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Geomechanics of the Spent Fuel Test—Climax

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Geomechanics of the Spent Fuel Test—Climax

Abstract

Three years of geomechanical measurements were made at the Spent Fuel Test—Climax (SFT—C) 1400 feet underground in fractured granitic rock. These measurements were made during the heating of the rock mass that resulted from emplacement of spent fuel as well as the heating by electrical heaters and during a portion of the cooldown of the rock after the spent fuel was removed and the heaters were turned off.

The objectives of the measurements program were to examine both gross and localized responses of the rock mass to thermal loading, to evaluate the thermomechanical response of sheared and fractured rock with that of relatively unfractured rock, to compare the magnitudes of displacements during mining with those induced by extensive heating of the rock mass, and to check assumptions regarding symmetry and damaged zones made in numerical modeling of the SFT—C.

Results of the measurements show that during the heating phase the rock mass behaved elastically, even including areas near significant shear zones or faults. However, the magnitudes of deformation near faults and shear zones were considerably larger than those in areas without significant fracture zones. We conclude that, during the heating phase, when stresses increase, the fractures become locked as they close and therefore behave similarly to intact rock.

During cooldown a significant difference was noted in rock mass behavior near shear and fault zones. Early in the cooling phase, the response remained elastic. We conclude that the fractures become unlocked upon cooling and no longer behave in a fundamentally elastic fashion.

1. Introduction and Background

1.1 Description of the Spent Fuel Test—Climax Project

The Spent Fuel Test—Climax (SFT—C) is a unique test of retrievable deep geologic storage of spent fuel from an operating commercial nuclear reactor. This field test has recently been completed in a granitic stock at the U.S. Department of Energy's Nevada Test Site. The SFT—C is part of the Nevada Nuclear Waste Storage Investigations (NNWSI), managed by the DOE Nevada Operations Office. The Lawrence Livermore National Laboratory (LLNL) is responsible for the technical direction of the SFT—C (Ramspott et al., 1979) and is now completing the documentation of the test results.

Although the overall objective of the SFT—C was to evaluate the feasibility of geologic storage of spent fuel assemblies at a depth representative of actual repositories, the test provided an unexcelled opportunity to study large-scale responses of a granitic rock mass to extensive heating and subsequent cooling. Specific test objectives related to the thermomechanical behavior of the rock mass were to:

- Examine both gross and localized responses of the rock mass to thermal loading.
- Evaluate the response of sheared and fractured rock to thermal loads with that of relatively unfractured rock.
- Compare the magnitudes of displacements during mining with those induced by extensive heating of the rock mass.
- Check assumptions made in numerical modeling of the SFT—C regarding symmetry and damaged zones around the facility.

1.2 Purpose and Scope

The purpose of this report is to describe the interpreted set of geomechanical data from the thermal phase of the SFT—C. These data reflect extensive heating of the granitic rock mass for 3 years, followed by cooling of the facility by ventilation for 6 months. The data were analyzed (1) to examine how the rock mass responded to changing thermal loads in a gross sense and (2) to discern how the overall rock mass deformations were affected spatially by geologic structure and were affected in time by variations in thermal

loading and ventilation rates. Displacements within rock around the SFT—C drifts and deformations of the drifts themselves are considered.

The analyses in this report are constrained by the resources available as the SFT—C Project concludes and by the results from rock mass response calculations. Recommendations for further analyses of the SFT—C geomechanical data are given in the concluding section (Section 5); research work in these areas of rock mechanics and *in situ* characterization are continuing at LLNL.

1.3 Previous Analyses and Reports

A number of reports and analyses related to geomechanical aspects of the SFT—C have been published. A complete listing of all reports can be found in the final project report (Patrick, 1986). Many of the reports are referenced within this report. There are certain subject areas that deserve special mention. The Mine-By experiment, which preceded the thermal phase of the SFT—C, has been reported many times and will not be discussed here. Instrument installation, calibration, repair, reliability, and accuracy are examined in detail in several of the reports; a table in this report summarizes relevant information regarding instrument accuracy. The geologic setting of the SFT—C facility has had a definite effect on the data; this setting has been described in reports on fracture mapping, core logging, and the structural geology of the site. Previous analyses and reports have dealt only with data from the mining of the SFT—C facility or with relatively incomplete data sets from the thermal phase of the SFT—C. This report is the first to analyze and interpret the entire set of geomechanical data from the thermal phase of the SFT—C. The conversion parameters and algorithms necessary for temperature correction of the remotely read instruments are reported by Carlson (1985); data used in this report have been corrected for the effects of temperature changes on instruments by systematic application of these parameters and algorithms. Also, certain types of offsets in plots of the time series data have been removed using an approach described in Section 4. Plots of temperature-corrected data from which offsets have not been removed are available in the report by Carlson (1985).

Numerical modeling of the thermomechanical behavior of the SFT—C with finite element codes has been the subject of several previous reports. Extensive comparisons are not made be-

tween the calculated and the measured rock mass responses in this report; limited comparisons with a portion of the data set are made in a report by Butkovich and Patrick (1985).

2. Site Description

2.1 Site Geological Setting

The SFT—C is situated in the Climax Stock near the northern end of the Nevada Test Site. The Climax Stock outcrops over an area of approximately 1.6 mi² (4 km²), as shown in Fig. 1. Geophysical evidence suggests that the stock expands in a roughly conical fashion to an area of approximately 100 km² at a depth of several kilometers. The stock is estimated to be approximately 100 million years old.

The Climax Stock consists of a granodiorite unit and a quartz monzonite unit; the SFT—C is located within the quartz monzonite unit. Both units contain varying proportions of quartz, potassium and sodium feldspar, plagioclase, and biotite. The rock also contains large alkali feldspar phenocrysts up to 150 mm in length; these phenocrysts compose an average of 8 percent of the total

rock volume. The stock includes Paleozoic carbonates and Precambrian quartzites; contacts between the stock and the surrounding country rock are either steeply dipping or are fault contacts.

Wilder and Yow (1984) describe in detail the structural geology of the Climax Stock, along with its overall geologic setting. Investigations at the SFT—C indicate that the rock mass is moderately jointed and also that it is transected by shears and faults (shears are discontinuities of moderate scale lacking direct evidence of shear displacement).

Wilder and Yow (1984) identified eight joint sets at the stock. In terms of their potential impact on the mechanical behavior of the rock mass under loading, these joint sets can be grouped into four dominant sets (one of the dominant sets is actually made up of two subsets) and three less prominent sets. In addition, three sets of shears and one major fault zone were found to cut across

Figure 1. Climax geology map.

the SFT—C. Preferred orientations of the dominant joint sets, the shear sets, and the fault zone are shown in Table 1.

Although the average spacing of discontinuities within sets was not completely evaluated, the frequency of occurrence of the four dominant joint sets can be estimated as roughly 23, 23, 35, and 12 percent, respectively. The remaining few percent of the joints are distributed among the less dominant sets. These estimates are based primarily on data from the SFT—C test level within the Climax Stock. In a fully three-dimensional sense, the first set listed in Table 1, which has an average spacing of approximately 1 ft, increases in prominence substantially.

The SFT—C was located above the water table, but the host rock was not entirely dry because water seeped into the facility at several locations in the drifts and in the shaft. Seepage occurred primarily along faults and shears; water entering the facility either was pumped out from a sump or was evaporated by the ventilation air flow.

Table 1. Preferred orientation of dominant rock mass discontinuities at the SFT—C (after Wilder and Yow, 1984).

Discontinuity type	Strike	Dip
Joint set	N44degW	20degN
Joint set	N24degW	Vertical
Joint set	N59degW	Vertical
Joint set	N46degE	80degSE
Shear set	N40degW	85degNE
Shear set	N55degE	80degSE
Shear set	N53degW	85degNE
Fault zone	N45–50degE	65–70degSE

2.2 Properties of the Intact Rock and of the Rock Mass

Mechanical and thermal properties of the Climax Stock quartz monzonite in which the SFT—C was situated were measured using small specimens or core samples in laboratory tests. Also, field tests and observations provided measurements and back-calculated estimates of mechanical and thermal properties for the rock mass. During the SFT—C, joint samples were not tested for stiffness or strength, but Yow (1985) provides estimates for representative joint surfaces using approaches suggested by Barton and Choubey (1977).

Tables 2 and 3 list many of the rock properties that are relevant for geomechanical or thermal analyses; the indicated references can be consulted for further information. Table 2 lists thermomechanical properties from laboratory tests on several sizes of samples; Fig. 2 and Table 3 list values for *in situ* deformability.

2.3 In Situ Stresses

Ellis and Magner (1982) measured the *in situ* stresses at the SFT—C, prior to the heated phase of the test, with U.S. Bureau of Mines (USBM) borehole deformation gauges and, after the heated phase, with USBM gauges and Commonwealth Scientific and Industrial Research Organization (CSIRO) hollow inclusion cells. Both techniques use overcoring to relieve the stress around a borehole in which the gauge or cell is installed; stress values are computed from the measured strain relief using equations based on theories of elasticity. Tables 4, 5, and 6 summarize stress measurements obtained during these two sets of measurements.

Table 2. Summary of laboratory thermomechanical properties of Climax Stock quartz monzonite (after Pratt et al., 1979).

Properties	Sample source		
	G-1 core	G-2 core	Large core
Physical properties			
Dry bulk density (g/cm ³)		2.635 ± 0.036	
Grain density (g/cm ³)		2.723 ± 0.027	
Total porosity (%)		3.2 ± 0.7	
Permeability (μD)	0.12	3.10	
Mechanical properties			
Compressive strength (GPa)			
@ σ ₃ = 0 MPa	0.20 ± 0.03	0.20 ± 0.03	
@ σ ₃ = 3.4 MPa			0.275 ± 0.007
@ σ ₃ = 6.9 MPa			0.282 ± 0.044
@ σ ₃ = 10.3 MPa			0.337 ± 0.027
@ σ ₃ = 20.7 MPa			0.452 ± 0.016
@ σ ₃ = 41.4 MPa			0.569 ± 0.032
Young's Modulus (GPa)			
@ σ ₃ = 0 MPa	48 ± 5	51 ± 5	
@ σ ₃ = 3.4 MPa			66.7 ± 5.9
@ σ ₃ = 6.9 MPa			54.4 ± 5.1
@ σ ₃ = 10.3 MPa			61.5 ± 7.0
@ σ ₃ = 20.7 MPa			63.7 ± 6.4
@ σ ₃ = 41.4 MPa			66.8 ± 1.9
Dynamic	82.8	73.3	67.2 ± 3.9
Poisson's ratio			
@ σ ₃ = 0 MPa	0.21 ± 0.02	0.22 ± 0.22	
@ σ ₃ = 3.4 MPa			0.35 ± 0.02
@ σ ₃ = 6.9 MPa			0.27 ± 0.06
@ σ ₃ = 10.3 MPa			0.31 ± 0.05
@ σ ₃ = 20.7 MPa			0.31 ± 0.05
@ σ ₃ = 41.4 MPa	0.240	0.253	0.248 ± 0.012
Bulk modulus (GPa)			
Dynamic	53.2	45.4	44.5 ± 4.4
Ultrasonic velocities (km/sec)			
P-wave	6.058	5.767	5.501 ± 0.208
S-wave	3.541	3.317	3.185 ± 0.080
Tensile strength (MPa)^a			
	16 ± 2	14 ± 2	

^a Brazilian test.

Table 3. Moduli calculated using a 12-term general linear model for deformation modulus in GPa (after Patrick et al., 1985a).^a

Time of measurement	North pillar		South pillar	
	Vertical loading	Horizontal loading	Vertical loading	Horizontal loading
Preheating	46.5	57.2	26.3	37.3
Post-heating	62.7	52.9	54.6	44.8

^a Consult the final report (Patrick, 1986) for more inclusive summaries of both laboratory and field data.

Laboratory

LLNL NX cores
Terratek NX cores
USGS 15 cm ϕ cores

Field

NX jack
Modified NX jack
Petite sismique
Tunnel relaxation (3,4)
RMR rating
Q-system rating

Δ Mean value

Figure 2. Estimates of laboratory and field modulus for Climax granite (after Heuze et al., 1981b).

Table 4. Pretest *in situ* stress determinations (after Ellis and Magner, 1982).

Component	Magnitude ^a (MPa)	Bearing ^b	Inclination ^c (deg)
σ_1 (max)	11.56	N56degE	- 29
σ_2	7.13	N26degE	+ 57
σ_3 (min)	2.75	N43degW	- 14

^a All stresses are compressive.

^b Drift bearing is N61degW.

^c Negative is below horizontal.

Table 5. Average bearings and inclinations of *in situ* stress measurement boreholes (after Creveling et al., 1984).

Borehole	Location	Bearing	Inclination (deg)	Final depth of borehole (ft)
ISS-8	South drift abutment, Station 260 ft	S29degW	+ 3	110.2
ISS-9	Tail drift horizontal, Station 258 ft	N62degW	+ 4	60.4
ISS-10	Tail drift inclined up, Station 258 ft	N60degW	+ 46	81.1
ISS-11	Tail drift inclined down, Station 258 ft	N60degW	- 43	95.9

Table 6. U.S. Bureau of Mines gauge principal stress solutions^a (after Creveling et al., 1984).

Borehole combinations ^b	Stress (MPa)	Azimuth: degrees cw ^c from north	Inclination degrees up from horizontal
ISS-8, 9, 10	12.38	248	18
	7.46	59	72
	4.92	157	3
ISS-8, 9, 11	12.72	338	13
	8.88	211	69
	3.84	72	16
ISS-8, 9, 10, 11	11.41	338	35
	8.24	227	26
	6.84	109	43

^a All stresses are compressive.

^b Borehole ISS-8 data includes all USBM gauge tests beyond a depth of 60 ft.

^c The abbreviation cw is clockwise.

