneously indicated by the data. The second set of adjustments is meant to eliminate these erroneous displacements from data used for analysis and comparison.

11.2 COMPARISON OF MEASURED AND CALCULATED DISPLACEMENTS

Section 11.2 is divided into three subsections. Subsection 11.2.1 describes the displacement data obtained with the CWE and tape extensometer (TX) measurements, and compares the available corrected data with calculated convergence values. Subsection 11.2.2 describes the data obtained with the GxE and MBI rod extensometer systems, and also compares available data with the calculations. Subsection 11.2.3 presents data obtained with the FMS and Whittemore gauge measurements.

In conventional geotechnical practice, analysis of rock displacement data typically includes plotting displacement as a function of the time elapsed since instrument installation or commencement of the measurement program. Analysis of SFT-C rock displacement data is somewhat different in that displacements are plotted as a function of the time since the spent fuel was removed from the reactor core, expressed as years out of core (YOC). This is necessary because the thermal load causing displacement varies continuously as the fuel decays, requiring that data be referenced to some specific starting time on the fuel decay curve. For the SFT-C this starting time was 2.46 YOC.

Calculations of the spent fuel repository response were made with finite element codes, primarily the ADINA stress analysis code and the compatible ADINAT heat flow code. The primary purpose for this was to provide calculated results based on the best available estimates of physical and mechanical properties and in situ stresses in the Climax stock granite. The calculated change in stress field and accompanying displacements from the thermal load are to be compared with data obtained by measurements. Although the existing jointing in the rock mass could have a significant effect on the actual displacements and stress field, such effects are not accounted for here since joint models have not yet been incorporated in ADINA. The calculations were two-dimensional plane strain using the isotropic thermal-elastic model

available in ADINA, and were representative of the middle portion of the three-drift experiment. A temperature-dependent thermal-expansion coefficient based on laboratory measurements was used for the rock.

The ADINAT thermal calculation used a power level for the spent fuel based on calorimetry measurements of 1530 W at 2.46 YOC at the start of the calculation. This is the date (May 6, 1980) by which the first half of the spent fuel canisters were emplaced in the drift. ADINAT was adapted to model internal radiative heat transfer within the drifts, as well as effects of ventilation (Butkovich and Montan, 1980). Compatible ADINA calculations using an elastic modulus of 27 GPa throughout the finite element mesh (both with and without a 0.5-m-thick excavation-damaged region surrounding each drift) are used for comparison with data. The excavation-damaged region had a reduced modulus of 13 GPa to account for the effect of explosive damage during excavation. These values of modulus are based on in situ measurements and are average properties of the Climax stock rock. The details and results from these calculations are reported in Butkovich (1981).

11.2.1 Drift Deformations from Calculations and from CWE, THE, and TX Measurements

The height and width of the SFT-C tunnels are monitored for convergence or divergence at 16 stations (Fig. 3-12). Six of these stations are in the canister drift and five are in each heater drift. Changes in the entire width of the SFT-C facility are monitored at two THE stations, also shown. The CWE and THE measurements are read remotely at regular intervals by the data acquisition system, while tape extensometer readings are made manually at roughly one-month intervals. Complete details of the instrument systems, including an error analysis of their use, will be presented in future reports.

Thermal correction of CWE and THE data has not been possible thus far because of the complex temperature regime to which the instruments are subjected. Temperature-corrected data from these two systems are not yet available for analysis, but will be presented in the next report of this series. TX data are available for use in the interim, but it should be kept in mind that the TX temperature corrections are approximations. This is because temperature is determined at only one point on the instrument during each reading. Furthermore, the manufacturer's claimed accuracy for the instrument of ± 0.003 in. translates into a possible data variation of as much

as ± 0.08 mm. This is probably most of the ± 0.10 mm difference noted between operators (Yow and Wilder, 1981).

Figures 11-1 through 11-6 show displacements monitored from the start of the TX measurement program. The displacement values on each plot are related to zero (which was assumed at the time measurements commenced). Convergence at the station being measured is indicated by negative values of displacements, and divergence by positive. The plotted data have been modified by temperature corrections and appropriate adjustments, which were described in Sec. 11.1. The relatively large vertical offsets and "seesaw" effects seen in the plots reflect the influences of different operators making readings on the same or consecutive days. No attempt has been made to smooth the data by means of curve-fitting or other techniques.

The level of accuracy of the TX data and the lack of TX data during the first few weeks of the test preclude the definite recognition of end effects of the type that might be expected at stations near the ends of the drifts.

Figure 11-1. North heater drift vertical tape extensometer data.

Figure 11-2. North heater drift horizontal tape extensometer data.

Six data plots (which average measurements of like orientation within each drift) are used for comparison with the calculations. As these plots were prepared, the TX stations in the receiving room were omitted because of their proximity to apparently significant known faults in the receiving room. TX stations at the northwest end of the south heater drift were also omitted because of their location at the curved end of the south heater drift.

Station-by-station comparisons of TX-measured displacements have not been made due to the level of accuracy of the data. However, general trends in the data beginning about 2.6 YOC are noteworthy. All vertical TX measurements indicate convergence of the crown and invert of each drift. The horizontal TX measurements in both heater drifts indicate displacements ranging from essentially zero to a very slight divergence of the drift walls. The horizontal canister drift measurements indicate an increasing net closure of the drift from the thermal load.

Figure 11-3. Canister drift vertical tape extensometer data.

The heater drift measurements indicate that closure is still slowly continuing, while the canister drift readings indicate a reversal in the closure. This reversal was caused by vertical motion of the canister drift floor as it initially expanded away from the thermal sources in the rock below. As the zone of rock affected by the heat expanded, the drift crown also moved away from the source, but at a somewhat slower initial rate. The movement of the crown eventually became sufficient to reverse the trend of increasing closure about 3.0 YOC, even though the floor continued to rise. The trend toward decreasing convergence appears to have abated at about 3.9 YOC, but further data will be required to verify this.

Tape extensometer records of the drift closures are compared with the calculated displacements at the floor and ceiling centerlines and at the midheights of the walls in each drift. The calculation used in this comparison is that which included no explosive damaged region. In other words, the modulus is 27 GPa throughout the finite element mesh because prior

Figure 11-4. Canister drift horizontal tape extensometer data.

Figure 11-5. South heater drift vertical tape extensometer data.

to instrument installation, damaged rock was scaled from the walls to ensure sound instrument anchorage. Figures 11-7 and 11-8 show the average of measurements of horizontal and vertical closure of the canister drift as a solid line. Measurements were begun on June 26, 1980 (2.6 YOC). The calculational result zero was adjusted for this time, and shows closure from the beginning of the calculation out to 4.0 YOC. Figures 11-9 and 11-10 show a similar comparison for the south heater drift, and Figs. 11-11 and 11-12 for the north heater drift. In each case, the calculational results and data track each other. For cases where the data indicate closure continuing throughout the total time of record, the calculational results also show this effect. Where the data show closure followed by dilation, the calculation shows this effect as well. In general, the agreement between measurement and calculation is quite good, although the measurements in the canister drift suggest that the field-measured modulus of 27 GPa may be somewhat low.

Figure 11-6. South heater drift horizontal tape extensometer data.

Figure 11-7. Horizontal measured and calculated canister drift convergence.

Figure 11-8. Vertical measured and calculated canister drift convergence.

Figure 11-9. Horizontal measured and calculated south heater drift convergence.

Figure 11-10. Vertical measured and calculated south heater drift convergence.

Figure 11-11. Horizontal measured and calculated north heater drift convergence.

Figure 11-12. Vertical measured and calculated north heater drift convergence.

11.2.2 Rock Deformations from Rod Extensometer Measurements and Calculations

While the CWE and TX measurements record the deformation of the SFT-C drifts with time, multiposition borehole extensometers record the deformation of the rock below the canister drift floor and between and above the drifts. Two sets of rod extensometers--the GxE series and the MBI series--are installed at selected locations described in Chapter 3 and shown in Figs. 3-9 through 3-11. The temperature correction routines are not yet operational for any of the rod extensometers, but hand-calculated corrections of selected MBI data have been made and are discussed below. The operational status of these instruments is covered in Sec. 11.3 of this chapter.

Displacements from the thermal loads were measured with rod extensometers emplaced to measure relative displacements between hole collars and anchor points in holes drilled from the north and south heater drifts during the mining of the canister drift. These instruments were emplaced in the pillars between the drifts in horizontal holes and in holes inclined at 34° and 50° upward from horizontal at two stations. Temperatures are monitored with thermocouples emplaced near each anchor point in separate boreholes. Temperature corrections for the expansion of the extensometer rods and associated components were made for each anchor position for the comparisons described below. Since these displacement measurements were not available from before 3.0 YOC, all the relative displacements are referenced to 3.0 YOC. Figures 11-13 through 11-15 show the positions of the extensometers superimposed on the finite-element mesh. Displacement vectors for each node in the vicinity of the excavations are shown at 3.0, 3.5, and 4.0 YOC. The node displacements at 3.0 YOC are taken as zero. Therefore, only the effects due to thermal load are indicated,

The temperature corrections needed in the MBI data were, in every case, a factor of 2 and, in some cases, many times larger than the magnitudes of the recorded displacements. This is because the MBI coefficients of expansion are so similar to that of the rock, that both rock and instruments expand nearly the same amount under a given thermal influence. As a result, the rock displacements indicated by corrected MBI data contain a large component from the expansion of the instrument, a small component reflecting the difference between rock and instrument expansion coefficient, and a third component due to inelastic rock response.

Figure 11-13. Orientation of MBI extensometers and FEM mesh nodes.

Figure 11-14. Orientation of MBI extensometers and FEM node displacements at 3.5 YOC.

Figure 11-15. Orientation of MBI extensometers and FEM node displacements at 4.0 YOC.

Comparisons between temperature-corrected relative displacements from the hole collars in the heater drifts and the calculated relative vector components projected to the extensometer anchor positions were made. The calculation that was used for comparison in this case included the damaged zone around each excavation. Figures 11-16 and 11-17 show the calculational result compared with measurements made since 3.0 YOC at Station 2+83 for times 3.5 and 4.0 YOC, respectively. Figures 11-18 and 11-19 show similar results for these times at Station 3+45. The upper number at each indicated anchor point is a corrected data value and the lower is the corresponding calculated value. An "n.a." in place of a numerical value indicates that the data are missing. In general, the magnitude and direction of the displacements agree quite well. Where comparisons can be made, the agreement of calculations with data is quite good, except for the region immediately above the canister drift.

Generally speaking, the displacements recorded indicate lateral expansion of the pillars between drifts, and upward expansion of the rock between and above the drifts as it is heated. The temperatures within the rock are not uniform, so the deformations were not expected to display a uniform linear distribution along the length of each extensometer. However, the data contain irregularities in the displacements beyond those expected solely from a

Figure 11-16. Relative rock displacements at station 2+83 between 3.0 and 3.5 YOC. Upper numbers measured, lower numbers calculated.

nonlinear temperature (and rock expansion) distribution. Complete correlation of these variations with known shears and other extensive discontinuities has been unsuccessful. At this time it seems clear, though, that deformations detected by successive anchors along each extensometer are influenced by the discontinuities. Problems in correlation may result at least in part from the difficulty of assessing the relative significance and the continuity of the fractures within the rock mass. Blast-induced damage may also complicate interpretation; this may contribute to the relatively large deformations recorded by anchors immediately above the canister drift crown, for example. As more complete MBI data become available, comparisons with tunnel convergence (TX, CWE, and THE) data will be made, and the correlation of displacements with geologic structure further examined.

Figure 11-17. Relative rock displacements at station 3+45 between 3.0 and 3.5 YOC. Upper numbers measured, lower numbers calculated.

Figure 11-18. Relative rock displacements at station 2+83 between 3.0 and 4.0 YOC. Upper numbers measured, lower numbers calculated.

Figure 11-19. Relative rock displacements at station 3+45 between 3.0 and 4.0 YOC. Upper numbers measured, lower numbers calculated.

11.2.3 FMS and Whittemore Gauge Measurements

Most displacement instruments at the SFT-C monitor integrated rock displacements, including movement of the rock mass as well as movement along discontinuities within the rock mass. The FMS and Whittemore gauge data, however, reflect movement on selected discrete fractures in the rock and in the concrete floor of the canister drift, respectively. FMS locations are shown in Fig. 3-12. No FMS data have been corrected for temperature effects although these corrections will be made as soon as possible. No further discussion of FMS data will be included here, except to say that the instruments appear to be functioning correctly and are recording displacements on the order of up to 0.1 mm.

The Whittemore gauge is being used to monitor displacements on discrete fractures at six locations in the concrete floor of the canister drift. The fractures monitored were reported here last year as radial features fanning out from canister emplacement holes. In the months since the fractures were

first noted, extension of the fractures continued until cracks originating at adjacent holes intersected. Cracking continued even after the original features coalesced, and the character of the cracking, as it now appears, gradually changes from a radial pattern in the immediate proximity of each hole to a roughly rectangular pattern in the middle of the between-hole intervals.

Figures 11-20 through 11-25 show the change in crack aperture with respect to YOC for each of the six measurement stations. Although operator effects have not yet been analyzed for the Whittemore gauge, some of the "seesaw" effect and all of the vertical offsets seen in the plots are results of differing instrument operators. Positive displacements represent opening of the crack since commencement of measurements, and negative displacements indicate closure. Shear movements along each crack are not illustrated, but are usually less than half the magnitudes of the aperture movements. In all cases some unknown amount of opening was missed before the initial gauge

Figure 11-20. Whittemore measurements--aperture vs time (0102).

Figure 11-21. Whittemore measurements--aperture vs time (0203).

readings were made since the cracks had already formed before the measurements were started. Three of the cracks (Figs. 11-20, 11-22, and 11-23) show a distinct continued opening or widening trend with time, while the other three do not.

All of the plots show some closure at about 3.3 YOC and again at about 3.7 YOC. These correspond to periods of time when drift ventilation was at a significantly reduced rate and drift air temperature was correspondingly higher. The associated near-surface temperature increase of the concrete floor produced a temporary small closure of the cracks. The overall long-term behavior of the cracks, which reoccurred when the normal ventilation rate was resumed, seems to result from material expansion below the immediate floor surface, and probably represents both heave (or rise) and lateral expansion in the invert.

Figure 11-22. Whittemore measurements--aperture vs time (0506).

11.3 SUMMARY OF INSTRUMENT COMPONENT FAILURES AND REPAIRS

Two classes of component failures have been observed in the displacement-measuring devices. The first, and by far the most serious, is failure of linear potentiometers in the G-series rod extensometers. The second is loss of anchorage pressure in these same units. Other minor problems have occurred that have affected one or two instruments of each type. The latter problems are documented in project quality assurance files, but are not discussed here.

Figure 11-23. Whittemore measurements--aperture vs time (1415).

11.3.1 Failure of Linear Potentiometers

11.3.1.1 Summary of Potentiometer Failures. Computer-recorded readings of relative displacement at one extensometer (GCE023) began to be significant in late-August 1980 (Fig. 11-26). The recorded displacements caused no concern since they were "reasonable" by at least three criteria. First, they were in the correct direction for early-time displacements since they reflected relative compression between the anchor point and the head assembly, as well as thermal expansion and upward motion of the rock near the anchor. Second, they were in the range of expected displacements. Third, they were following a familiar S-shaped response curve.

Figure 11-24. Whittimore measurements--aperture vs time (1516).

Early in September, routine monitoring showed other units (GCE014, GBE013, GCE033, and GCE063) responding in similar fashion. Apparent displacements became large enough (over 5 mm) to cause concern and a field inspection of these units took place. This inspection revealed that, although the data acquisition system was recording voltages indicating displacement of several millimetres, the potentiometer shaft had not moved relative to the potentiometer body. In all, 23 of 56 (41%) of the linear potentiometers on the G-series extensometers failed.