3. Test Description and Geometry

3.1 Facility Layout

The SFT—C consists of three parallel drifts approximately on 10-m centers. The central canister drift, in which the spent fuel canisters and the electrical simulators were emplaced, is approximately 6.1-m high by 4.6-m wide. The heater drifts, which flank the canister drift, are each 3.4-m high by 3.4-m wide. Figures 3 and 4 show the drifts in plan and section view, respectively.

A variety of instrument types were installed throughout the three-drift complex (Figs. 5 and 6). To record the response of the rock mass and selected geological discontinuities, 12 borehole rod extensometers were installed for a Mine-By experiment to measure displacements within the rock immediately surrounding the central drift. Three vibrating-wire stressmeters were also deployed. Although originally not intended for use during the heated phase of the SFT—C, the Mine-By extensometers were refurbished and were used to monitor pillar deformations during the heated phase.

Displacement measurements within the rock were augmented by two sets of six 4-anchor

borehole extensometers grouped near the center canister emplacement hole (designated GCE) and near the end of the canister drift (designated GBE). In addition, single 4-anchor units (designated GAE and GDE) were installed at the far ends of the facility to monitor displacements where temperature changes were relatively smaller.

Additional sets of vibrating-wire stressmeters were installed as rosettes of three: two sets (designated NSG) approximately 0.7 m from the canister drift rib in the north pillar, two sets (designated NSG) near the center of the north pillar, and one set (designated CSG) at the depth of the center of each spent fuel assembly stored in CEH03 and CEH09. Stressmeters that were used during the Mine-By experiment were removed for post-test evaluations and were not replaced for the heated phase.

From a facility operational point of view, drift closure is often more important than rock displacements that occur far from the drift surface. Convergence wire extensometers (CWEs) were designed, fabricated, and installed to monitor relative displacement between opposite surfaces of the drifts. Five sets of horizontal and vertical

Figure 3. Spent Fuel Test layout in Climax granite.

Figure 4. Spent Fuel Test cross section.

CWEs were installed in each drift, and one unit was placed in the Receiving Room near the base of the canister access shaft where a fault zone was identified during mining. Redundancy could be obtained by means of manually acquired tape extensometer readings at each of these locations. In addition, two so-called through-hole extensometers were installed to span from the far south to the far north ribs of the three-drift array. Excessive frictional effects on the portions of the wire catenary that passed through the pillars resulted in data of limited value, so these are not discussed further.

Three orthogonal components of displacement at selected locations on five discrete geological discontinuities were measured using seven fracture monitor systems (FMSs). These units were developed and deployed to monitor displacements that were associated with possible discontinuum responses.

When the concrete floor forming the canister drift invert began cracking during the early stages of heating, reference pins were installed and relative displacements across the cracks were measured with a Whittemore gauge. Although no attempt was made to replicate the measured phenomena with model calculations, crack development and response were consistent with the other aspects of calculations and measurements, as discussed later.

After retrieval of the spent fuel assemblies, two rosettes of three instruments (CDGs) were installed in CEH03 and CEH09 to measure displacements

within the 0.61-m diameter emplacement boreholes as cooling progressed. These highly sensitive instruments provided data on the very-near-field response.

Calculated root-sum-square errors and measured calibration errors for the various rock mechanical instrument types are provided in Table 7. In comparing data with calculations, it is essential that these errors be considered. It is impossible for the calculated values and the measured values to display better agreement than is permitted by the inherent errors in the measurement system. However, it is also important to consider the sources of errors and whether they are random or systematic since trends that can sometimes be discerned in time series data plots must be ignored if only the magnitude of error is taken into account. The effect of systematic errors on data trends can sometimes be likened to the free play or looseness of gears in a gear box. The looseness of the meshing of the gears has no effect unless the direction (trend) in which the gears are driven is reversed.

3.2 Instrumentation

The overall philosophy of instrumentation was derived from a need to monitor rock mass response to the thermal perturbations that would be imposed as a result of the emplacement of spent fuel. Deformations and stress changes due to drift excavation had already taken place, so the thermal phase instrumentation reported here was

Figure 6. Cross section showing thermal phase and Mine-By instrumentation arrays.

designed to monitor only those changes that would result from the spent fuel emplacement and subsequent retrieval. Other considerations included the finite size of the automated data acquisition system, which limited the amount of monitoring that could be done, and the symmetry of the facility. The data acquisition system (DAS) consisted of more than 850 channels of data, which provided a very large data set. However, it

was not possible to monitor everything of interest. The other consideration, the symmetrical design of the canister and heater drifts, would allow the monitoring to be less extensive if the rock behaved in a homogeneous fashion since symmetry could be assumed in analyzing rock behavior. Based on the number of data acquisition system channels available, as well as on the expectation of symmetry, it was decided to neglect the far

Table 7. Summary of calculated errors and calibration errors for rock mechanical instrumentation deployed on the SFT—C (after Patrick et al., 1984b).

Instrument type	Number deployed	Calculated RSS error	Mean (standard deviation) calibration error
Mine-By series extensometers (data for typical 5-m rod)	12 units, 60 anchors	56 μm	- 5.6 (55.3) μm^a
GxE extensometers with potentiometers	8 units, 32 anchors	33 μm	- 8.6 (36.3) μm^a
GxE extensometers with LVDTs	3 units, 12 anchors	122 μm	- 3.6 (7.7) μm^a
GxE extensometers with proximeters	3 units, 12 anchors	63 μm	176.9 (309.0) μm^a
Convergence wire extensometers	32	84 to 306 μm^b	3.8 μm^c
Fracture monitor system	7 units, 21 components	10 μm	0.8 μm^c
Borehole closure monitor	14 (including two for instrument evaluation)	15 μm	1.2 μm^c
Vibrating-wire stressmeters	18	0.02 MPa	+ 38 to - 58% of reading ^d

^a Composite values for all rod extensometers are 10.7 (115) μm ; 75% of post-test calibration results were in a ± 50 μm window and approximately 29% were within a ± 5 μm window.

^b Dependent upon wire length.

^c Mean error due to change in sensitivity; no field calibration.

^d Range of errors for six calibrated stressmeters.

field (outside the vicinity of the test) and to neglect displacements and stress changes except in directions where it was anticipated that they would have maximum magnitudes. Because of funding and schedule constraints, as well as channels available, a decision was also made not to place rod extensometers in the heater drift inverts angled downward toward the canister emplacement holes. More detailed discussions follow for certain types of instrument installations.

The rod extensometers installed for the thermal phase monitoring consisted of vertical multi-point borehole extensometers (MPBX) at each of the extreme ends of the canister drift and arrays of vertical MPBXs centered around CEH09 and CEH03. The extensometer locations in the canister drift were designed to monitor the effects of shear zones on displacements. The array at CEH09 had three MPBXs on either side of a shear zone to detect the response in what appeared to be two separated rock blocks. There was a similar array of instrumentation around CEH03 where there were no significant shear zones. Thus, a direct comparison could be made between sheared and unshattered rock.

Convergence wire extensometers were designed and fabricated to measure deformations of the drifts themselves. These extensometers were installed in both vertical and horizontal orientations. Five CWE stations were established in each of the drifts, with stations spaced to assess end effects as well as rock mass responses in the cen-

tral portions of the drifts and to consider the influence of major shear zones. In addition to these 15 stations, one station was set up in the Receiving Room, with the vertical wire extensometer monitoring a single fault block and the horizontal extensometer arranged to monitor three major fault exposures that cut through the Receiving Room.

Because both rod and convergence wire extensometers have large distances between the monitoring points or anchor points, the response they detect is an integration of the rock response over some distance, including the response of a series of fractures as well as the intact rock matrix. This is particularly true for the vertically oriented instrumentation where there were many low-angle joints between the respective measurement points. Therefore, fracture monitor systems were designed and fabricated to investigate the responses of single fractures. The system was intended to monitor the behavior of individual major geologic features to assess how much of the integrated response seen by extensometers was due to rock matrix deformation and how much was due to motion along individual fractures. The system was also to aid in assessing whether or not different types of fractures behaved in fundamentally different manners; i.e., did some fractures (faults, shear zones, and joints) respond differently than other types of fractures (e.g., stick-slip in some features but not all). Fracture monitors were placed across the fault, across

shear zones, and across joints, with three orthogonal components of motion regularly measured on each of these fractures.

In addition to the displacement instrumentation, vibrating-wire stressmeters were emplaced in vertical holes near the two canisters where the rod extensometers were emplaced. These instruments were set up to monitor horizontal stress changes, with three stressmeters oriented 60 degrees from one another. Their locations allowed comparison of the stress changes in sheared rock at CEH09 as contrasted to unshaded rock in CEH03. Two additional sets of vibrating-wire stressmeters were placed in each of two boreholes drilled in the pillars to monitor stress changes occurring on a vertical plane along the pillar axis. Sets of three gauges were located near the rib at two positions (Figs. 5 and 6), and two other sets were in the centers of the north pillar. The locations were chosen so that the stressmeters would be near displacement instrumentation even though the parallel holes dictated gauge orientations that were orthogonal to the component of deformation being measured by the extensometers. The installation and calibrations are reported in Abey and Washington (1980), Carlson (1985), and Mao (1984); other aspects of the instrumentation are described by Wilder and Patrick (1981) and Carlson et al. (1980).

3.3 Principal Events of the Spent Fuel Test—Climax

The primary loading imposed on the rock mass during SFT—C was thermal loading during the heated phase of the test, followed by unloading during the subsequent 6-month cooling period. Table 8 summarizes the principal events re-

lated to this loading; consecutive numbers in the table indicate days since January 1, 1980. An alternative time system used occasionally in this report (and in many other SFT—C reports) is to reference events to the age of the spent fuel from the reactor (years out of core). This is pertinent since the fuel (the heat source for the test) decays with age. Montan and Patrick (1986) provide additional detailed information on thermal aspects of the tests.

Table 8. Principal events subsequent to fuel emplacement.

Days since 1/1/80	Event
108	First fuel emplaced
148	Last fuel emplaced
178	Auxiliary heaters to 1850W
183	Auxiliary heaters to 925W
350	Auxiliary heaters to 1250W
377	First fuel exchange
414	Ventilation to 1/2 flow
465	Ventilation to normal flow
555	Ventilation to 1/2 flow
605	Ventilation to normal flow
616	Ventilation test 1/2 flow
664	Second fuel exchange
780	Auxiliary heaters to 925W
790	Auxiliary heaters to 1400W
828	Auxiliary heaters to 1350W
874	Start ventilation test
937	Complete ventilation test
958	Third fuel exchange
1157	First fuel retrieved
1184	De-energized heaters
1191	Last fuel retrieved

4. Data Analysis and Interpretation

4.1 Interpretation of Data by Instrument Type

4.1.1 Mine-By Extensometers

Plots of data collected from the Mine-By extensometer (MBI) instrumentation contained offsets similar to those seen in other types of instrumentation. To the extent that it was feasible to do so, these offsets were backed out of the data, and the data were plotted as a continuous curve shown without offsetting. Judgments of which offsets were indications of actual motion in the rock and which were merely artifacts of the instrumentation or the DAS were based on the character of the offset. Offsets that occurred suddenly, with the shape of the curve of the same form on both sides of the offset, were judged to be artifacts of the instrumentation or the DAS system. Similar offsets were attributed by Patrick et al. (1982) to exchanges of DAS digital voltmeters (DVMs) to allow voltmeter calibration. However, although most of the offsets in the geotechnical data did not correspond to DVM exchanges, their simultaneous appearance in multiple channels implicates the DAS as the source. Because of offsetting in opposite directions at different times in the same instrument and occasionally opposite offsetting of different measuring points of the same instrument at the same time, it appeared that, although most of the offsets must have come from the DAS, the actual source could not be identified.

Individual offsets could not be examined on an individual basis. Offsets were not backed out where there was an identifiable legitimate source (such as a change in the heat load or ventilation).

In addition, offsets that were retained in the data plots were those that occurred over a period of time as incremental offsets (although the change could have a steep slope) and those that occurred at a time when the spent fuel was being removed or when there was a change in the ventilation system that could influence the heat load. No attempt was made to correct offsets that were small or offsets where curves did not appear to be radically shifted. The MBI plots shown in this report have been smoothed somewhat by removing the very small variations, which were not significant in the interpretations. Thus, the original character of the data plots may not always be represented.

In general, the MBI extensometer data is the most complete and stable set of data, with the possible exception of the FMS data. Though the MBI extensometers did not have thermomechanical monitoring as an original objective, they were refurbished to monitor during the thermal phase and appear to have been effective for that purpose.

Two obvious characteristics of the time series data from the MBIs are that the data are complete and the data set is quite consistent. Because the MBI data were continuous in most cases, there was no need to try to connect portions of curves to complete the time series or to try to make judgments between the beginning and end of valid data. Data consistency is evident in several aspects. First, the time series plots show general shapes consistent with heating for a period of time, followed by cooldown effects (Figs. 7 through 18). After cooldown, the readings approached their original values but, in general, had

Figure 7. MBI 1 (horizontal) time series data.

Figure 8. MBI 4 (horizontal) time series data.

Figure 9. MBI 8 (horizontal) time series data.

Figure 10. MBI 11 (horizontal) time series data.

Figure 11. MBI 2 (35-degree inclined) time series data; north heater drift; Station 2 + 83.

Figure 12. MBI 5 (35-degree inclined) time series data; south heater drift; Station 2 + 83.

Figure 13. MBI 9 (35-degree inclined) time series data; north heater drift; Station 3 + 45.

Figure 14. MBI 12 (35-degree inclined) time series data; south heater drift; Station 3 + 45.

Figure 15. MBI 3 (50-degree inclined) time series data; north heater drift.

Figure 16. MBI 6 (50-degree inclined) time series data; south heater drift; Station 2 + 83.

Figure 17. MBI 10 (50-degree inclined) time series data; north heater drift; Station 3 + 45.

Figure 18. MBI 13 (50-degree inclined) time series data; south heater drift; Station 3 + 45.

not completely recovered their original values because monitoring ceased before cooling was complete. It is possible (as is discussed later) that rock deformations did not entirely return to pretest values because permanent deformation of the rock mass was induced during the heating cycle. Second, the data are internally consistent in that, generally, the deepest anchors show the greatest displacements relative to the borehole collar, and the anchors each show decreasing amounts of displacement with proximity to the rib. Third, comparison of the data from similarly oriented extensometers at the four measurement stations indicates, in general, very similar time series response. Thus, the data (with offsets removed) were judged to be a good data set.

Specific differences between extensometers and also differences between the calculated and the measured displacements are informative. Figures 19 and 20 show the comparison between the calculated and the measured displacements as percentages for the period of time from 3.00 to 5.25 YOC. This does not cover the entire period of

monitoring but was chosen as the comparison period because finite-element (FE) model results at the time of analyses included only that period of time since a few of the instruments had not been turned on at the start of the test (2.46 YOC). This period of time is shown in Figs. 7 through 18 by the vertical time lines. As is apparent, the comparison is quite good considering the accuracy of the instruments (see Patrick et al., 1984, for a complete assessment of instrument accuracy). However, the comparison does have a low correlation coefficient. Figure 21 is a correlation curve of measured versus calculated data. There seem to be two different correlations. The first correlation includes the points representing measured displacements that are greater than the calculated displacements. The second correlation would result from considering only points that represent measured displacements less than or equal to the calculated displacements. The significance of these different correlations is not fully understood but appears to be related to anchor position. If the data from Figs. 19 and 20 are divided into two sets

Figure 19. Comparison of thermal phase measured versus calculated deformations for 3 YOC to end of heating, 2 + 83 MBIs.

Figure 20. Comparison of thermal phase measured versus calculated deformations for 3 YOC to end of heating, 3 + 45 MBIs.

(near rib anchors and deeper anchors), the average values of the data from the deeper anchors are nearly equal to (Fig. 19) or greater than (Fig. 20) those calculated. The average values for shallower anchors are less than those calculated for data from both measurement stations (Figs. 19 and 20). To check if there was a different correlation for the values higher in magnitude, the larger values were left out and the correlation was checked again for the subset of data that was left. As can be seen in Fig. 22, the correlation coefficient has been slightly (but not significantly) improved.

The geologic structure seemingly has caused the differences between calculated and observed displacements, as was noted early during the project as part of the Mine-By monitoring. The first monitoring took place as the canister drift was mined out and has been, therefore, termed the Mine-By experiment. During that monitoring, there seemed to be a relationship between the lack of agreement between the calculated and ob-

served displacements and the presence of shear zones (Wilder and Patrick, 1981; Wilder, 1979; and Heuze et al., 1981b). The heated phase monitoring does not show identical patterns but may be responding to the same structural features.

Figures 23 and 24 show cross sections at Stations 2 + 83 and 3 + 45 along with the major shear zones, a representation of the trend of the most prevalent low-angle joint set and prevalent vertical joints. Although the low-angle joint set is healed and probably responds similarly to the intact rock overall, the healing is not continuous and the wall rock is known to be altered. Tests with an NX borehole jack (Patrick et al., 1985b) indicated that the low-angle joints were somewhat compliant, with apparent closing or deforming of the joints so that the modulus changed during the heating cycle. More importantly, compliance was stress/heating dependent and possibly irreversible (inelastic).

Figure 21. Correlation of measured versus calculated deformations, all MBIs.

Figure 22. Correlation of measured versus calculated deformations, selected MBIs.

Figure 23. Fracture sets and potential blocks (shaded areas) at Station 2 + 83.

Figure 24. Fracture sets and potential blocks (shaded areas) at Station 3 + 45.

Blocks may be formed by the intersection of joints with the shear zones or with the nearly vertical joints that are not healed. Conceptually, during the mining process, the blocks formed by the fracture intersections would tend to deform into the drifts, with accompanying opening of the low-angle joints. Indeed, the planned drift cross sections with rounded corners were usually not achievable because of breakouts along the low-angle joints and because the crown often slabbled along the low-angle joints. Therefore, the sections of rock shown by the "Zip-a-Tone" patterns in these figures conceptually represent blocks bounded by features of lower stiffness because of opening of the low-angle joints. The blocks that are further from the drifts may not be so influenced.

As is evident in Fig. 23, the south pillar area of Station 2 + 83 is subject to modulus reductions as explained above. This is one of the sections where the comparison between measured and cal-

culated displacements during Mine-By was in poorest agreement. (A reversal in displacements between measured and calculated was observed in the horizontal extensometers in the pillars during the Mine-By. This reversal has not been satisfactorily explained and cannot be explained by the loosening of blocks or opening of the low-angle joints.) As was noted earlier, the extensometer anchors that were directly over the drifts showed consistently larger displacements during heating than expected from the calculations. This may reflect closure during heating of the low-angle joints that had opened as a result of mining. As can be seen in Figs. 23 and 24, blocks of rock immediately above the canister drift are subject to opening during excavation. If closing of joints occurred during heating, then the comparison between the measured and the calculated displacements should be worse during the early heating phases and should become progressively better as heating (and therefore closing) progresses, which

would result in progressively larger percentages of the low-angle joints having greater compressive stresses. The net effect would be a transition in rock mass behavior from a somewhat blocky state to a more monolithic condition, which would be better represented by the continuum elastic analyses of Butkovich and Patrick (1985). This was not evaluated at the time this report was prepared since the calculated displacements for early heating times were not available (Butkovich and Patrick, 1985).

A comparison of the measured and the calculated displacements during cooling may help to explain whether joint opening has influenced the rock displacements. During cooldown, the measured and the calculated values correlate better although the slope is not unity (Fig. 25), indicating that there is not a one-to-one correspondence. The correlation remains poor ($R^2 = 0.58$) but is much better than had been seen in data from the heating phase, which supports the premise that the low-angle joints tended to close during the heating so that when initial cooldown deformation started, the joints behaved more like the surrounding rock mass. Upon further cooling, the low-angle joints are expected to open so that the correlation would become poor; however, a correlation at later times cannot be made, and the thesis must remain unresolved. Figures 26 and 27 show the comparisons between the calculated and

the measured displacements during the cooling cycle up to the time that monitoring ceased.

In summary, the low-angle joints tended to open during mining or just after the mining was completed. This reduced the overall rock mass stiffness in sections of the rock where modulus reductions were not considered during the modeling (a blast-damaged zone was considered during the modeling but it did not extend into the rock mass more than a few feet and was not related to the fracture system present). Because of the inelastic effects of jointing, the correlation between modeling and measured displacements is not as strong as desired.

The largest ratios of observed versus calculated displacements took place in sections of rock above the canister drift. The agreement between the calculated and the measured displacements improved during the cooling cycle, which is most likely a result of closing of the low-angle joints during the heating cycle, with reopening not fully developed at the time that monitoring ceased. This nonrecovered displacement was also noted in the CWE monitoring, as discussed in Section 4.1.3. Therefore, the data seem to be consistent and seem to support the interpretation.

4.1.2 Canister Drift Extensometers

The multiple point rod extensometers that were installed vertically to monitor thermal deformations beneath the canister drift [canister drift extensometer (GxE) instruments] experienced significant failures of many sensors and a few rods (Patrick et al., 1984b). The time of the sensor failures were identified initially in the data by Patrick et al. (1984b), based on the character of the data trace, and were confirmed later by electronic diagnosis. New sensors were installed to replace all of the original sensors; however, there were significant time gaps in data for nearly all of the GxE instrumentation. In some cases, the replacement sensors also failed and were replaced again. Therefore, the data traces from these instruments were a series of disconnected segments. Continuous or nearly continuous records were developed by matching segments based on (1) curve shapes prior to instrument failure; (2) curve shapes from instruments that did not fail; and (3) the assumption that after the cooldown phase of the project, the rock deformations would tend toward recovery so that the total deformation would approach zero. The latter interpretation was applied with recognition that total cooldown and, therefore, deformation recovery had not been achieved prior to removal of instrumentation. According to

Figure 25. Correlation of cooldown phase measured to calculated deformations, all MBIs.

Ballou et al. (1982), temperature changes in the first 6 months of cooldown at midpillar and at a point 10 m below the canister drift floor are only 20–40 percent of the temperature differential existing at the end of heating. Points further from the heat sources would have correspondingly smaller recoveries.

Therefore, a judgment of the amount of deformations that had been recovered was applied. This judgment was based on the shapes of the cooldown time series deformation curves with the observation that the curves tended to approach full recovery or zero deformation asymptotically. For data curves where the recovery rate remained high (as indicated by steep curve slopes), the cooldown recovery was interpreted to be less complete than where the rate was lower (as indicated by less steep curve slopes). Data curve segments that included a steep recovery curve were offset higher from the zero than were those that appeared to be approaching the zero asymptotically.

Two different philosophies were applied to determine what the final remnant deformations could be after cooldown was entirely completed.

The first philosophy was that any deformations that remained would be positive; that is, the rock expansion experienced during heating would be entirely recovered or slight deformations would remain, probably due to nonrecoverable fracture surface deformation. The second philosophy was that, although remnant deformations were most likely to be as interpreted in the first philosophy, fracture closure and thermally caused mineralogical changes during the thermal phase may have resulted in rock volume changes that would not be fully recoverable upon stress reduction such that the apparent remnant displacements could be negative. In the second philosophy, the curves were not forced to approach zero if there was other evidence to indicate that a negative value was appropriate. The evidence might include a fairly continuous data segment that could be pieced together with confidence, which would then force the recovery curve to go negative. Alternatively, if other anchor point data curves approached zero as expected and if the data curves crossed the curve from intermediate anchor points, then internal consistency of the data could dictate a negative endpoint. Negative values

Figure 26. Comparison of cooldown phase measured to calculated deformations for 5.25 to 5.86 YOC, 2 + 83 MBIs.

Figure 27. Comparison of cooldown phase measured to calculated deformations for 5.25 to 5.86 YOC, 3 + 45 MBIs.

were not frequently seen but could not be considered as impossible; therefore, curves based on the second philosophy are included in this report.

Heated phase data were very limited as a result of GxE sensor failures before the peak deformations were recorded. Because there were very few data channels that obtained continuous data over sufficient time to judge the curve characteristics, it was decided not to use heated phase data during the analyses. The cooldown was monitored fairly well (although there were additional failures at this time), and an analysis of the response during cooldown is useful.

The unconnected segments of the data were related to each other as described earlier (Figs. 28

through 41). The data traces appear to be reasonable in presentation as continuous data. During the heated phase, a general expansion of the rock is indicated by the positive-sloped curves, with the deepest anchor exhibiting the most motion. After the early expansion, which has a steep slope, there is a period of much less expansion with time that continues until the cooldown phase begins. The early occurrence of maximum expansion is consistent with the maximum thermal gradients occurring early during the heating. Further, the deformations seen by the GBE and GCE series extensometers display similar characteristics (Figs. 42 and 43).

Figure 28. GAE extensometers time series data; offsets adjusted; X—sensor failure noted (Patrick et al., 1984b).

Figure 29. GBE01 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 30. GBE02 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 31. GBE03 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 32. GBE04 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 33. GBE05 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 34. GBE06 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 35. GCE01 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 36. GCE02 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 37. GCE03 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 38. GCE04 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 39. GCE05 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 40. GCE06 extensometers time series data; X—sensor failure noted (Patrick et al., 1984b).

Figure 41. GDE extensometers time series data; •—removal; X—sensor failure noted (Patrick et al., 1984b).

Data from different locations allowed an evaluation to be made of the influence of geologic structure on deformation (particularly during cooldown). During cooling, the magnitudes of rock deformations at GCE were consistently greater than those at GBE. There was not sufficient difference in temperature to explain the difference in deformation between the two instrument stations. The difference is illustrated in Fig. 44, which shows the correlation between anchor points of the six extensometers that surrounded CEH09 (GCE) and the six that sur-

rounded CEH03 (GBE). The comparison between the data is good, with a correlation coefficient of 0.92. However, the comparison indicates that GCE deformations were not quite the same as those of GBE since the correlation curve is offset by -0.03 mm (maximum deformations were in the range of 0.1 to 0.6 mm) and has a slope of 1.05. This indicates that rock displacements (note that negative indicates recovery displacements) during cooldown measured by GCE extensometers were consistently greater than those measured by GBE extensometers.

The greater recovery displacements during cooling near CEH09 are most probably a result of the presence of the significant shear zone that runs through the canister drift at that location. The GBE extensometers were specifically located in an area relatively free from faulting or shearing to compare responses in sheared versus unsheared rock. These responses indicate that the sheared rock responded with greater deformation during cooldown than did the unsheared rock, which is consistent with data measured by other instruments that indicate a different rock mass response near the fault (either greater magnitudes or apparent permanent deformations). This is also consistent with the greater deformability of sheared rock, which controls the magnitude of displacement associated with a given stress change.

The data were separated into two subsets to evaluate whether geologic structure was an important influence. The first subset included the GBE and GCE extensometers that were southeast

Figure 42. Pattern of vertical deformations in rock below invert at GBE array.

Figure 43. Pattern of vertical deformations in rock below invert at GCE array; cooldown displacements.

Figure 44. Correlation between GBE and GCE cooldown deformations.

of the respective emplacement holes (GBE and GCE 1, 2, and 3). The extensometers southeast of CEH09 were the ones in the "hanging wall" side of the shear zone and, as such, were the closest to the shear. Therefore, if the shear zone caused a different response in the rock deformations, these extensometers should show a greater difference from their counterparts at CEH03 than would extensometers to the northwest of the emplacement hole (GBE and GCE 4, 5, and 6). Figure 45 shows the data from extensometers 1, 2, and 3. The correlation is quite good, with $R^2 = 0.93$, where $GCE = -0.035 + 1.07 \text{ GBE}$. The correlation for extensometers 4, 5, and 6 (Fig. 46) is also strong. The correlation coefficient is $R^2 = 0.92$, where $GCE = -0.027 + 1.0 \text{ GBE}$.