Voltage measurements at the instrument head revealed that the problem was located there and not in the DAS hardware or software. A further set of voltage measurements and confirming resistance measurements indicated that the resistance of the potentiometers was changing in a nonlinear manner with time.

A series of field and laboratory tests were then undertaken, which indicated the possibility of chemical vapor action on the potentiometer resistive element (Patrick, Carlson, and Rector, 1981). Based on this assessment, the head assembly covers were removed to vent such vapors.

Figure 11-25. Whittemore measurements--aperture vs time (1617).

Figure 11-26. Example data showing failure of G-series extensometer (after Patrick, Carlson, and Rector, 1981).

Replacement Bourns potentiometers were then ordered, received, and calibrated at EG & G-Atlas facility. About two weeks later (prior to fielding), a sample of the replacement units was checked for total resistance (RT) and several were found to be out of specification. In all, 21 of the 64 replacement units (or 33%) failed; all with linear changes in RT.

A second series of laboratory tests and close interaction with Bourns personnel ensued. Failures were found to have large, linear changes in RT-- a marked difference from earlier nonlinear failures observed in the field.

11.3.1.2 Potentiometer Evaluations. In assessing the cause of both the nonlinear and linear failures (in the original and replacement G-series potentiometers, respectively), we developed a failure analysis matrix (Table 11-5).

It is evident that most of the factors considered are present in both failed and functioning units. Seven failure hypotheses were considered (Patrick, Carlson, and Rector, 1981):

1. Failed units were from a bad batch.
2. The cause of failure was introduced in the calibration laboratory.
3. Electrical damage was caused by overpowering the units.
4. Dithering produced excessive wear to the resistive element.
5. Shock-loading by explosives damaged the units.
6. Higher downhole temperatures caused the sealing agents to cure, producing chemical vapors that damaged the resistive elements.
7. Hygroscopy of the resistive element produced the observed changes in resistance.

The evaluation of the observed failures included field resistance measurements, gas sampling, hygroscopy studies at low pressure and elevated temperature, microscopic textural inspections, and chemical interaction tests. These evaluations are documented in Patrick, Carlson, and Rector (1981). Although these investigations led to elimination of several possible causes of failure, a totally satisfactory answer to the problem has not been found to date.

11.3.1.3 Remedial Actions. We decided to revise our original decision to install only "off-the-shelf" instrumentation (Brough and Patrick, 1981) to correct the problem of the failed potentiometers. A period of instrument evaluation is now planned for the remaining life of the SFT-C. We based our

Table 11-5. Potentiometer failure analysis matrix.

Condition	Unit location				
	GxE	GxE replacement	CWE	FMS	MBI
Current status	Nonlinear changes	Linear changes in RT	OK	OK	OK
Status on receipt	OK	OK	OK	OK	OK
Calibration performed by	EG&G	EG&G	LLNL	LLNL	Terrametrics and EG&G
Date code No.	3578,3978, 4078	1780,4480, 4880,5280, 0581	0680	0680	3478,3578, 3678,3978
Orientation	+90° (vert.)	0 (horiz.)	+90°	+90° (various)	0,-33° -50°
Transducer temp (°C)	25-32	23-27	25-32	25-32	25-32
Instrument temp (°C)	40-60	N/A	25-32	25-32	25-32
Transducer enclosure	O-ring sealed	None	None	None	Some O-rings sealed
Shock and vibration	Infrequent (<0.1 g)	0	Infrequent (<0.1 g)	Infrequent (<0.1 g)	Infrequent (<100 g during excavation)

change of philosophy on three facts. First, since the cause of the potentiometer failures has not been definitively established, it seems prudent to install several instrument types to minimize the likelihood of further massive failures. Second, installation of several instrument types would facilitate evaluating the relative performance of the selected instruments. Third, judicious choice of alternative transducers would not degrade the quality of acquired data and might even improve the quality.

These three considerations led to selection of four transducers to replace the 48 GBE- and GCE-series units, where all failures have occurred to

date. Each group of three extensometers received one type of transducer. Bourns Model 5184 rectilinear potentiometers were reinstalled in GBE24x, GBE25x, and GBE26x. Vernitron Model 113 rectilinear potentiometers were installed in GCE24x, GCE25x, and GCE26x. Schaevitz Model 250HCD linear variable differential transformers (LVDT/DCDT) were installed in GBE21x, GBE22x, and GBE23x. Kaman Model KD-2310-6U electromagnetic proximeters were installed in GCE21x, GCE22x, and GCE23x. Table 11-6 summarizes the characteristics of the selected transducers. Each of the three alternates compares favorably in several ways with the original Bourns potentiometers.

We had observed in previous installations that some nonconcentricity existed between potentiometer shafts and the rods to which they were coupled. This condition introduces side loading which causes binding of the shaft and body of the potentiometers. This phenomenon may be responsible for some of the "stick-slip"-type motion observed in the rod extensometers. During replacement operations, a modification was introduced to circumvent this problem. All screw couplings of potentiometer and DCDT shafts to rods were replaced by spring loading the shaft against a flat smooth stainless-steel fitting attached to the rod. A stainless-steel sphere screwed onto the shaft provides a point contact against the stainless steel, machined flat surface attached to the rod. This modification was implemented on both potentiometer types and on the LVDT. The proximeter is a noncontacting device that utilizes a 19-mm-diam $\times$ 6.4-mm-thick aluminum target attached to the rod. These modifications are expected to enhance the quality of the acquired data.

Another modification was to subject each of the head assemblies associated with the Bourns, Vernitron, Schaevitz, and Kaman transducers to three different environments. The three selected environments were 1) sealed with an O-ring on the cover of the head assembly; 2) flushed with dry nitrogen; and 3) ventilated of potentially harmful vapors with a small vacuum. Should further transducer failures occur, the different environments should provide new data on potential causes of failure.

As an added precaution, all Vishay precision resistors were replaced with hermetically sealed units. This change was implemented in response to the two observed failures.

Prior to installation, all transducers were laboratory-calibrated. All refurbished rod extensometers were calibrated in situ in accordance with established procedures (Brough and Patrick, 1981). Because of the shorter range of the Schaevitz and Kaman transducers, these units were calibrated in

Table 11-6. Summary of replacement transducer characteristics.

Parameter	Bourns Model 5184	Vernitron Model 113	Schaevitz Model 250 HCD	Kaman Model KD-2310-6U
Case diam (mm)	12.7	12.7	19	19
Case length (mm)	90	60	104	25
Power supply (Vdc)	10	10	± 15	± 12
Range (mm)	25	25	± 6	± 3
Resolution (μm)	2.5	2.5	0.6	0.6
Linearity (% full scale)	± 1.0	± 0.1	± 0.25	± 0.50
Hysteresis (% full scale)	0.1	0.1	0	0
Stability (% full scale)	N/A	N/A	0.125	$\pm 0.01/\text{mo}$
Temp/coefficient ($\mu\text{m}/^\circ\text{C}$)	N/A	N/A	< 4.8	< 2.4
Actuation force (g)	570	230	0	0
Temp range ($^\circ\text{C}$)	-30 to 80	-55 to 125	-55 to 95	0 to 55

0.5-mm steps over a range of 2.5 mm, rather than in 1.0-mm steps over a range of 5.0 mm.

11.3.2 Loss of Anchorage Pressure

The near-field (G-series) rod extensometers utilize a nitrogen over hydraulic fluid system to maintain stable anchor pressure. At approximately one-month intervals the pressure of each anchor is checked for conformance to a 1750 ± 50 -psi criterion. Addition or release of nitrogen is used to adjust the observed pressure to the acceptable range.

Pressure decreases may be due to system leaks, continued deformation of the anchor in the borehole, or differential expansion of the borehole relative to the anchor. Pressure increases are generally thought to be due to thermal expansion of the hydraulic fluid and differential contraction of the borehole relative to the anchor.

To date we have found that about 45% of the G-series anchors have required no adjustment, 25% have required anticipated minor adjustments, and 30% have required major adjustments. No one problem appears to be responsible for the pressure losses in these latter units. Leaks have occurred in pressure gauges, fittings, expansion chamber components, and the downhole system. Problems in the downhole components cannot be repaired.

Although we have not performed anchorage tests at LLNL, the manufacturer claims that pressure loss does not adversely affect the extensometer performance, provided that full anchorage pressure was obtained during installation. Note that the common installation technique is to pressurize the anchor until the plastic inflation line bursts and a check valve is set. In this case, the anchor pressure is unknown and may often be less than optimum.

12.1 BACKGROUND

A potential repository monitoring method, which possesses the natural advantage of concentrating expected long-term effects into less frequent, yet much larger, transient effects, is based on the observation of acoustic emission (AE) or microearthquake (ME) phenomena. Differing only in time and distance scales (AE involves kHz frequencies and cm distance; ME involves Hz and km), both phenomena represent strain relief through discrete faults or failure events within the respective media. There are well-established methods (Johnson, 1979) in ME seismology for locating and describing the nature of such sources of elastic wave radiation. With proper scaling, these methods might be applicable in investigating AE events from an underground repository. The current study addresses the applicability of ME seismology techniques to AE in monitoring the integrity of an underground waste repository.

Few studies of this scale on seismic activity have been reported. One such experiment at the Stripa iron ore mine in Sweden was conducted by the Lawrence Berkeley Laboratory (LBL) of the University of California and the Swedish Nuclear Fuel Safety Agency (KBS). It employed electrical heaters in granite to study thermal stress effects. AE studies were begun well after the heaters were turned on and only one sensor was used. However, considerable AE activity was still observed during the later stages of the heating phase, and activity increased during the initial stages of the cool-down period (Paulsson et al., 1980).

Two mechanisms are generally thought to be responsible for AE activity induced by heating: the contrasting thermoelastic behavior of different minerals within the rock and the thermal gradient effects. Yong and Wang (1980) investigated AE from air-dried Westerly granite at atmospheric pressure and over the temperature range 20^o to 120^oC. An abrupt increase in AE was observed at a threshold temperature of approximately 70^oC. Yong and Wang found that above this threshold temperature the rate of AE depended strongly on the rate of heating.

In further experiments, Yong and Wang compared AE from specimens of air-dried and water-saturated Westerly granite. The rate of AE in a dry

specimen was observed to be higher than for one that had been water-saturated at the same temperature and heating rate. This behavior was attributed to differences in thermal gradient within the specimen (the thermal gradient being smaller in the water-saturated than the dry specimen).

It is not known what mechanisms will predominate in a scaled-up version of these heating processes. Differential thermal expansion will undoubtedly be important. The scale on which this will occur, however, remains unclear, although King and Paulsson (1981) have observed the same effect on a heated block of granite 300 mm x 300 mm x 600 mm during acoustic velocity crosshole experiments at the Stripa mine. Finally, uneven cooling due to partial water saturation of heterogeneous material may also play an important role in the fracture process.

12.2 SEISMOLOGICAL REPOSITORY MONITORING

Over the past 15 years, seismologists have paid considerable attention to detailed source descriptions (Johnson, 1979). Both static and dynamic source characterization have been addressed in the literature. Of the static descriptions, the semiempirical approach of Brune (1970, 1971) is the most widely applied. In this method, three independent source parameters are estimated from the frequency spectrum of either the compressional or shear wavetrain. Brune hypothesizes that the low-frequency level of the spectrum is a measure of the strength, or seismic moment, of the source, and that the high-frequency character is determined by the source dimension. Two events with identical low-frequency levels, but differing high-frequency content would imply different stress drops. Pollock (1980) reports application of spectral analysis to the field of acoustic emission. Efforts to date appear to have aimed towards defining various AE source processes from the frequency content of the signals. Jax (1974) reported that even sources with a frequency content as high as 500 kHz showed a correlation between material properties and source duration. Wolitz et al. (1978) have been able to categorize types of fiberglass failure from spectral content. Spectral data have also proved useful in discriminating signals from noise, and in studies of plastic vs brittle deformation (Pollock, 1980).

Other techniques used in earthquake studies include the fault plane solution (Byerly, 1928) and "b-value" determination. AE studies appear generally to have ignored the fault plane approach to determine the principal

stress direction and geometry of the fracture plane. However, AE researchers have employed b-value studies ($\log N = a - bM$; where N = cumulative number of events and M = magnitude of events) to infer particle size and ductility of material (Pollock, 1980). On the other hand, earthquake studies using the b-value to characterize the failure mode have generally concluded that the b-value appears to vary with the distribution of the applied stress field and with the homogeneity of the material (Mogi, 1962; Scholz, 1968; Wyss, 1973).

Several different stress field perturbations will exist for the AE experiment described here and for monitoring AE within a nuclear waste repository. The already heterogeneous tectonic stress field will be affected by the mine geometry. Thermal effects (including those due to cool water seeping into previously heated areas) will superimpose additional stresses. Radiation degradation and heterogeneity of the rock mass may provide other factors influencing failure rates and mechanism. The Climax AE experiment is designed to isolate these factors, if possible, and to estimate their relative significance.

We intend to correlate the AE results with the available stress, displacement, and temperature data to infer fracture and material properties. The location and size of events relative to the stress perturbations will influence future repository design with respect to the spatial density and configuration of canister holes and mine openings. Analysis of the manner and rate of energy release will contribute to our evaluation of granite as a repository medium.

In addition to the questions already addressed, there remains that of overall mine stability and safety. The use of AE to predict failure in metals and alloys has met only limited success (Pollock, 1980). However, better results have been achieved from predicting rock bursts and roof falls in mines (Blake et al., 1974; Brady, 1978). Common methods applied in AE studies involve monitoring the variations in source locations, the number and amplitude of events, the time between events, event duration, energy release, and spectral content. By far the most widely used of these techniques have been event location and counting methods (Hardy and Leighton, 1980). This is mainly because the available equipment is incapable of handling the fast, on-line processing required for sophisticated real-time analyses. The principal aim of this study will be the characterization of the AE activity in more complete terms relative to the continuing physical process, using microearthquake methods scaled to the Climax experiment.

Table 12-1. Specifications for accelerometers and charge amplifier.

<u>Columbia 5002 accelerometer</u>	
Sensitivity	13 pcoul/g ^a
Freq. response	2 Hz to 10 kHz (<u>+5%</u>)
Resonant freq.	50 kHz
Capacitance	850 pF
Output resistance	2 10 ¹⁰ Ω
 <u>Columbia 9021 charge amplifier</u>	
Source impedance	Capacitive device (500 pF max)
Charge gain	100 mv/pcoul (40 dB)
Output impedance	125 Ω
Freq. response	1 to 10 kHz (<u>+5%</u>)

^a_g = acceleration of gravity.

12.3 GEOMETRY AND HARDWARE

The equipment selected to monitor AE activity includes accelerometers, charge amplifiers, and a 15-channel transient-waveform recorder system interfaced to a microprocessor-based automated seismic processor (ASP). The specifications of the equipment, the frequency response of the system, and a system diagram are listed in Table 12-1 and are shown in Figs. 12-1 and 12-2.

After consideration had been given to the frequency content of the background noise, the attenuation properties of the granite, and source dimensions of the expected cracking, we decided to concentrate on the 1- to 10-kHz frequency range. These frequencies correspond to source radii of the order of several centimetres, using Brune's static model. Although much higher frequencies will be generated by smaller fractures, they would remain undetected in the 50 × 20 × 10-m array employed in this experiment. The lower frequency was selected on the basis that sources larger than several metres in dimension would probably be too infrequent at the stress levels encountered 420 m into the subsurface. Furthermore, cultural noises are a problem at frequencies less than 1 kHz.

Figure 12-1. System response (acoustic emission sensor mounted on stainless steel plus preamplifier), obtained by placing the mounted sensor on a block of granite and pulsing the system for 1- μ s. The rock seems to act as an effective anti-alias filter. Units are in Hz and acceleration response is relative.