As can be seen by comparing these figures, the deformation in rock further away from the shear at the GCE series location is more similar to the response at the corresponding GBE series extensometers where shearing is present. For comparisons of unsheared rock conditions, the response is nearly identical. As noted, the deformations at the GCE series southeast of CEH09, which are closer to the shear, do not match those of the corresponding GBE extensometers. Furthermore, the correlation diverges with depth, which would be expected since the shear zone has an easterly dip and would, therefore, be closer to the deeper anchors (Fig. 47). Station GCE03 is quite close to the shear zone such that the shear should pass between GCE03 between anchors 3 and 4 (033 and

034), and the shear zone should also pass close to anchor 4 of GCE02 (024).

Inspection of Fig. 45 supports the interpretation of influence by the shear zone on rock displacements. The points that are farthest from the match line are the 014 and 024 pairs (because the rod broke in GBE034, there is not a 034 pair), which are closest to the shear zone. However, 033 and 032 are also very close to the shear zone and do not appear to be influenced by the shear zone; rather, they are almost perfect matches with corresponding GBE points. It is not known whether this phenomenon is a result of reduced stress conditions from more complete cooling and whether this phenomenon will weaken the thesis of shear zone influence on deformations. The emplacement of canisters was in the area of the top three anchors and, as such, this zone of rock experienced maximum thermal expansion whereas the deeper anchors were placed in comparatively undisturbed rock and therefore serve as the reference points for determining the head assembly motions. If the rock expansion were influenced by the shear zone, all anchor points above the shear zone would monitor a relatively monolithic portion of the rock while deeper anchors would see the effects of the shear with respect to the head assembly. In contrast, if the shear zone had not experienced significant thermal expansion (the case when the shear zone is below all anchors) but had responded to the increased stresses imposed by rock expansion above it, then, as the increased stresses were removed during cooling,

Figure 45. Correlation between GBE and GCE "hanging wall" extensometers; sheared SFT GxE cooldown data.

Figure 46. Correlation between GBE and GCE "foot wall" extensometers; unsheared GxE cooldown data.

the shear would relax more than the intact rock would. This seems to be the situation in Fig. 45. Because the data are not continuous and are subject to much interpretation, no further attempt was made to compare the results with numerical

Figure 47. Location of GCE anchors relative to shear zone.

models or to make comparisons or analyses of the data.

4.1.3 Convergence Wire Extensometers

The data for convergence wire extensometers (CWEs) are complex, particularly for those extensometers located in the canister drift. The reason for the complexity of this data set was that these wires had to be removed periodically to allow movement and emplacement of the spent fuel. In addition, the wires were subject to accidental jarring by the large number of visitors walking through the drift, which could cause the wires to jump a groove in the pulleys. Therefore, much interpretation of the data set was required to determine whether offsetting occurred, which had to be taken into account in the analyses. In addition, not all of the convergence wires had been installed to take baseline data before the fuel was initially emplaced. Baseline ambient temperature data that would normally accompany data of this type is therefore, in many cases, not available from the canister drift itself. The data curves had to be shifted to match the amount of displacement judged to have already occurred when the instruments began recording data. This judgment was based on the necessary adjustment to the curves so that displacements for CWEs that had not been set up would be similar to displacements seen by CWEs that were operational.

Offsets that occurred in the CWE data were taken out of the data in cases where (1) the offsets were abrupt, similar to the approach used with the MBI data; or (2) there was a hiatus in data acquisition when the instrument had been taken down and then reinstalled. In particular, this offsetting was backed out when the curves on either side of the offsets were similar in shape. A new set of curves was thus prepared that were continuous in nature. When offsets were more gradual, they were left in. In the special case of canister drift extensometers, which had been taken down during fuel removal and left down except for the weekends, the offsetting that appears in the data was judged to be actual rock response to the cooldown that was occurring. In general, these offsets were indicated as real by the trend of the spot measurements taken during weekends. These offsets were retained in the data even though the effects of cooldown were apparently much more rapid for the CWEs than were experienced by instrumentation in the pillars and in the adjoining areas.

In summary, the philosophy of interpretation applied to the convergence wire extensometers

was to look at the general curve shape, to adjust the curves to match endpoints that seemed reasonable, and to back out offsets that were abrupt and appeared to be artifacts in the instrumentation or DAS system. There was no need, however, to try to piece together segments (except where the instruments had been removed) since the sensors of these instruments did not experience failures. The smoothness of the curves, the internal consistency where one curve does not cross another curve, the general shape consistent with heating followed by cooling, and the responsiveness to fuel removal all suggest that this data is of high quality.

Data from convergence wire extensometers have been analyzed by looking at the deformations during the heated phase and during the cooldown phase and by comparing the two. Figures 48 through 53 are the time series plots of the data so analyzed.

The first comparison that was made was with the tape extensometer data that had been collected at the same stations. This was an important comparison since previous analyses of the tape extensometer data had been made for comparison with the FE model calculations. Figures 54 and 55 show a comparison of generalized curves of tape extensometer data, CWE data, and calculated data for the canister drift. In general, the comparison between the tape and CWE data for both horizontal and vertical measurements is good since the shapes of both curves are similar and since their

magnitudes roughly agree. The accuracies of the CWEs are greater than those of the tape extensometer. The smaller short-term variations in tape data magnitudes are within the judged measurement accuracies. Although the general shape of the vertical tape extensometer data matches the general shape of the CWEs, there is considerable variation in details and, toward the end of the heating cycle, there is considerable divergence.

Comparison of the CWE-tape extensometer data with the calculated deformations required that some assumptions be made regarding the early times when incomplete CWE and tape extensometer data were available. Early time vertical CWE data were available so that the comparison with calculations could be made directly. The data from CWEs that were not monitored at the beginning of the fuel emplacement were assumed to be very similar in shape to those that were, considering the same time intervals. Therefore, the CWEs and tape extensometer data plots were tied to the same point as recorded by the CWEs that did provide early time data. Data collection from the horizontal CWEs and tape extensometers did not begin during the early times. Therefore, previous comparisons with tape extensometer data adjusted the magnitudes of the readings to match calculated results. With the more complete CWE data, this approach does not seem entirely justified. As is evident in Fig. 54, the shape of the CWE data from approximately 2.5 to 2.9 YOC is nearly flat, which does not match the

Figure 48. North heater drift—horizontal CWE time series data.

Figure 49. Canister drift—horizontal CWE time series data.

Figure 50. South heater drift—horizontal CWE time series data.

Figure 51. North heater drift—vertical CWE time series data.

Figure 52. Canister drift—vertical CWE time series data.

Figure 53. South heater drift—vertical CWE time series data.

Figure 54. Comparison of CWE, tape extensometer, and calculated horizontal convergence—canister drift.

Figure 55. Comparison of CWE, tape extensometer, and calculated vertical convergence—canister drift.

trend of the calculations during this time. Therefore, two comparisons are shown. The solid lines indicate the CWE and tape data starting at zero magnitude, and the dotted line shows the CWE data adjusted to the magnitude of FE calculation 2, the more representative calculation (Butkovich and Patrick, 1985).

The comparison of trends for the measured and the calculated horizontal convergence for the canister drift indicates that during the early time (major heating phase), the calculations did not properly model the actual responses. The curve shapes for later heating and cooling stages are more comparable.

Depending on the assumptions used to determine the initial deformation magnitudes, the measured responses were approximately one-half to one-fourth those of the calculations, or were very close to the same magnitudes at approximately 5.0 YOC.

The comparison between the measured and the calculated vertical convergence is less subject to assumptions since the CWE record is more complete. In this case, the trends are quite comparable, indicating that the calculations were properly modeling the rock. However, the magni-

tudes are considerably smaller than calculations indicate (from twofold to fourfold smaller depending on which calculation is used). The much smaller magnitudes might reflect the influence of floor heaving. The comparison between the measured and the calculated rock deformations (particularly MBI data) were in somewhat closer agreement (less than a twofold difference). Since the records of below-invert deformations are too incomplete during thermal phase to compare with calculations, indirect measurements and observations are relied on to confirm the influence of heaving. The floor concrete cracked during the thermal phase. This cracking was monitored by Whittemore gauge measurements and is consistent with floor heaving.

The difference in magnitude was noted by both horizontal and vertical measurements. This consistently smaller-than-calculated deformation seems to indicate that the effective modulus of the rock was higher than that used in the calculations and was approaching laboratory values. This most simple explanation is contrary to conventional wisdom which would say that the modulus of the rock mass would be significantly less than the laboratory modulus. An alternative interpretation of

the difference is that the near-surface joints were closing during the thermal cycle (as previously discussed) so that the rock mass responded more as intact rock (thus approaching laboratory modulus values). Also, see the discussions on boundary conditions used in the FE calculations. A complete and demonstrable explanation for this apparent difference has not yet been developed.

It should be noted that a model can easily adjust the magnitude of a trend by changing the elastic modulus. The shape of the trend is a much more difficult thing to match, even though it is more qualitative, because it involves mechanics as well as data parameters. Comparison between tape extensometer and calculated displacements have been discussed in previous reports (Yow and Butkovich, 1982; Butkovich et al., 1982; Patrick et al., 1982; and Butkovich and Patrick, 1985) and will not be discussed further.

Because several assumptions were needed to make the previously published comparisons between the measured and the calculated drift closures (e.g., tape readings from each station within a given drift were averaged), the independence of the data from geologic structure was considered. Figure 56 shows the maximum vertical deformation

tions (from before fuel emplacement until just prior to fuel removal) in each drift referenced to the stationing within the canister drift. The measurements are quite constant with stations except for the stations near the far end of the drifts, near the Receiving Room. The reasons for this difference are discussed later, but averaging the measurements within a given drift (particularly the canister and south heater drifts) is acceptable for overall drift response. Figure 57 shows the readings from the horizontal CWEs. There is considerably greater variability with stationing in the heater drifts, but the canister drift readings are quite uniform. Therefore, the averaged comparisons made in the canister drift should be valid. Figures 58 and 59 are similar plots for the cooldown cycle. Once again, the variations are similar, and the comparisons using the averaged data set can probably be made without introducing much error into the comparison.

Because of the difference in values towards the Receiving Room end of the drifts, the influence of stationing (location) on the data was evaluated further. The evaluation takes into consideration both the heating and the cooling phase responses of the CWEs. In general, the ends of the

Figure 56. Vertical CWE deformations during heating as a function of location; negative deformation is convergence.

Figure 57. Horizontal CWE deformations during heating as a function of location; negative deformation is convergence.

Figure 58. Vertical CWE cooldown deformations as a function of location.

Figure 59. Horizontal CWE cooldown deformations as a function of location; negative deformation is convergence.

drifts should have experienced less total deformation because the thermal loads were smaller. However, interestingly, the station in the north heater drift closest to the Receiving Room has larger maximum horizontal and vertical deformations than any other station in this drift. Also, some of the largest deformations in the canister drift were at the Receiving Room end. As can be seen on the combined drift curves, there is considerably different vertical and horizontal responses toward the end of the canister and north heater drifts. These particular stations are much closer to the Receiving Room fault than any instrument station in the south heater drift. This may be an indicator of the influence of the presence of the fault in this area. Since strain is proportional to stress, a lower modulus (E), as would be expected in this faulted rock, would result in larger thermal strains for the same thermal stress.

The vertical cooldown curves show differences in magnitude near the fault similar to that seen by the maximum or heated phase deformations; that is, the recovery was smaller during the cooling deformations for the ends of the canister drifts than for the midpoints of the canister drifts. However, the opposite is true of the horizontal

CWEs. Though this might lead one to conclude that there was some change in the rock mass in the area of the fault, the total magnitude of deformation during cooling in the canister drift does not vary significantly. There appears to be a slight overall increase in cooling deformation towards the far end (Station 4+00) of the canister drift, whereas the north heater drift appears to have a significant decrease in cooling deformation towards the fault. The station nearby the fault has the smallest amount of cooling deformations and the smallest maximum deformations.

This general trend is better understood by comparing the response during cooldown to the total expected response if the rock behaved elastically. This comparison was made by taking a ratio of the cooldown response to the maximum thermal response. If the cooldown were complete and the rock behaved elastically, then the magnitude of deformation during cooldown would be the same as the magnitude of deformation during heating (i.e., a ratio of 1.0). As can be seen in Figs. 60 and 61, at any given station in the north heater and canister drifts, the ratios of cooling to maximum deformations are similar for both the vertical and horizontal extensometer wires, and

Figure 60. Comparison of heating and cooling CWE deformations—north heater drift.

Figure 61. Comparison of heating and cooling CWE deformations—canister drift.

the curves have the same shapes with position in the drifts. These results indicate that, in these drifts, the relationship between thermal loading and drift convergence is similar both horizontally and vertically. Data from the south heater drift is less conclusive (Fig. 62).

Stations at the ends of the drifts experienced the smallest amount of thermal perturbations while the central portions encountered the largest thermal perturbations and, as such, should probably show the greatest amount of response to heating and subsequent cooling. However, as seen in Figs. 56 through 59, the general shapes of the curves are not consistent with this assumption. During both heating and cooling, some of the largest drift deformations took place at the ends.

Analysis of this data is complicated by a lack of prethermal base-line data as well as by insufficient cooldown data to observe the effects of the complete thermal cycle. In two specific cases, CWE082 and CWE092, the monitoring continued somewhat longer and the recovered cooldown deformations were essentially that of the heated or thermal phase deformations. Therefore, part of the reason for the difference between cooling and

maximum deformations may be that the monitoring did not continue to the end of the cooldown cycle. This cannot be stated categorically, however, because some permanent changes may have occurred along joints, particularly along some of the more heavily mineralized joint systems. The latter case is strongly supported by the modulus measurements and therefore is considered the more likely case.

It is interesting that towards the center of the heater drifts the cooldown and the maximum deformations were more nearly the same. This is particularly true for the vertical deformations in the north heater drift. However, the ratios of recoveries in the central portions of the canister drift are overshadowed by a large increase in recovery at CWE array 7 (CEH03), which might be related to block response. The larger percent recovery at the beginning of the drift (Station 2+00) might be expected due to the ventilation of the drift. A similar increase is noted in the vertical (but not horizontal) CWEs of the south heater drift.

No continuum mechanism has been identified that explains the greater amount of cooling deformations at specific measurement stations.

Figure 62. Comparison of heating and cooling CWE deformations—south heater drift; note: intermediate points are missing.

The smaller percent recoveries are usually associated with the location of shear or fault zones. Since the converse is not always true, this observation may merely be coincidental. With ventilation proceeding from the Rail Car Room towards the Receiving Room the greatest amount of recovery during cooldown for any given time should conceptually be in the sections or stations nearest the Rail Car Room, with decreasing amounts of recovery along the drift towards the Receiving Room because of warming of the ventilation air as it flows towards the Receiving Room. However, this is not indicated by the curves in Figs. 60 and 61 but might be in Fig. 62. Furthermore, Montan and Patrick (1986) have shown this effect to be minimal, based on 3-D calculations, and the air temperature varied by 2–3°C from point to point within the canister drift. This implies that large convection cells might have been operating in the drifts to even out heat transfer from the rock to the air.

Neither heating nor cooling deformations are as would be expected if they resulted purely from elastic response to thermal loading. No instrument response or errors can be identified that would cause the different responses in isolated areas across all instruments. Therefore, geologic structure is the most likely explanation, which is indicated by the strongly similar horizontal and

vertical curves of recovery (ratio) for the north heater and canister drifts. Since, at each station, both horizontal and vertical instruments saw the same type of responses, something has influenced the recovery in both orientations; however, the behavior noted is not always associated with specific, observed geologic features.

It is important to recognize how the orientation of features could influence individual CWEs. The shear zones are essentially vertical or very steeply dipping features. As a result, vertical wire extensometers would not be able to measure normal deformations of a shear zone directly; rather, they would monitor normal deformations of low-angle joints and shear deformations of shear zones. However, vertical extensometers could monitor the influence of vertical shear zones either as spatial differences in cumulative deformations of the pervasive low-angle joints or as a block response. The block response would be similar to that discussed in Section 4.1.1 (Figs. 23 and 24). Thus, block response may have been seen both by rod extensometers in the pillars and by convergence instruments in the drifts. The spatial differences of deformations of low-angle joints might result from greater potential opening of the low-angle joints where they intersect shear zones, as illustrated in Fig. 63. Although the basic mechanism of opening is similar to that for blocks, the

Figure 63. Cross section showing intersection of shear zone with low-angle joints.

opening would be in response to shear zones cutting the rock between low-angle joints, thus creating the equivalent of cantilevered beams rather than defining one edge of a block. Thus, opening of low-angle joints would be more prevalent near intersections of low-angle joints and shear zones than along low-angle joints without shears.

In contrast, the horizontal CWEs would be able to measure permanent normal deformation of the steeply dipping shear zones and vertical (open) fractures but would measure only a small component of normal deformation of low-angle joints as well as shear along low-angle joints. Unless the same phenomena were able to take place on the shear zones as on the low-angle joints, there should not be the strong correlation of recovery between vertical and horizontal CWEs that is shown on the curves.

The location of shearing, as shown in Fig. 64, indicates that the fourth CWE station in the north heater drift (Station 2 + 85) spans a shear zone; this is the specific CWE station in which there is a drop in the ratio between cooling and heating deformation. Also, there is a definite drop in magnitude of the maximum deformations at this station observed by the horizontal CWE. The decrease, if any, for the vertical CWE is very subtle. It appears that there is a reduction in the percentage recovery and an increase in magnitude of deformation due to the presence of shear zones.

4.1.4 Canister Emplacement Hole Deformation Gauges

Data sets from the canister emplacement hole deformation gauges (CDGs) are among the best in quality of those obtained from the SFT—C. These gauges were installed in CEH03, CEH07, and CEH09 immediately upon removal of the spent fuel from these holes in order to monitor changes in emplacement hole diameters during the 6-month cooling portion of the SFT—C. Although six of the transducers failed before the cooling period was completed, the failures are easily recognized in plots of the emplacement hole diameter changes. All of the CDGs yielded data that plot in smooth curves up to the approximate time of failure, without sudden unexplained offsets that are typical of some of the other instrument systems.

As described in Section 3, the two CDGs installed in CEH07 monitored instrument creep effects as a check against the data from CEH03 and CEH09. Both CDGs in CEH07 experienced an apparent drift or creep phenomena that exceeded the instrument root square error of 15 microns (Patrick et al., 1985a) approximately 142 days after

installation. All of the CDGs in CEH03 failed prior to this time without any apparent drift in the data; creep effects seem to have been preempted by complete failure of the instrument. The CDGs in CEH09 provided data until approximately 190 days after installation, but plots of their data do not show any changes in the overall data trends near the times that instrument drift should become noticeable. The CEH09 data thus appear to be free from the drift phenomenon.

Plots of data from the CDGs are shown in Figs. 65(a-c) through 69(a) and (b). Figures 65(a-c) and 66(a-c) show CDG data from CEH03, and Figs. 67(a-c) and 68(a-c) show data from CEH09. Three diameters were monitored at two locations in each of the two emplacement holes. These diameters were oriented parallel to and ± 60 degrees from the centerline axis of the canister drift. Figures 69(a) and (b) show CDG data from CEH07; these two curves reflect the creep effect tests of the CDG instrument systems.

Figures 65(a-c) and 66(a-c) reveal that even though all of the gauges in CEH03 failed within 100 days of installation, convergence data were recorded by all six instruments before failure. The data sets consistently track one another with time; a small offset approximately 30 days following installation is apparent in all three traces of Figs. 65(a-c), and an unidentified step or transition can be seen approximately 60 days after installation in all three traces of Figs. 66(a-c).

Figure 70 shows changes in three different emplacement hole diameters calculated with a thermomechanical FE model (Patrick et al., 1984a). In Fig. 71, these results have been resolved into displacements for hole diameter orientations that were monitored by CDGs. Comparison of the calculated diameter changes in Fig. 71 with the measurements in Figs. 65(a-c) through 68(a-c) reveals that diameter changes measured with time were, in some cases, qualitatively very similar to calculated values but were typically three to four times as large. This qualitative similarity, best seen in data from CEH09, confirms expectations from numerical simulations that emplacement hole diameters would initially contract during cooling and would subsequently recover part of this initial convergence. However, the disagreement in convergence magnitude may indicate that the numerical modeling was conducted with material property values or stress boundary conditions that were incorrect for the rock mass adjacent to the canister emplacement holes.

Since transducers used in the CDG instrument systems failed at different times, it is useful

Figure 64. Location of thermal phase instrumentation relative to geologic structure.

to examine data at intervals before any of the devices failed. This constraint is also important since the dummy instruments installed in CEH07 in Figs. 69(a) and (b) experienced drift after approximately 100 days, and Figs. 67(a) and (c) reveal similar trends in the data. Displacement data from approximately 36.5 and 73 days after installation were therefore selected for analysis. Data from each array of three CDGs can be resolved into major and minor components of displacement in the emplacement hole diameters. The orientation of these principal displacements indicate the directions in a horizontal plane in which maximum and minimum stress changes and associated diameter changes occur about the emplacement hole. Table 9 indicates the measured displacements and the resolved principal displacement magnitudes and orientations for each of the four arrays.

Inspection of Table 9 reveals two interesting aspects of emplacement hole convergence behavior during cooling. First, the cumulative convergence in the direction of the drift axis tends to be

essentially the same for all four instrument assemblies at a given time into cooling. This phenomenon holds true for the two time increments summarized in the table, but plots of data from CEH09 show that convergence trends tend to separate after approximately 75 days of cooling, which occurs for deformations parallel to the drift axis as well as for deformations in other orientations. Second, although convergence parallel to the axis of the canister drift is essentially uniform for initial portions of cooling, convergence magnitudes in other directions vary widely, which is reflected by the convergence values and by changes in theta values.

Taken together, the above observations imply that rock mass deformations during cooling are dominated at first by the relief of a thermal stress regime that had overridden any local stress variations caused by geologic structure. However, as cooling continued, the anisotropy of the free field stresses and the presence of discontinuities may have increasingly affected the data.

Figure 65. CEH03 deformation (CDGs) time series data (upper gauge array); (a) CDG 031, (b) CDG 032, and (c) CDG 033.

Figure 66. CEH03 deformation (CDGs) time series data (lower gauge array); (a) CDG 034, (b) CDG 035, and (c) CDG 036.

4.1.5 Fracture Monitor Systems

The fracture monitor systems (FMS) data set was, in general, complete and without significant local variation or noise. There were offsets in the data that were taken out using the same guidelines discussed previously for other instrumentation. The DAS system induced offsets that made it difficult to assess the stick-slip behavior of the rock mass and the "sticktion" behavior of the instrument itself. Therefore, even though this assessment was a major objective of the FMS instrumentation, few attempts were made to interpret the data for indications of stick-slip behavior of the rock.

Fracture monitors were emplaced to monitor individual fracture deformations. Seven monitors were emplaced on five different fractures; three of the monitors were placed on the same fault zone. The responses seen by the fracture monitors were complex and are not fully understood. They appear to be consistent with each other in terms of

Figure 67. CEH09 deformation (CDGs) time series data (upper gauge array); (a) CDG 091, (b) CDG 092, and (c) CDG 093.

Figure 68. CEH09 deformation (CDGs) time series data (lower gauge array); (a) CDG 094, (b) CDG 095, and (c) CDG 096.

Figure 69. CEH07 deformation (CDGs) time series data; (a) CDG 071, and (b) CDG 072.

the general time responses of each of the instruments (Figs. 72 through 74). Furthermore, instruments monitoring the Receiving Room fault, which has a dip of approximately 65 degrees to the southeast, all show up-dip motion with a slight right lateral offset. The motions normal to the fractures, however, are not as consistent. This is probably due to the difference in rock tempera-

tures at the Receiving Room (far) end of the drift near the crown. As can be seen in Figs. 72 through 75, the monitors at the end of the drift that were located higher on the ribs show fractures opening with time. Monitors on the fault near the invert show closing of the fractures. This is consistent with greatest expansion of the rock nearest the canisters (which were emplaced below the invert),

Figure 70. Calculated CEH diameter changes at 0, 45, and 90 degrees to canister drift axis.

Figure 71. Calculated CEH diameter changes resolved into measured directions.

Table 9. Canister emplacement borehole diameter changes following spent fuel removal.

Emplacement hole convergence 36.5 days after fuel removal ^a				
Orientation	CEH03	CEH03	CEH09	CEH09
Parallel to axis (mm)	0.200	0.205	0.195	0.200
+ 60 deg from axis (mm)	0.165	0.190	0.220	0.195
- 60 deg from axis (mm)	0.155	0.215	0.140	0.170
Major principal (mm)	0.200	0.220	0.230	0.210
Minor principal (mm)	0.1145	0.190	0.140	0.170
Theta from axis ^b (deg)	cw 6	ccw 42	cw 39	cw 26
Emplacement hole convergence 73 days after fuel removal ^a				
Orientation	CEH03	CEH03	CEH09	CEH09
Parallel to axis (mm)	0.255	0.250	0.255	0.260
+ 60 deg from axis (mm)	0.220	0.250	0.300	0.280
- 60 deg from axis (mm)	0.210	0.315	0.205	0.235
Major principal (mm)	0.255	0.315	0.310	0.285
Minor principal (mm)	0.200	0.230	0.200	0.230
Theta from axis ^b (deg)	cw 6	ccw 60	cw 44	cw 43

^a All convergence values are rounded to the nearest 0.005 mm.

^b Theta is the direction of the maximum displacement vector in the horizontal plane, referenced from the centerline of the canister drift; the abbreviation cw is clockwise and ccw is counterclockwise.

Figure 72. Time series displacement data normal to fractures; FMS-normal.

Figure 73. Time series displacement data parallel to dip of fractures; FMS-parallel to dip.

which would cause transverse rotation of the invert and flexing of the rock mass above the invert. In turn, this would cause the fractures above the springline to open slightly; rock blocks would tend to shear past each other, with blocks nearer the heat source expanding more than those further away from the heat source. The majority of

the heating and, therefore, the majority of deformations took place in the rock below the drifts, as shown in Figs. 76(a) and (b). Thus, much of the deformation response by FMSs (on ribs) would have been a stress-strain response from expansion of the rock mass below the pillars. Figure 76(b) shows calculated stress trajectories for the

Figure 74. Time series displacement data parallel to strike of fractures; FMS-along strike.

Figure 75. Cross section showing fracture response parallel to drift ribs during heating.

heated phase (from Butkovich, 1982) and also shows the greatest stress changes to be below the inverts.

Two fractures near CEH09 exhibited closing and slight up-dip motion, which is consistent with greatest expansion of the blocks nearest the center

of the canister array. Such expansion would cause closing of the fractures with largest upward expansion occurring southeast of the fractures, which would cause greater motion in the vertical direction to be on the up-dip side of southeasterly dipping fractures. However, FMS 4 and FMS 7

(a)

(b)

Figure 76. Temperature profiles at 5.0 YOC at (a) Station 2 + 83 and (b) Station 3 + 45.

indicate that the fractures were opening, which is not consistent with greater expansion in the central canister drift.

It appears that complex block interactions might have taken place; however, the data set is not extensive enough to allow analysis of the data to indicate what these interactions might be. Figures 77 through 80 show the vectors of motion during the heating and cooling cycles of the test. As is apparent, the deformations during cooling often did not reverse the apparent response to the heating. No mechanism has been identified for this behavior. Based on deformation data from the fractures, all of these structural features experienced deformation during heating that was not recovered during cooldown, which is consistent with the response seen by the CWEs and GxEs but is more complex in that the FMS data show the vector of deformation so that the difference between normal and shear components is more evident. As can be observed in Figs. 73 and 77, deformations along the fault included a significant dip component (the strike component is not addressed in these figures). However, during cooling, the deformations were essentially normal to the fault. Therefore, the shear component remained as a permanent deformation.