The accelerometers were mounted in 40-mm-diam stainless-steel stock. These assemblies were epoxy-cemented into the 48-mm-diam drill holes shown in Figs. 12-3 and 12-4. Those numbered AE1, 2, 3, 8, 9, 10, 11, 12, 17, 18, and 19 are shallow horizontal holes 0.3 to 0.6 m above the mine floor. Those numbered AE4, 5, 6, 7, 13, 14, 15, and 16 are inclined holes 6.5 to 7 m deep, drilled from the side drifts to a level even with the bottoms of the canisters. The deep holes numbered AE5, 6, 14, and 15 contain accelerometers. The one numbered AE13 contains a piezoelectric source for velocity and attenuation monitoring. In total, 15 accelerometers are installed to form a three-dimensional array centered on the row of canisters.

The amplified signals from the sensors are sent to the instrument alcove and digitized to 10-bit accuracy at 100,000 samples/s by the transient waveform analyzer. If the signal level rises above a preset threshold, a 4096-point data window is captured by the waveform analyzer and played back at

Figure 12-2. Total system showing the AE sensor (transducer), preamplifiers (mounted as close as possible to the sensor), transient waveform analyzer (Physical Data 515-A), and data handling device [either a tape recorder or the automated seismic processor (ASP)].

Figure 12-3. Plan view of Climax experiment showing waste canisters, heaters, and acoustic emission sensors. Signals from the AE sensors are hardwired to the instrumentation alcove.

Figure 12-4. Cross section of mine openings showing AE sensor locations in "deep" holes (dashed lines) and on the surface.

20 samples/s to a slow-speed, 14-channel tape recorder (frequency response dc to 40 Hz) or to the automated seismic processor at 200 samples/s. A triggering module monitors 8 of the 15 stations. If the signals of any 1 to 8 of these 8 selectable stations rise above a preset threshold, the event triggers playback at the reduced rate for the 4096-point data window on all 15 channels. Between events the raw data are sent real-time to the recorder and ASP. A visual monitor on one of the trigger stations provides a continuous record of events so that they can easily be located on the magnetic tapes. Except for the transient waveform analyzer, the system is identical to that used to monitor and record earthquakes. The waveform analyzer permits the scale-down from high AE frequencies to the much lower earthquake frequencies.

Unfortunately, when many events occur, full processing of the data becomes tedious, time-consuming and far too labor-intensive. A similar problem was encountered in applying passive seismic techniques to geothermal exploration (Majer and McEvilly, 1979). During that study, fully processing 100 events recorded at 12 stations required several months work. We, therefore, designed and fabricated an in-field processing and virtual real-time display of seismic event source parameters. This ASP is a microprocessor-based, parallel-processing computer. It is self-contained, low-power (CMOS, 1 W/channel), and capable of providing sophisticated data analysis, eliminating the need for peripheral data storage devices or computers. Basically, a set of real-time algorithms perform event detection, P- and S-wave timing, and amplitude functions. Then Fourier transforms are calculated and processed to determine source parameters for the events. The present modes of calculation are

1. Event count, number of events (from test initiation) that have met amplitude and occurrence criteria.
2. Event location, x,y,z,t, residuals.
3. Cumulative and interval b-values, for P- and S-wave amplitudes (maximum-likelihood method).
4. Source properties from spectral data, i.e., using dc level, corner frequency, and high-frequency slope to estimate the moment, source area, displacement, and stress drop.
5. First-motion polarity for fault plane solution.
6. Debug mode (all raw data are printed out).

A more detailed description of the ASP can be found in McEvilly and Majer (1982).

12.4 RESULTS TO DATE

Continuous monitoring of AE activity in the Climax stock began on January 11, 1980. Several experiments were carried out to obtain a velocity model for event location. Using a sledge hammer and a piezoelectric source at known distances from the sensors, we determined the velocities of P- and S-waves to be ~5.5 to 5.9 km/s and 3.2 to 3.6 km/s, respectively, for a Poisson's ratio of 0.20 to 0.25--a value consistent with the 0.21 measured by static methods on core samples (Carlson et al., 1980) and the 0.246 estimated from other field measurements (Heuze', et al., 1981). The in situ values are

averaged over a larger distance and, thus, include alteration zones, joints, and fractures that tend to reduce the shear modulus of the rock mass, whereas the laboratory value was measured on intact samples. Paulsson and King (1980) found similar values using cross-hole velocity methods for Stripa granite in Sweden. The accuracy of our velocity model for event location was tested by striking the rock at known sites and using the arrival times to locate the event. For sources near the mine floor, the accuracy of the locations appears to be about ± 1 m. For sources outside the array, the travel paths are obscured by the drifts and the location accuracy decreases significantly. Our interest lies, however, mainly in events induced by the heaters and canisters, which are all within the array. Our precision is a function of sample interval (10 μ s) and P-wave velocity. Assuming a point source, our basic distance uncertainty is $5.5 \times 10^5 \text{ cm/s} \cdot 10^{-5} \text{ s} = 5.5 \text{ cm}$. However, deviations from the homogeneous whole-space assumption in rock properties introduces the observed errors in location. We expect to achieve an accuracy of a few tens of centimetres by using repeated calibration sources and station corrections with the assumption that the velocity model is both time- and space-dependent.

12.4.1 Thermally-Induced AE Events

Figure 12-5 shows the rate of acoustic emission activity through May 1982. As can be seen, there was a background level of activity of two to three events per week prior to waste emplacement. The first recorded natural event (shown in Fig. 12-6) occurred approximately six days after monitoring began, before any heaters or canisters were installed. The event was located in the north pillar near AE 2, where a convergence-monitoring hole had just been completed. At this time, the preamplifier gains were 20 dB. After several weeks, the gains were increased to the present setting of 40 dB, resulting in an increase of detected events from one per week to two or three per week. Several features of the event in Fig. 12-6 are note-worthy. First is the signal character: it has an impulsive beginning, P- and S-waves are generated, and the first motion of the P-waves varies with azimuth. Were the scale in seconds, rather than milliseconds, Fig. 12-6 could be an average microearthquake as might be recorded over a seismograph network with dimensions of 10 to 20 km. These facts imply that the source theories developed for earthquakes can be applied on this scale for this particular

Figure 12-5. AE activity and temperatures from January 1980 to March 1982.

event. Assuming scaling laws apply to earthquake source parameters, the source radius of this fracture is of the order of several centimetres.

Since waste emplacement in April 1980, there have been several peaks in activity. The first peak in activity (around day 190, 1980) corresponded to the events called swarms. These events occurred at rates up to 10 to 15 h, but only once or twice per week. They are characterized by their emergent onsets, as illustrated in Fig. 12-7. These swarms are also all equal in magnitude, implying stress distribution and material properties under normal rock-type behavior. The swarms were located at shallow depths near the mine floor in the vicinity of canisters 11 to 15, possibly in the concrete. Later visual inspection revealed cracking in the concrete around the canister hole tops (see Chapter 11).

The second peak in activity (around day 230, 1980) occurred several months after emplacement. Unlike previous activity, these acoustic emissions were located beneath the mine floor between the canisters. These events were closer to "normal" rock fracturing events, having impulsive beginnings. Their

Figure 12-6. At top, an event near station AE2 in the Climax experiment. The amplitudes are all of equal gain, but have been shifted in time to demonstrate amplitude differences between stations equidistant from the source (AE11 and 9, AE1 and 3, AE14 and 15).

Figure 12-7. An example of a "swarm" type of event. Relative amplitudes and arrival times are correct.

distribution in space and time was also as would be expected of microearthquakes.

The third major peak in activity occurred in December 1980. These events were located in the north pillar between AE2 and AE11, near mapped fracture zones. They appear to be the result of stress released along the existing fractures. It is likely that these fracture events are a response to overall thermal loading of the repository region, although there had been only minor increases in temperature at the location of the events.

After the peak in activity in December 1980, there was a long period with surprisingly few events. This lack of activity may be due to the fact that the temperature was decreasing slightly near the canisters and that most of the transient effects had already occurred. The maximum rock temperature for this simulation of waste storage was 80° to 85°C on the borehole wall and 65° to 70°C 360 mm into the rock. Laboratory experiments indicate that acoustic emission activity does not begin for granite until ~70°C.