There appears to be rebounding during later stages of heating at FMS 3, which might reflect the influence of ventilation tests or might indicate that stick-slip of either rock or (more likely) instrument overreacted to initial stress changes and, therefore, readjusted over time to an equilibrium position. The data curves (Fig. 72) indicate the latter might be more likely. At FMS 4 (Fig. 79), heating and cooling deformations consisted of both normal and dip (shear) deformations with similar

FMS 3

Figure 78. Total response of FMS 3 parallel with rib.

FMS 1

C - Cooling
H - Heating
R - Residual

Figure 77. Total response of FMS 1 parallel with rib; the record is incomplete for FMS 2.

FMS 4

H - Heating
R - Residual

Figure 79. Total response of FMS 4 parallel with rib.

Figure 80. Total response of FMS 5 parallel with rib.

proportions of each, and with the same sense. The mechanism that results in displacements in the same direction during heating and cooling is not understood. Figure 80 shows that FMS 5 recorded much larger dip component than normal component deformations during heating. Upon cooling, a minor amount of the dip component was recovered, but the cooling deformations were principally normal. Thus, once again, a very small amount of shear (or dip) deformations were recovered. In this case, the recovery of normal displacements was also not very large or complete. At FMS 6 (Fig. 81), both dip and normal components during heating are exhibited. This array also shows a change between early and late stages of heating. However, the differences are strictly in the dip or shear component. As a result, there is principally a normal component of deformation at the end of heating. During cooling, a small dip component is observed, but the majority of deformation is normal. The result is that there is a minor residual dip component but a large residual normal component of deformation at the end of cooldown monitoring. At FMS 7 (Fig. 82), both dip and normal components of deformation during heating are exhibited. Cooldown recovery deformations were very small so that nearly all of the thermal deformations remained. The dip component of deformation during cooling was in a direction opposite of the thermal deformations; how-

Figure 81. Total response of FMS 6 parallel with rib.

Figure 82. Total response of FMS 7 parallel with rib.

ever, the normal component was in the same direction as during heating. This deformation in the same direction is puzzling and, as mentioned earlier, is not understood. The deformation might

indicate that the other side of the block was locked up in some complex way. Because the magnitude of deformation is small, the apparent same deformation sense during heating and cooling might be a result of instrument errors.

As mentioned, residual deformations at the time that the FMSs were removed are difficult to understand due to the incomplete nature of the data (not all blocks were monitored and monitoring was not fully three-dimensional). As shown in Fig. 83, there was net compression of fractures near CEH09 on the north rib. However, on the south rib, there was residual opening of the same fractures that had closure on the north rib. Furthermore, all other fractures opened.

An attempt to consider whether blocks may have moved relative to each other show some inconsistent motions (Fig. 84); the third dimension was not considered. No block responses could be identified that would explain all inconsistencies. Therefore, based on the FMS data, we conclude that fracture motions are not fully understood.

4.1.6 Vibrating-Wire Stress Gauges

Because of early failures of the vibrating-wire stress gauges (CSG and NSG series), the data

from these instruments were broken into two segments that were significantly separated in time. This data hiatus made the interpretation of total stress changes over the life of the project impossible. Therefore, the interpretation was divided into early heating and cooldown phases. Arbitrarily, the data curves were matched so that the cooldown data started at values approximating the values seen just prior to the early instrument failures, although this was not critical to the analyses.

In general, the data from the stressmeters were quiet, with very little noise in the traces and with very few offsets. Therefore, adjustments to curves that were typically made to data from other instrument types were not necessary with this data. The data are shown in Figs. 85 through 88.

Vibrating-wire stressmeters experienced a high failure rate during the early portions of the test. As a result, after the first few months of the test, the data were either missing or questionable. The stressmeters near CEH09 all failed during the first few weeks. The data indicate that stresses increased between 4–12 MPa, at which time the data curve was interpreted to indicate the beginning of instrument failure. The stress increases seen by meters near CEH03 were smaller, on the order of

Figure 83. Cross section showing final (residual) fracture deformation parallel to drift.

Figure 84. Plan view showing total normal and strike deformations along fractures.

0–4 MPa, with instrument failures also occurring approximately 6 months after installation. Larger stress increases in the central portions of the canister drift are not a result of thermal loading being greater in the center of the drift since, as calculations and temperature monitoring both show, temperatures in the rock beneath the drifts were not significantly different except near the ends of the drifts.

A significant shear zone passes through CEH09 and dips toward the stressmeters so that the rock monitored by this set of stress gauges should be more fractured than that monitored by the gauges near CEH03. However, if the presence of fractures influences the stresses, then the actual stress changes in fractured rock should be less than those in unfractured rock rather than greater,

as was noted by the gauges. This apparent difference in response from that expected may be a result of the zone of stress influenced by the fractures and subsequently monitored by the gauges. The gauges by CEH03 are located within the Receiving Room fault zone and are near the main fault trace. Presumably, the fault would have a greater influence on stresses than would the shear zones. If the gauges were detecting stress changes over more than a few borehole diameters, then the greater influence of the fault might be reflected in the data. This analysis is complicated by the unknown stiffness of the gauge–rock system at each gauge installation.

The other influence that fracturing can have on stress measurements results from the inability to measure stress directly. The gauge actually

Figure 85. Time series data from vibrating-wire stressmeters below canister drift at Station 2 + 98; X—sensor failure noted (Patrick et al., 1984b).

Figure 86. Time series data from vibrating-wire stressmeters below canister drift at Station 3 + 58; X—sensor failure noted (Patrick et al., 1984b).

measures deformations, and stresses are then calculated, using the rock modulus and gauge factor. Since the modulus of elasticity is a subtracted factor in the denominator of the calculation formula, an erroneously high estimated or assumed modulus would result in calculated stress changes that are larger than the actual stress changes that caused the measured deformation, which appears to have been the case for the data from the canister drift stressmeters. Figure 89 compares results from each of the three gauges located at CEH09

with the gauges from CEH03. The comparison is made between gauges with similar orientations and depths so that stress changes seen by corresponding gauges from the two boreholes should be similar. Because of instrument failures early during the heated phase, the comparison was made for the same time interval for the initial gauge installation and for the heated segment of data from the second gauge installation and from the cooldown phase, resulting in nine data comparisons.

Figure 87. Time series data from vibrating-wire stressmeters in north pillar at midpillar position; X—sensor failure noted (Patrick et al., 1984b).

Figure 88. Time series data from vibrating-wire stressmeters in north pillar at near canister drift rib; X—sensor failure noted (Patrick et al., 1984b).

As can be seen in Fig. 89, stress changes calculated from gauge measurements near CEH09 were consistently larger (during initial heating, late phase heating, and cooling) than the changes calculated from gauge measurements near CEH03. The stress changes calculated were 4–10 MPa, depending on the assumed modulus of elasticity and loading stress configurations used in the calculations. The stress changes noted by individual

gauges (not secondary principal stresses as shown by the calculations) were 4–10 MPa near CEH09 and 1–3 MPa near CEH03. It appears likely that the presence of fractures influenced the stress changes measured, but it is not clear from the data whether this represents an actual influence on stresses or on the calculations of stresses.

An additional critical factor is the accuracy of the gauges themselves. After the initial gauges

Figure 89. Comparison of stress changes measured below the canister drift near CEH03 and CEH09 (both heating and cooling).

failed, new gauges were installed. At the end of the test, the new gauges were calibrated. As reported by Patrick et al. (1984b), the errors of the gauge readings were in the range of ± 50 percent. Therefore, considerable variation can be expected in measurements from these instruments. However, the differences between the two station readings are not likely to be strictly due to accuracy problems since the CEH03 readings are approximately one-third those of the CEH09 readings, which is a greater difference than can be attributed solely to accuracy of the gauges. Furthermore, the magnitude of stress change is rarely (only one case) greater at CEH03 than at CEH09, as is indicated by the correlation coefficient. If the differences were due to instrument accuracy, a scatter would be expected rather than a systematic difference. Therefore, the presence of the shear zone that runs through CEH09 has influenced the results of the stress measurements.

Butkovich and Patrick (1985) report that within the accuracy of the instrumentation, the calculated and the measured stress changes agree for the cooldown cycle. Because data were un-

available for individual data points (as contrasted with nodes in a mesh), it was difficult to assess the secondary principal stresses based on the orientation of the single direction deformations measured by each gauge. Therefore, the stress changes that were indicated by individual gauges were considered, although the FEM stress calculations were for the secondary principal stresses. No attempt has been made to compare the early heating cycle measurement to the calculations because the data record is too short to be meaningful. Figures 90 and 91 show calculated stress changes for the rock beneath the canister drift. As mentioned earlier, data from measurements were not converted from secondary stress information. However, as can be seen by comparing the trends of the data and the calculations, the general responses are similar, and it appears that stress calculations in general were indicative of the actual changes that took place, at least within the ± 50 percent errors of the stressmeter data.

Stress changes were also measured in the north pillar between the canister drift and the north heater drift. The gauges were emplaced in

Figure 90. Calculated in plane horizontal stress versus time for point midheight in the spent fuel canister, 1.8 m from its axis.

the pillar in a single horizontal borehole. Therefore, the measurements of stress changes were made along a vertical plane. Two sets of measurements were made by instrument arrays or rosettes, consisting of three gauges at each location oriented 60 degrees from each other. One was near the rib of the canister drift and one was approximately midpillar. The data indicate that the stress changes seen by the gauges near the rib were consistently higher than those seen in the midpillar (Fig. 92). This is not reflected by calculations reported by Butkovich and Patrick (1985), as shown in Fig. 93 for vertical stresses, but is reflected for horizontal stress (Fig. 94). Reasons for the greater stress changes monitored near the rib than in the midpillar are probably similar to the reasons for the differences in the canister drift. In the pillar monitoring, the gauges closest to the rib would have been in areas where the modulus was

decreased in response to rock opening along the joints towards the canister drift (free face). This decrease in modulus was noted by Heuze et al. (1981a) and was considered in the calculations. If the modulus were estimated too high during the data analysis, then the readings near the ribs would appear to be too high. However, it appears that opening along fractures had a greater influence than merely an error in assumed modulus since reducing the modulus by half only causes a 10 percent decrease in calculated stress change. The difference between the rib and pillar measurements is nearly 2 to 1. Therefore, the presence of the free face with potential block movement along the fracture sets (Fig. 63) can be concluded to have influenced the stress changes in the pillar closest to the rib, which, once again, is consistent with observations from the MBI rod extensometers and the CWE measurements.

Figure 91. Calculated in plane vertical stress versus time for point midheight in the spent fuel canister, 1.8 m from its axis.

Before a rigorous comparison between the calculated and the measured stress changes can be made, the individual readings from the monitoring need to be converted to secondary principal stress changes and a time series plot needs to be constructed (or conversely, component stresses to reflect the orientations of the gauges need to be calculated from the computer model and a plot needs to be constructed) for comparison with the calculated time series plots.

4.2 Interpretation of Integrated Data

4.2.1 Gross Geomechanical Response to Heating and to Cooling

In this section, the overall responses observed in all of the geomechanics instrumentation in the

Figure 92. Comparison of stress changes in pillar at midpillar and near rib locations (both heating and cooling).

Figure 93. Calculated in-plane vertical stress versus time for a point midheight in pillar, 0.7 m from spent fuel drift and 3 m from heater drifts.

SFT—C are summarized. To do this, a combination of overlays of the data plots from individual channels as well as from average values (where appropriate) are used. This information should provide the reader with a feeling for the gross response of the rock during both heating and cooling. This is the information that will be most readily compared with models since it is representative of the facility as a whole, without consideration of localized influences. Because each instrument type looked at a different set of data, this section is organized in the same way that the overall report is; that is, the MBI data will first be discussed, followed by the GxE data, etc.

Pillar and Canister Drift Crown Deformations (Mine-By Extensometer Data). The MBI instrumentation monitored the response of the pillars between drifts and the deformation of the rock immediately above the canister drift. The deformations monitored by the horizontal-oriented MBIs were entirely pillar deformations.

Deformations monitored by the inclined extensometers varied between pillar and above-roof deformations. Also, since the orientations of the extensometers varied, the deformations that were monitored resulted from different orientations within the stress field. No attempt is made to discuss deformations as an equivalent strain; rather, the total deformations are compared and reported.

The time history data curves from the four horizontal MBIs (MBIs 1, 4, 8, and 11) are very similar. In each case, the maximum deformations occurred approximately 4 YOC, just after one of the ventilation tests, with the maximum deformation near the canister drift rib of approximately 0.4–0.5 mm of expansion. The deformations then varied with ventilation or heat load, until cooldown started. The smallest deformations, those seen by the first anchor in from the heater drifts, were all similar at approximately 0.15 mm. Cooldown deformations were also similar for all of the horizontal extensometers. However, MBI 11

Figure 94. Calculated in-plane horizontal stress versus time for a point midheight in pillar, 0.5 m from spent fuel drift and 3 m from heater drifts.

data does not exhibit the same shape as the other extensometers. It is unlikely that this is due to real differences since the curves of each anchor in this extensometer cross each other, which indicates that the data from this extensometer was becoming less reliable during the cooldown portion of the test. Therefore, MBI 11 data was not incorporated into the analysis of gross response. The remaining extensometers showed that, during cooldown, the recovery near the canister drift rib was approximately 0.25–0.3 mm, with approximately 0.5–1.0 mm of deformation not recovered at the time that monitoring ceased. Midpillar recoveries were quite similar to those of the rib, with slightly smaller magnitudes (0.2–0.25 mm). The nonrecovered deformations were nearly the same magnitude as near the ribs. The smaller recoveries were near the heater drifts since the total deformations were the smallest. These recoveries were on the order of 0.1 mm, with little residual

deformations. The percentage recovery near the canister drift was approximately 75–80 percent, the recovery near the heater drifts was approximately 80–100 percent, and the recovery in the midpillar position was approximately 70 percent. These results are as would be expected with the midpillar cooling only slightly slower than the ribs.

The 35-degree inclined extensometers monitored the rock both within the pillars and near the canister drift crown. Roughly speaking, the first three anchors monitored the pillars and the last three monitored the canister drift crown. The responses at Station 2 + 83 were quite similar for the pillar and the crown, with the possible exception of the last anchor in MBI 2. The anchors at Station 3 + 45 appear to see relatively more response above the crown than in the pillar (there appears to be more separation of the curves). With the intersection of fault and shear zones in the crown near this area, it is possible that the rock modulus

was different in this particular area. During heating, the maximum deformations seen by the deepest anchor (nearly directly above the canister drift center) were roughly equal for each of the MBIs, with magnitudes between 0.5–0.7 mm (heating phase) of expansion. The minimum deformations seen (nearest the heater drift rib) were approximately 0.05–0.15 mm.

Cooldown responses were not as consistent between extensometers as were the thermal phase responses. Responses varied for the deepest anchor from 0.2 to 0.5 mm. Recovery of the shallowest anchors was consistently approximately 0.05 mm. Because of the widely differing responses, it is difficult to judge the comparative amounts of recovery with depth into the rock. The most uniform-appearing time history data are from MBI 5. These data indicate nearly 100 percent recovery for all anchors. Recoveries for other extensometers were not as uniform, and often the lower recoveries (that is, the higher residual deformations) were seen above the canister drift. The mechanism for this difference is not well understood since the rock nearest the drift surfaces should be that which cooled the most rapidly. Therefore, if the data are accurate, they must indicate that deformation of rock was not entirely elastic (possibly due to fracture opening as discussed previously) or that a change of modulus took place during heating that could not be entirely recovered.

The 50-degree inclined extensometers monitored rock both above the pillars and above the canister drift; however, as can be seen in Fig. 6, they mainly monitored the deeper rock so that less of a distinction would be expected between pillar and drift anchors. In general, the time history data curves indicate this to be the case. The data show a somewhat uniform increase in total deformation measured with depth. The maximum deformation occurred at the end of the heating phase and was approximately 0.5–0.6 mm of expansion. The deformations were quite consistent among all extensometers. The minimum deformations (nearest heater drifts) were consistently approximately 0.1 mm.

Cooldown deformations of approximately 0.25–0.3 mm were monitored by all of the deeper anchors, which amounted to approximately 50 percent recovery of the thermal deformations. Recovery varied for the shallow anchors (near heater drifts) from 100 percent to less than 50 percent. The

data are insufficient to draw conclusions as to the source of this variability in the cooldown data.

GxE Data. As discussed earlier, the GxE data set is one of the least consistent or complete data sets because of the multiple instrument failures. The gross response of the rock cannot be as usefully analyzed nor considered in as much detail as the responses from other instrumentation. These data reflect vertical deformations of the rock below the canister drift that resulted from thermal loads imposed by the emplacement and subsequent removal of spent fuel and electrical simulators. Because all instrument sensors were replaced during the test, it is not possible to determine what the total thermal deformations were nor the percentage of these deformations that were recovered during the cooldown phase; rather, the amount of cooldown deformation as related to position is discussed.

As shown in Figs. 42 and 43, the amount of deformation seen by the anchors in GBE and GCE series extensometers were quite consistent with distance away from the center of the canister drift and with depth below the floor. The shallow anchor (anchor 1) monitored cooldown deformations of approximately -0.1 to -0.2 mm, the higher values being those from GCE extensometers. There is a trend in both extensometer series to have greater deformations near the center of the drift, but the differences are not large. Anchor 2 data varied from -0.3 to -0.35 mm and was quite comparable for both extensometer arrays. Anchor 3 data showed the same trend with less deformations noted to the southeast; the reason for this trend is not understood. The values fall in the range of -0.6 to -0.4 mm. Data from the deepest anchor was inconsistent. At three of the extensometers, the fourth anchor indicated less deformation than did anchor 3 or even anchor 2. Since the anchors are measuring cumulative deformations, this is equivalent to the rock between anchors 3 and 4 somehow responding in a fundamentally opposite fashion than the rock above anchor 3. Specifically, during heating, the rock above anchor 3 expanded while the rock below anchor 3 contracted and, during cooling, the rock above anchor 3 contracted while the rock below anchor 3 expanded.

Convergence Wire Extensometer Data. The data from the horizontal convergence wire extensometers in each of the drifts are fairly tightly clustered. The maximum convergence is between

0.4 and 0.6 mm. As discussed earlier, there was an apparent fracture-controlled permanent convergence near the fault zone that influenced the amount of recovery during cooldown. The cooldown recovery ranges from approximately 80 percent to less than 20 percent.

Data from the vertical convergence wire extensometers are not as well clustered, particularly in the north heater drift, which is interpreted to be caused by the presence of the Receiving Room fault. As noted in Figs. 51 through 53, the measurements cluster quite well except for the data from the stations nearest the fault. The magnitudes of convergence measured at the station closest to the fault in the north heater drift (Fig. 51) are more than double the magnitudes measured at all other stations within this drift. The maximum vertical convergence in the unfaulted sections of the drift was 0.6 mm, and the maximum vertical convergence near the fault was 1.2–1.3 mm. Maximum convergence in the canister drift was comparable to the unheated maximum in the north heater drift (approximately 0.6 mm). Maximum vertical convergence in the south heater drift was approximately 0.55 mm. The data from the south heater drift are the most consistent relative to position within the drift. There is no indication of geologic structure influence in the data. Therefore, it appears that intact rock convergence of approximately 0.55 mm maximum is representative of that of the heater drifts. The canister drift convergence was of similar magnitude, even though the drift is much larger in cross section than are the heater drifts.

Response during cooldown was even more dramatically influenced by the presence of the fault. As noted in Fig. 57, cooldown recoveries on the order of 0.3–0.4 mm were measured in the majority of the north heater drift. These recoveries amount to 50–100 percent of the thermal convergence. Near the fault, however, the recovery is less than 0.3 mm, which is less than 30 percent of the thermal convergence. In the tightly clustered data from the south heater drift, the cooldown recovery is approximately 0.3 mm, which is roughly 50 percent recovery.

Emplacement Hole Convergence Measurements. The CDGs were the only displacement monitors oriented such that a direct (or nearly direct) comparison could be made with monitored stress changes. This comparison is possible for CEH03 and CEH09, where the CDGs were monitoring deformations in the horizontal plane and

where the nearby stressmeters were monitoring stress changes in the horizontal plane. Since the deformations of the holes can be related to stress changes, there should be consistency between both the sense and the magnitudes of deformation if the thermoelastic properties are chosen correctly. A plane stress analysis performed with a modulus of 38 GPa gave stress relief results of 6–9 MPa. However, plane stress conditions are not entirely correct beneath the invert of the canister drift.

Fracture Monitor Data. Because the fracture monitors were deployed to measure individual fractures, conclusions regarding overall (or generalized) behavior must be carefully made. In general, the data curves indicate that rock response was not stick-slip but was more of a semiuniform behavior. There is variation in the response and some stick-slip behavior may be reflected, but stick-slip is not the dominant behavioral pattern. The displacements parallel to the dip are, in general, the larger displacements, and those along the strike are (with one exception) quite small.

The displacements normal to the fractures range from -0.15 to $+0.05$ mm during the heating phase of the project. Recoveries during cooldown are inconsistent; in some cases, the displacements continue with the same sense during cooldown as during heating. In other cases, the recovery of displacements during cooldown are greater than the thermal displacements. Assuming that the data accurately reflect rock motions, some type of block movement appears to be involved. Block movement that would result in more recovery than the original thermal deformation would cause opening of fractures which should be reflected in other data. Although some data indicate the influence of shear zones, most other data consistently show less than 100 percent recovery of the original thermal deformations. No further attempt is made to assess the general response during cooldown.

Displacements measured along the dip of the fractures during the thermal phase appear to be consistent. The maximum displacements range from $+0.10$ to -0.05 mm. Cooldown phase data are sparse and not worthy of discussion.

Displacements along the strike were the smallest and in general are consistent. These data cluster better than the data measured either normal to or along the dip of the fractures. The general trend of the cooldown data is more consistent

for this data than for the normal or dip data. There is only one case where the cooldown and thermal phase responses are clearly in the same direction. In all other cases, the responses are of opposite sense or are ambiguous. Therefore, the cooldown response appears to be recovery of the thermal displacements, as would be expected.

Stress Change Measurements. Stress change measurements during the early thermal phase were successfully made only in the pillar between the north heater and canister drifts. A fairly complete indication of the changes at the end of the thermal phase are available, but since most of the stress changes are expected to have taken place early, the data are not very helpful. Therefore, the emphasis of analysis is on the cooldown data, which are complete for canister floor and pillar emplacements.

Because of gauge orientations, the stress changes measured in the pillar do not relate directly to any of the displacement measurements. The stress changes were measured in a vertical plane parallel to the drifts. Therefore, stress changes measured in the pillar were parallel to the drifts and subhorizontal as well as vertical. Displacements measured in the pillar were essentially horizontal and perpendicular to the drifts. The stress changes measured in the holes near the canisters relate to the borehole deformation measurements since the changes were essentially measured along a horizontal plane that cut through the middle of the canister emplacement hole.

Stress changes in the pillar are strongly clustered at approximately -1 MPa. It is surprising that there is such uniform change regardless of orientation. The stress changes along the canister emplacement holes are more significant. During cooldown, the measured changes ranged from -2 to -10 MPa at Station 2+98 and from -1 to -4 MPa at Station 3+58.

Overall Interpretation. An important part of the analysis of gross geomechanical response of the rock mass during the heated phase of the SFT—C is a comparison of thermomechanical measurements with calculated values from finite element modeling. This comparison provides insight into both the effectiveness of the modeling and the nature of the rock mass responses. Data sets are available for comparison from a variety of geotechnical instrument systems. However, for maximum benefit, such comparisons should be based on data that are relatively complete and for which intrinsic sources of error are relatively small. For these reasons, the following paragraphs compare MBI data with the results of finite ele-

ment calculations of the rock mass thermomechanical response.

Comparisons of model results with data for 6-month intervals have been made by Butkovich and Patrick (1985), so the analysis here focuses on maximum deformations rather than on deformation trends over time. The high quality and relative completeness of the MBI time series data plots allow maximum recorded deformations from the heated phase of the SFT—C to be picked with confidence for comparison with model results. Figure 95 plots maximum calculated rock mass displacements against maximum measured rock mass displacements for each MBI anchor. These values are given with respect to the instrument heads, which are located at the collars of the boreholes in which the instruments are installed. This analysis excludes MBI 4, MBI 5, MBI 6, and MBI 11 because the operation of these instruments inadvertently missed displacements that occurred in the first few weeks of the SFT—C.

A perfect match between model results and measurements would allow a straight line to be fitted through the points, with an axis intercept of zero and a slope and a correlation coefficient of unity. A straight line through the points of Fig. 95 has $R^2 = 0.012$, indicating a poor fit between the calculated and the measured maximum deformations. The displacements can be divided into three geometric subsets for further analysis according to whether the MBI extensometers are horizontal, dipping at 34 degrees above horizontal, or dipping at 50 degrees above horizontal. Figures 96 through 98 show these comparisons, and Table 10 describes the characteristics of a straight line fitted through these points with a least squares approach.

Figure 95. MBI data compared with ADINA calculation 2, maximum.

Figure 96. MBI data compared with ADINA calculation 2, horizontal.

Figure 97. MBI data compared with ADINA calculation 2, 34 degrees.

Figure 98. MBI data compared with ADINA calculation 2, 50 degrees.

The match between thermomechanical model results and all MBI data is indicated to be very poor by the magnitude of the axis intercept and by the correlation coefficient. When the data are broken into subsets, the quality of the overall match is degraded by the 34-degree MBI data subset, which might reflect the nearness of larger portions of these particular instruments to the perimeter of the canister drift excavation. In contrast, the calculated maximum displacements compare more favorably with the horizontal and 50-degree MBI extensometers as axis intercepts. The slopes of the fitted lines, however, diverge in opposite senses from unity for these two comparisons. These variations indicate that calculated maximum displacements during the heated phase of the SFT—C were more than twice the measured values for the horizontal instruments but were only approximately 30 percent of the measured values for the 50-degree instruments. The observed difference in slope for these two orientations suggests that either the mesh boundary conditions or the isotropic elastic properties used in modeling the SFT—C were incorrect. Butkovich (1982) examined the effects of finite element mesh size on the results of thermomechanical calculations of rock mass deformation at the SFT—C. However, all of the models used constant-stress boundary conditions in both the vertical and horizontal direction. Imposition of lateral boundary conditions that increased in stiffness with increasing lateral displacement may bring both the horizontal and 50-degree MBI comparisons in line.

These implications can be explored further as follows. If the horizontal deformations of all three drifts as measured by the CWE instruments are added to the displacements recorded by horizontal MBI extensometers, the resulting sum represents the lateral deformation of the entire SFT—C facility at a given time. This summed deformation is between the extreme opposite ribs of the north and south heater drifts. Although the deformations of a relatively small amount of rock between the deepest anchors of the horizontal MBI instruments and the immediately adjacent canister drift ribs are omitted, the sum is a good approximation for comparison with the thermomechanical models. A comparison of model results with CWE data is made in Section 4.1.3 and is recalled here to contrast horizontal and vertical deformations of the SFT—C facility cross section (Fig. 99).

From Section 4.1.3, the average lateral drift deformations measured by CWE at the time of maximum MBI displacements is approximately 0.6 mm of convergence in the canister drift and is

Table 10. Correlation of maximum calculated heated phase MBI displacements with measured maximum displacements.

MBI Subset ^a	R Squared ^b	Intercept (mm)	Slope (mm/mm)
All MBI data	0.012	0.235	0.129
Horizontal	0.981	0.041	2.242
MBI at 34 deg	0.038	0.281	-0.091
MBI at 50 deg	0.865	0.078	0.317

^a Excluding MBI 4, MBI 5, MBI 6, and MBI 11.

^b "R Squared" is the correlation coefficient.