In recent months, this inactivity seems to have ceased. As can be seen in Fig. 12-5, there have been one to two events occurring per week. These events are located in the same vicinity as the swarm of December 1980, between AE sensors 2, 5, and 11. As noted earlier, this is near a known fracture zone and these events may be due to thermal stress release on preexisting

fractures. Also noteworthy in Fig. 12-5 is a fourth peak in activity. This 12-event sequence was located in the same area as the other events. Two interesting events occurred on days 14 and 15, 1982. They were nearly identical in size, both being the largest events recorded to date (see Fig. 12-8 for an example). Both these events were located in the center of the canister drift, 3 m beneath the floor near canisters 14 and 15. Figure 12-5 shows that the rate of one to two events per week is continuing. Thermal stresses generated by continuing thermal expansion of the granite as the heat pulse travels outward are apparently producing a stick-slip response on preexisting fractures.

During the initial monitoring period, several nuclear test explosions were fired at NTS, providing an opportunity to study the potential for induced fracturing within the SFT-C due to strong ground shaking. The ground acceleration estimated within the SFT-C is approximately 0.05 g. This would be considered strong motion in the context of an earthquake. There were, however, no AE events detected that were associated with ground motion from these explosions. This observation includes one test occurring after the spent fuel was emplaced and the heaters were energized. Indications are that repository integrity may be maintained despite fairly strong ground motion from nearby sources.

12.4.2 P- and S-wave Attenuation Measurements

The apparent attenuation characteristics for different paths of the P-waves' first cycle are also interesting. Referring to Figs. 12-1, 12-2, and 12-6, it can be seen that the amplitudes are not the same for stations AE14 and AE15, which are equidistant from the source. In general, it appears that amplitudes at AE15, 9, and 1 are smaller than those at AE14, 11, and 3. A mapped fracture zone cuts across the SFT-C and separates these six stations (Chapter 3). The stations with the larger amplitudes were on the same side of the fracture zone as the source. It is also interesting that most of the detected seismic events recorded to date have occurred roughly along this zone, although this may reflect the network having been set with maximum response in this central zone.

Since late October 1980, the wave propagation characteristics (travel time and amplitude) of the P- and S-waves have been monitored daily. These waves are created by a piezoelectric source set in the bottom of the

Figure 12-8. An example of one of the largest AE events near the canisters. Relative amplitudes and arrival times are correct.

water-filled hole AE13. There has been little change in the P- or S-wave velocities through the canister area (10- μ s accuracy in 2.8-ms travel time) during the monitoring period. However, the S-wave amplitude relative to the P-wave amplitude has increased significantly for travel paths through the heated zone, as shown in Figs. 12-9a and 12-9b. The cause is not known, but may be due to a change in water content in the heated zone or a change in the shear and bulk modulus of the rock matrix due to thermal expansion.

There have been fluctuations in the P-wave amplitudes relative to a reference station (AE19), but these changes have not been systematic and vary only by a factor of 2. All amplitudes were measured peak to peak on the first cycle only. It is interesting to note that, for path AE13 to AE5, the S- to P-wave ratio shows signs of returning to previous levels. This path is primarily through the canister region, perhaps reflecting a net decrease in temperature, which results in a decrease in S/P amplitude. Path AE13 to AE3 still shows an increase, indicating that this path may still reflect a net increase in temperature. This coincides with the known increases in guard heater power levels near AE3 (Chapter 4).

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Figure 12-9a. P- and S-wave amplitude changes up to day 285, 1981.

Figure 12-9b. P- and S-wave amplitude changes from day 285, 1981 to day 175, 1982.

CHAPTER 13

DATA MANAGEMENT SYSTEM

13.1 PROCESSING TECHNIQUE

Copies of data tapes are delivered approximately monthly to LLNL from NTS. Their processing follows an outline shown in Fig. 13-1. All data processing at LLNL is done on CDC 7600 computers.

The two main programs, BREAD and REVERT, need subsidiary data tables for decision-making and calculations. The BREAD interface file contains an up-to-date description of the licenses and data ranges expected on the tape. The file is in ASCII and is easily modified and printed by Livermore Time Sharing System (LTSS) utility routines. This feature requires that BREAD reload and expand the data into its tables as a first stage of each execution. However, it allows BREAD to respond to field modifications of both hardware and software. The REVERT table (HPDATABASE) originates as a system dump tape from the HP computer at NTS (Chapter 5). The table is in the same form as data tapes and must be translated in a similar manner. Several such tapes are merged. Additional data is added manually, as appropriate, to obtain a file in which all data is in CDC 7600 binary format, and easy to use as needed in the data reversion process. This master binary file is saved, and can be modified, reused, or printed by REVERT in subsequent executions. The compilation of this 100,000-word data base is the critical element in getting REVERT operational. This compilation is complicated by the fact that it must accurately describe the operating state of the instrumentation and DAS continuously over the three- to five-year duration of the SFT-C.

Since January 1981, BREAD has had five major revisions to incorporate features found to be needed as more experience was gained in processing SFT-C data tapes.

Since September 1981, REVERT has had two revisions; the second of which incorporates a major change in the way the HPDATABASE is made and used. Revised algorithms for the reconversions are included in this version. It is not completely operational as of the writing of this report, because the HPDATABASE is not complete and is required for final validation of REVERT operations.

To convert a raw reading of certain instruments into a temperature-corrected value in the desired units at a given time, REVERT must be able to

Figure 13-1. Block diagram of Data Management System.

find the reading during the same time as that of other instruments on which conversion depends (Chapter 5). This requires that the data file on which REVERT operates contain data from all instruments used in the conversions and be sorted in a monotonically time-increasing order (i.e., there must be no time overlap between files). Many of the tapes delivered to Livermore exhibit

some time overlap, and recently there have been two files for every time period: one for Node 100 and a separate tape for Node 200. This required development of an additional program MFAB (merge files ASCII to binary). MFAB is given a list of 1-3 ASCII file names and a time interval, and merges all data from that time interval on the three files into one binary file. In addition to the three ASCII files, MFAB can take as input one of its own binary output files. Thus the number of ASCII files that can be merged is unlimited. The first binary file made contains 10 ASCII files. The name of the final binary file is BXXXXXX, where the XXXXX is the last Julian day in the file. The files are created at Julian day boundaries. That is to say, integer Julian times are input to determine the time interval for data accumulation. The time interval is selected to produce a BXXXXXX file of just under 10^6 words.

SFIX was developed to correct two specific known problems in the early raw data.

1. For the first 20 days of the test (44311 to 44350 in Julian days) EMFs for thermocouples on Node 100 were recorded on tape in microvolts. All subsequent thermocouple readings are recorded in volts. The problem was corrected in the field toward the end of Tape SF005.
2. For the first 140 days of the test (Julian Day 44311 to 44451) thermocouples SGT011 and SGT044 were interchanged due to a wiring error. The correction was made between tapes SF016 and SF017, so fortunately, no tape has the data both ways.

SFIX multiplies raw TC data values prior to 44350 by 10^{-6} , changes all occurrences of SGT011 to SGT044 and vice versa. It was run on all files through SF016B/C (see Table 13-1).

An additional processing step has been added this year to accomplish the tasks of merging all data for each instrument into an individual file and of making available for analysis data that does not require reconversion before REVERT can become operational. This step requires that the SF (Spent Fuel) files put out by BREAD be read and rewritten by a program called UFO (Uniformly Formatted Output) to prepare them for the final matrix inversion. UFO produces two output files from each input file. The first is a uniformly formatted data file, sorted alphanumerically by instrument identifier and chronologically for each instrument. These are the input to the matrix inversion. The second file is a statistical summary of the former and are

Table 13-1. Summary of processed data.

File name	Time		No. data points			No. errors		
	Start	Stop	Copied	Discard	Total	TOR	VOR	License Channel
000A/B	44331.437	44569.498	30191	0	30191	--	--	--
002A/F	342.196	354.011	25393	11407	36800	0	144	39
003A/D	344.790	345.250	1692	2245	0	0	0	143
004A/D	345.389	346.967	11181	6548	17729	32	90	32
005A/D	346.960	351.929	26491	13114	39605	18	21	0
006A/D	351.914	351.917	37567	7027	44594	0	81	0
007A/E	357.845	358.507	7145	1636	8781	0	4	0
008A/D	358.485	360.566	8883	2427	17310	0	231	0
009A/E	359.926	361.134	17281	5971	23252	0	1451	0
010A/D	361.143	370.452	119807	45263	175070	0	54	0
011A/E	370.452	375.167	50161	18770	68931	0	44	0
012A/D	375.161	388.456	150312	57590	207902	0	141	0
013A/D	388.196	409.271	159424	58090	217514	0	300	33
014A/E	409.266	416.590	91569	28941	120510	0	73	196
015A/D	416.590	421.242	45953	14735	60688	0	28	67
016A/D	421.246	438.653	182950	68700	251650	0	108	409
016B/D	438.648	451.121	138409	52772	191181	0	79	320
017A/C	451.107	467.378	178892	68629	247621	0	50	0
017B/C	467.161	474.286	72545	23302	95847	3	10	0
018A/F	474.278	490.198	154345	56843	211188	6	35	220
019A/C	490.193	501.576	118107	40305	158412	0	58	24
020A/B	501.563	513.328	97757	48058	145815	0	7	21
021A/B	513.321	526.480	156160	69170	225330	0	2	0
022A/B	526.478	541.537	172533	64458	236991	0	5	0
022B/A	541.532	550.332	115831	73133	188964	0	4	0
023A/B	550.252	562.241	113601	50159	163760	0	24	161
024A/B	557.484	576.247	72573	31718	102071	0	38	2
025A/C	529.807	590.272	104444	31095	135539	0	60	39
026A/C	577.327	610.263	84131	117970	202101	0	13	8
027A/C	610.564	618.247	40686	203970	244650	12	8	84
028A/C	618.247	632.397	84205	165522	249727	2	16	204
029A/C	632.368	651.453	88284	164419	252703	0	11	12
029B/C	650.669	661.224	30935	53536	84471	0	26	13
030A/C	650.339	686.127	90861	157447	248308	1	7	3
030B/B	686.067	695.245	45207	95148	140355	0	4	3
031A/C	695.350	705.889	48884	43058	91942	14	186	19
032A/C	703.304	722.290	78070	80297	158367	3	8	102
033A/C	722.617	781.117	124320	108318	248159	1	37	1
034A/B	722.271	772.087	141038	108318	249356	0	79	11
034B/B	772.087	781.122	22451	20664	43115	0	2	1
035A/C	781.126	801.610	72433	56439	128872	0	22	1
036A/C	781.122	802.173	45460	54589	100049	0	286	3
037A/B	802.184	826.246	125763	122361	248124	0	6	3
037B/B	826.180	842.202	60618	60467	121085	0	5	184
038A/C	837.205	852.215	59890	51625	111515	1	2	1
039A/B	852.223	873.582	106996	129470	236466	0	12	206
039B/B	873.582	890.343	139520	72851	212371	1	28	28
040A/A	890.566	905.159	65577	89464	155041	0	10	20
041A/A	905.151	932.186	137485	114641	252126	0	31	6
041B/B	932.184	939.266	30576	27134	57710	0	2	1
042A/B	939.300	965.522	119826	124187	244013	2	102	80
042B/A	965.484	984.225	78904	82118	161022	0	5	75
043A/E	990.234	5005.301	101456	119178	220634	1	117	1869
044A/B	45005.305	5053.225	132236	114582	246818	2	6	109
045A/A	45005.260	45030.390	87612	48097	135709	0	44	333
045B/A	45030.397	45053.204	81367	47567	128934	0	72	0

called tabular, or TF, files. These tabulate the number of records associated with each instrument identifier and the number containing only a raw data value (no conversion to engineering units has been done). The TF files are, in turn, summarized in a FLIT (File Length Index Table) file that keeps cumulative totals of records for each instrument since the beginning of the test (i.e., the file space needed to contain the history to date of the data from each instrument).

The next step in the process is to transform the matrix of data to merge and store the chronology of each instrument's data for the duration of the test. This is accomplished in a directory structure useful for periodic updating of the files, and providing easy access for the data analysts. The file merger is accomplished by a program called VFO (voluminous file output), which sequentially opens each of the 907 individual instrument files, expands or creates them as necessary, and appends the new data in chronological order to the end of the previous file. The file handling (between storage medium and computer) and maintenance of a cross-indexed directory structure is implemented through the LLNL utility program XPORT.

The user-oriented file index organizes the data files into logical groupings, such as all the thermal data from the very-near field at one storage hole location, or all the displacements and thermal correction data for one set of rod extensometers. Once data are processed through REVERT, they too will be added to the set of individual instrument files.

13.2 SYSTEM EFFICIENCY AND OPERATING TIME

Computer time (CPU*) used in the several stages varies linearly with the amount of data, except for the sorting stage of BREAD (Fig. 13-1). Typical times in minutes would be--TAPECOPY 0.1, BREAD 1.0, MFAB 0.1, UFO 1.4, VFO 2.0, REVERT $\geq$ 1.0, and PLOTCMP 1.0. Jobs not processing a complete data file are PLOTR, from 0.03 to 0.95 for a single-license plot; REVERT 0.1 to load tables from an HPDATABASE, 0.25 to make a new HPDATABASE from an HP system dump. Wall clock time is usually at least 10 times the CPU charge time. The iteration loop with BREAD on Fig. 13-1 has on occasions taken weeks, since it may require a decision from project personnel on the acceptability of some data.

*CPU = central processing unit.

No effort has been made to optimize the system programs for speed. There are many places where improvements can be made after the complete system is running smoothly. More important is the human interaction time, which is only slightly affected by such improvements. Gains in productivity will come from further reduction in the number of steps required to completely process the data. TAPECOPY is one candidate for removal; if its functions are incorporated into BREAD.

13.3 QUANTITY AND QUALITY OF DATA RECEIVED TO DATE

Table 13-1 synthesizes BREAD processing to date. As the tapes are taken off the DAS in Nevada they are assigned a sequential number. Sometimes the tapes contain too much data for one disk file and are split into alphabetically labeled parts. The file name in Table 13-1 consists of the letters SF; the three-digit sequential number of the DAS tape, from which the file was generated; and a letter sequence, such as A/A or B/A. The letter before the slash indicates which part of the tape the data came from. The letter after the slash is a processing sequence number. For example, SF030 B/A is a file from the second (B) part of tape No. 30, generated in the first cycle of the processing loop described in Sec. 13.1.

The start and stop time are in Julian Days, with first digits truncated. Thus, the earliest data record in SF004 A/B is at Julian time 2544345.389 (21:19:47 on 4/15/80). The vertical lines to the left of the file name indicate overlapping times. This indicates that two or more files must be merged to provide a complete data base for that time interval.

The number of data points copied, discarded, and total are self-explanatory except for why the discard number is such a large fraction of the total. This is because a substantial fraction of the instrument channels are installed for personnel safety reasons, system status, and other operational functions and are, thus, not considered part of the scientific data set. BREAD automatically discards these channels, based on instructions in the Interface file. Some discards continue to occur due to data errors. These are shown in the last four columns of the table. Time out of range (TOR) indicates that the time value was outside the five-year time frame of the SFT-C. Value out of range (VOR) means the raw data value was outside the range that instrument could feasibly produce. The "License" column tabulates the number of data records containing an invalid format for the instrument

name (it was not three letters followed by three numbers). These lines are not discarded unless they contain other errors. Instead the license name is corrected based on channel number, and tests continue for other error types. Channel error occurs when the channel number on the data record is neither 0-500 nor 1000-1500. The order of testing is channel, nonscientific discard based on channel, license, time range, and data value. Thus, a record rejected because of channel, could also have bad license, time, and/or data fields. On average, for every million records accepted, 21 were rejected on time range, 961 on data value, 1031 on license form, and 556 on improper channel number. This represents about 0.26% of the data acquired.

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REFERENCES

- Blake, W., F. Leighton, and W. J. Duvall (1974), "Techniques for Monitoring the Behavior of Rock Structures," USBM Bulletin #665.
- Brady, B. T. (1978), "Prediction of Failures in Mines--An Overview," USBM Report of Investigations #8285.
- Brough, W., and W. C. Patrick (1982), Instrumentation Report 1: Specifications, Design, Calibration and Installation of Instrumentation for an Experimental High-Level Nuclear Waste Storage Facility, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53248.
- Brune, J. N. (1970), "Tectonic Stress and Spectra of Seismic Shear Waves from Earthquakes," J. Geophys. Research **75**, 4997-5009.
- Brune, J. N. (1971), Correction (to Brune 1970): J. Geophys. Res. **76**, 5002.
- Butkovich, T. R., and D. N. Montan (1980), A Method for Calculating Internal Radiation and Ventilation with the ADINAT Heat-Flow Code, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52918.
- Butkovich, T. R. (1981), As-Built Mechanical and Thermomechanical Calculations of a Spent-Fuel Test in Climax Stock Granite, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53198.
- Byerly, P. (1928), "The Nature of the First Motion in the Chilean Earthquake of November 11, 1922," Amer. J. of Science **16**.
- Carlson, R. C., W. C. Patrick, D. G. Wilder, W. Brough, D. N. Montan, P. Harben, L. B. Ballou, H. C. Heard (1980), Spent Fuel Test-Climax: Technical Measurements Interim Report FY 1980, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53064.
- Carlson, R. C. (1981), Thermoluminescent Dosimetry in Climax Granite, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-86627.
- Durham, W. B. (1982), The Effect of Gamma Irradiation on the Strength of Climax Stock Quartz Monzonite, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-87475.
- Durham, W. B., and A. E. Abey [in prep. (also LLNL Report UCRL-86619 Rev. 1, 1981)], "Thermal Conductivity and Diffusivity of Climax Stock Quartz Monzonite at High Pressure and Temperature," Proceedings of the 17th International Thermal Conductivity Conference, Gaithersburg, MD, June 15-18, 1981.

- Dutta, P., R. Hatfield, and Runstadler (1981), Calibration Characteristics of IRAD Gage Vibrating Wire Stressmeter at Normal and High Temperature, Vols. 1 & 2, Lawrence Livermore National Laboratory, Livermore, CA, Contractor Report, UCRL-15426, Purchase Order 7989009.
- Emerson, D. O. (1978), Lawrence Livermore National Laboratory, Livermore, CA, private communication.
- Hardy, G. R., and F. W. Leighton (1980), "Proceedings of the Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials," Trans Tech Publications: Clausthal-Zellerbach, Clausthal, W. Germany.
- Heard, H. C., and L. Page (1981), Elastic Moduli, Thermal Expansion and Inferred Permeability of Two Granites to 350°C and 55 MPa, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-86603.
- Heuzé, F., T. R. Butkovich, and J. Peterson (1981), An Analysis of the "Mine-by" Experiment in Climax Granite, Nevada Test Site, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53133.
- Heuzé, F., W. Patrick, R. V. De la Cruz, and C. F. Voss (1981), In-Situ Geomechanics Climax Granite, NTS, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53076.
- Jax, P. (1974), "Schallemissionsanalyse bei plastischer Verformung von Metallen," Schallemission, Symposium der Deutsche Gesellschaft fuer Metallkunde, Munich, W. Germany, 59-117.
- Johnson, L. R. (1979), "Seismic Source Theory," papers in Seismology, 328-336 U.S. National Report to the IUGG (1975-1978), Amer. Geophys. Union,.
- King, M. S., and B. N. P. Paulsson (1981), "Acoustic Velocities in Heated Block of Granite Subjected to Uniaxial Stress," Geophys. Res. Letters 8, 699-702.
- Majer, E. L. and T. V. McEvilly (1979), "Seismological Investigations at the Geysers Geothermal Field," Geophysics 44, 246-269.
- Maldonado, F. (1977), Summary of the Geology and Physical Properties of the Climax Stock, Nevada Test Site, U.S. Geological Survey, Washington, D.C., Open File Report 77-356.
- McEvilly, T. V. and E. L. Majer (1982), "ASP: An Automated Seismic Processor for Microearthquake Networks," Bull. Seismol. Soc. Am. 72(1).
- Mogi, K. (1962), "Study of Elastic Shocks Caused by the Fracture of Heterogeneous Materials and Its Relation to Earthquake Phenomena," Bull. Earthquake Research Inst. 40, 125-173.

- Montan, D. N., and W. C. Patrick (1981), Thermal Calculations for the Design, Construction, Operation, and Evaluation of the Spent Fuel Test-Climax, Nevada Test Site, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53238.
- Murray, W. (1981), Geohydrology of the Climax Stock Granite and Surrounding Rock Formations, Nevada Test Site, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53138.
- Page, L. (Nov. 13, 1979), Lawrence Livermore National Laboratory, Livermore, CA, private communication.
- Page, L. (July 10, 1980), Lawrence Livermore National Laboratory, Livermore, CA, private communication.
- Patrick, W. C., and M. C. Mayr (1981), Excavation and Drilling at a Spent Fuel Test Facility in Granitic Rock, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53227.
- Patrick, W. C., R. C. Carlson, and N. L. Rector (1981), Instrumentation Report #2: Identification, Evaluation, and Remedial Actions Related to Transducer Failures at the Spent Fuel Test-Climax, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53251.
- Paulsson, B. N. P., and M. S. King (1980), A Cross-Hole Investigation of a Rock Mass Subjected to Heating, Lawrence Berkeley Laboratory, Berkeley, CA, Report 10849.
- Pollack, A. A. (1980), "Physical Interpretation of AE/ME Signal Processing," Proceedings of the Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, H. R. Hardy and F. W. Leighton, Eds. (Pennsylvania State U. Press, University Park, PA).
- Quam, W., and T. DeVore (1981), Climax Spent Fuel Dosimetry Progress Report, September 1980-September 1981, Lawrence Livermore National Laboratory, Livermore, CA, Contractor Report UCRL-15419, EGG 1183-2432.
- Ramspott, L. D., L. B. Ballou, R. C. Carlson, D. N. Montan, T. R. Butkovich, J. E. Duncan, W. C. Patrick, D. G. Wilder, W. G. Brough, and M. C. Mayr (1979), Technical Concept for a Test of Geologic Storage of Spent Reactor Fuel in the Climax Granite, Nevada Test Site, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52796.
- Scholz, C. H. (1968), "The Frequency Magnitude Relation of Microfracturing in Rock and Its Relation to Earthquakes," Bull. SSA 58, 399-415.
- Tewes, H. A. (1982), Research Results Reported by OEO Summer Student Employees of LLNL Working with Earth Sciences (K) Division Personnel, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19303.

Wilder, D. G., and J. L. Yow, Jr. (1981), Fracture Mapping at the Spent Fuel Test-Climax, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53201.

Wilder, D. G., and W. C. Patrick (1981), Geotechnical Status Report for Test Storage of Spent Reactor Fuel in Climax Granite, NTS, AEG Bull. XVII (4), 355-367, (also available as Lawrence Livermore National Laboratory, Livermore, CA, UCRL-85096.

Wolitz, K., W. Brockmann, and T. Fischer (1978), "Evaluation of Glass-Fiber Reinforced Plastics by Means of Acoustic Emission Measurements," The Fourth Acoustic Emission Symposium, High-Pressure Institute of Japan, Tokyo.

Wyss, M. (1973), "Towards a Physical Understanding of the Earthquake Frequency Distribution," Geophys. J. R. Astr. Soc. 31, 341-359.

Yong, C., and C. Wang (1980), Acoustic Emission in Thermal Cracking Processes of Westerly Granite, unpublished report, University of California, Berkeley, CA.

Yow, J. L., Jr., and D. G. Wilder (1981), Tape Extensometer Sensitivity and Reliability, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-86100.