Figure 99. Measured and calculated total deformations across drifts.

essentially nil in the heater drifts. Maximum horizontal MBI displacements are approximately 0.4 mm of pillar expansion; this totals to a change of approximately 0.2 mm of divergence between extreme opposite ribs of the heater drifts during the St-T-C heated phase. Calculated maximum horizontal deformations are approximately 0.25

and 1.10 mm of convergence in the canister and heater drifts, respectively, and approximately 0.95 mm of expansion in each pillar. Although magnitudes of calculated horizontal deformations are approximately twice those of the measurements in the pillars and in the canister drift, the sum of all horizontal calculated deformations between

extreme ribs of the heater drifts is approximately 0.3 mm, which compares well with the 0.2 mm sum of the measurements. However, the data are not sufficient to indicate whether the cancellation of rock and drift deformation differences is systematic or merely fortuitous.

The vertical deformation (from CWE data) is approximately 0.6 mm of convergence in the canister drift and approximately 0.5 mm of convergence in the heater drifts. The corresponding calculated deformations are 1.3 and 1.0 mm, respectively. The calculated deformations are approximately twice the measured values, as they were in the lateral case, but the differences for the vertical case are not canceled out by a summation process because the proper components of displacement were not available from the GxE instruments.

Taken together, the comparisons of the calculated and the measured deformations in both vertical and horizontal directions imply that the material properties used in the thermomechanical calculations may have been in error by up to a factor of two. This implication contrasts with the comparisons based on MBI data alone, which implied a possible anisotropy in the properties or a problem with the boundary conditions of the finite element mesh. The two types of comparisons are not mutually exclusive, however, since the MBI comparison examines rock mass response directly (and excavation response indirectly) and the comparison of lateral deformation given above integrates both excavation and rock pillar responses. A similar comparison in the vertical dimension is precluded by a lack of appropriate data from the GxE instruments. Although a model of either the excavation or the surrounding rock might be incorrect, an integrated model that includes both excavation and rock responses might tend to yield more realistic results.

The MBI extensometers at the SFT—C were installed in symmetric arrays so that the symmetry of the rock mass response to the mining and the subsequent thermal phases of the test could be evaluated. In addition, the displacements measured by these instruments can be resolved into horizontal and vertical components of motion to examine the deformation of the facility in a vertical direction. The maximum displacements measured by the MBI systems during the heated phase of the test were selected for this purpose.

It should be noted that this analysis includes all MBI instruments (in contrast to other discussions), even though some of the instruments were not operational during the first few weeks of the

test. Inspection of time series plots indicates that rock mass displacements occurred in a progressive fashion as the thermal pulse propagated through the rock. The progressive nature of the displacements, with the similarity of form of the data plots, implies that only a limited amount of the maximum displacement was missed by some of the instruments.

To examine the vertical deformation of the test facility, the maximum displacements measured at each MBI anchor (relative to the collar of the hole) were resolved into vertical and horizontal components of motion. The vertical components were averaged from the opposite sides of the symmetrical array, and the horizontal components were simply added together. The symmetry of the response of the facility to thermal loading is discussed in Section 4.2.4; however, if the response were perfectly symmetric, the horizontal components of displacement would add to zero. Figure 100(a) plots the vertical component of displacement as a function of anchor number (not depth) from the instrument collar for the MBIs at 34 degrees above the horizontal; Figure 100(b) plots the sum of the corresponding horizontal displacements. Figures 100(a) and (b) show similar plots for the MBIs at 50 degrees above the horizontal. The plots include data from the MBI arrays at canister drift Station 2 + 83 and Station 3 + 45.

The sums of the horizontal components of displacement in each case are less than 50 percent of the averaged vertical components at the deepest anchors. The horizontal sums do not show a tendency to change systematically with distance from the collar as the vertical displacement plots do, which implies that variation in the sum of the horizontal components is caused by local rather than systematic variations in rock mass response. The average of the vertical components of displacement increases with depth to reach a maximum over the SFT—C canister drift. Thus, the plots show a maximum upward movement of the rock above the centerline of the facility of up to 0.4 mm with respect to the MBI collars.

It is useful to consider how this vertical displacement is related conceptually to the overall deformations of the facility derived in discussions from CWE and from horizontal MBI data. This analysis of MBI data indicates that rock above the canister drift moved upward during the thermal phase of the test, even while the canister drift experienced a vertical convergence of approximately 0.6 mm. In both cases, the driving mechanism causing the displacement was thermal expansion of the rock mass. Thermal expansion of the pillars

Figure 100. SFT-C symmetry analysis (34-degree MBIs); (a) vertical, and (b) horizontal.

Figure 101. SFT-C symmetry analysis (50-degree MBIs); (a) vertical, and (b) horizontal.

between the drifts moved the rock above the facility progressively upward, while at the same time expansion immediately below the canister drift moved the drift floor upward by a larger amount to cause apparent convergence of the drift. This scenario agrees conceptually with calculations by Butkovich and Patrick (1985). It is important to note, from the relative smoothness of the plots in Figs. 100(a) and (b) and 101(a) and (b), that this mechanism of deformation overwhelmed the localized effects of geologic structures that are indicated by irregularities in the plots.

4.2.2 Repository Model Cell and Drift End Effects

Very few instruments were set up to address specifically drift end effects. In most cases, the instruments were located away from end effects. The MBI extensometers, CDGs, and vibrating-wire stressmeters were located such that they

should have been largely unaffected by end effects. Even though the fracture monitors were located in both the central portions of the canister drift and in the Receiving Room, they were not designed to look at end effects. They were designed to look at individual features and did not give information relative to similar features with similar orientations. Convergence wire extensometers could have seen end effects in that one array was located at the end of the canister drift. However, the purpose of this array was to monitor the response of the Receiving Room fault, and, as such, it spanned the fault. This prevented the comparison of end effects unencumbered by the influence of geologic structure. The only instruments specifically designed to consider the end effects were the GxE extensometers. Extensometers were located at the respective ends of the canister drift to provide comparisons with responses monitored within the canister drift itself.

Comparisons for end effects should be made between GAE/GDE series and GBE/GCE series extensometers. Specifically, this comparison should be between both the CAE and GDE extensometers and the GBE06 and GCE06 extensometers. Direct comparison is impossible because of instrument failures. A comparison has been made by assuming that data from the GBE and GCE series extensometers have been properly reconstructed to cover for the missing data and that data from GCE05 or GCE01 can be used for the missing GCE06. This comparison shows that deformations monitored by the GDE set of extensometers were slightly less than monitored by the GBE and GCE series for near-floor anchors and were approximately one-fifth the magnitude of the GBE and GCE series for the deeper anchors. The GAE series sensors failed prior to the end of the heating cycle and were not replaced. The GAE series extensometer apparently was monitoring displacements somewhat comparable with those of the GBE and GCE series extensometers prior to their failure.

The comparison between GAE and GDE series shows considerably smaller displacements in the Railcar Room end of the drifts than in the Receiving Room end. However, the data are not sufficiently complete to make firm conclusions, and the comparison is complicated by the presence of geologic structure. A significant difference between the GBE and GCE series extensometers has been interpreted in this report to be due to the presence of shear zones. Since GAE extensometers were in the Receiving Room fault zone with anchors and head assemblies were in a different fault block than the remainder of the GxG extensometers, it is quite likely that most, if not all, of the differences noted in displacements were caused by geologic structure.

The data from convergence wire extensometers indicate that the presence of the Receiving Room fault influenced the responses in the north heater drift and in the canister drift. However, data from the south heater drift do not show significant differences at the ends, indicating that end effects seen in the other two drifts may have resulted from the proximity of the Receiving Room fault. If localized structural effects such as this are ignored, it can be concluded that, in a thermomechanical sense, the SFT—C facility behaved in a rather homogeneous way during the heated phase of the test. Geologic structure significantly perturbed this gross overall performance on a local scale.

4.2.3 Influence of Specific Geologic Features

An attempt was made to investigate different classes of geologic features by using the fracture monitors. Although these data are not of sufficient quantity or uniform orientation to allow a thorough analysis to be made, there were indeed few instances (with exception of the Receiving Room fault) where clear examples of geologic structural influence on measurements were seen. An overall conclusion is that the joints influenced the gross facility behavior by reducing the rock mass stiffness while the fault and similar structures produced more pronounced (but also more localized) effects in the response.

The Mine-By extensometers crossed shear zones. Contrary to what was observed during Mine-By, shear zones did not appear to influence significantly the thermal rock response as seen by the MBIs. The canister drift extensometers did exhibit significant difference between the array at CEH09 and CEH03. These arrays were designed to compare unheated and shear rock response. It appears very likely that the presence of shear zones caused larger deformations. What is not clear, since the extensometers measured deformations that are parallel to the shear zones, is whether the influence on deformations was a result of modulus differences or a result of actual deformations along the fractures of the shear zones. There does not appear to be a significant difference in stress change measurements at these two arrays.

4.2.4 Drift Symmetry and Damaged Zones Used in Modeling

As mentioned in previous sections, part of the analysis of gross geomechanical responses of the rock mass during the SFT—C involves comparison of measurements with values calculated using thermomechanical models. The MBI data from the heated phase of the SFT—C provide a way to examine two assumptions made in modeling the test. These assumptions were that overall rock mass responses would be symmetric about the centerline of the canister drift and that a small zone of rock immediately surrounding each excavation had been damaged during blasting.

To check the validity of the assumed symmetry in gross rock mass behavior, maximum recorded displacements from the heated phase of the SFT—C were picked for comparison in terms of anchor location. Gross behavior in this sense

refers to overall displacements or deformations, without regard for local effects caused by geologic structure. Figure 102 plots maximum measured rock mass displacements for anchors in the north pillar of the facility against corresponding measurements (anchor by anchor) from the south pillar. The values are given with respect to the MBI instrument heads, which are at the collars of the boreholes in which the instruments are installed.

It should be noted that this analysis includes all MBI instruments, in contrast to some of the discussions in Section 4.2.1, even though some of the instruments were not operational during the first few weeks of the test. Inspection of the time series plots indicates that rock mass displacements occurred in a progressive fashion as the thermal pulse propagated upward from beneath the SFT—C drifts. The progressive nature of the displacements, along with the general similarity of form of the time series plots, implies that little of the eventual maximum displacement was missed by instruments that became operational only after the first few weeks of the test.

Returning to the analysis of Fig. 102, a perfect match between measurements from opposite pillars would be indicated by all points falling along a straight line with an axis intercept of zero and a slope and a correlation coefficient of unity. Such an ideally symmetrical response is unlikely because rock contains discontinuities that affect the displacements and, hence, the individual mea-

surements. Since the symmetry of the response (rather than local variation in behavior) is of interest here, the analysis focuses on a line fitted through points in Fig. 102. Using a least squares approach, such a line has an axis intercept of -0.035 mm, a slope of 1.022, and a R^2 of 0.833. The deviation of the R^2 from unity can reflect both asymmetry and local variability in the rock mass behavior. Thus, the comparison appears to validate the symmetry that was assumed in the modeling.

A similar analysis was performed by comparing maximum heated phase displacements measured by the MBI array at canister drift Station 2+83 with those from the MBI array at Station 3+45. This provides some insight into whether it is appropriate to use a single two-dimensional model calculation for different locations along the SFT—C facility centerline. Figure 103 plots displacements measured at Station 3+45 against displacements from corresponding anchors at Station 2+83. A line fitted through the points has a slope of 0.713 and a correlation coefficient of 0.703. The fit in this case is not quite as good, which might be indicative of a stronger influence by geologic structure, as discussed earlier.

The zone of rock that was assumed to have been damaged by blasting would have an elastic modulus somewhat lower than that of the rock mass, in general. The existence of such a zone has been verified by NX borehole jack tests (Patrick et al., 1985a); the effect of the damaged zone on

Figure 102. MBI displacements in north and south pillars.

Figure 103. MBI displacements at Stations 3+45 and 2+83.

Figure 104. Displacement as a function of depth—north pillar 2 + 83 MBI array; (a) MBI 01, (b) MBI 02, and (c) MBI 03.

Figure 106. Displacement as a function of depth—north pillar 3 + 45 MBI array; (a) MBI 08, (b) MBI 09, and (c) MBI 10.

Figure 105. Displacement as a function of depth—south pillar 2 + 83 MBI array; (a) MBI 04, (b) MBI 05, and (c) MBI 06.

Figure 107. Displacement as a function of depth—south pillar 3 + 45 MBI array; (a) MBI 11, (b) MBI 12, and (c) MBI 13.

MBI displacement data is evaluated here. Figures 104(a-c) through 107(a-c) plot the maximum displacements from the heated phase of the test as a function of anchor depth from the hole collar. Each plot includes a line drawn from the collar (zero displacement) depth to the point representing the deepest anchor. Deviations of intermediate points (anchors) from the line indicate deviations of the rock mass from a continuous field of deformation. Such deviations could be caused by geologic discontinuities such as shear zones or by a damaged zone at the excavation surface (between the hole collar and the first anchor).

Inspection of Figs. 104(a-c) through 107(a-c) indicates that, in general, there is not much deviation of displacement trends between the hole collar and the first MBI anchor. This is not surprising because the instrument collar locations were sited in rock that appeared to be sound with loose or "drummy" sounding rock removed. Furthermore, a uniform damage zone is not expected because the zone of rock damaged by blasting can vary in thickness from place to place. Deviations that can be identified do occur with MBI 6, MBI 10, MBI 11, and MBI 12; however, these deviations are not straightforward to interpret because in the first two instances the measured displacement is high while in the second two instances it is low. Of perhaps more interest are deviations between adjacent anchors at depths away from the surface of the excavation. These deviations might indicate which shear zones of several crossed by instruments were subject to displacement during the test. Figures in Section 4.1 illustrate conceptually how movements along discontinuities affected CWE and FMS data; such localized displacements are also reflected by MBI data in these plots and might be the subject of future analyses.

4.2.5 Comparison of Mine-By and Thermally Induced Responses

Measurements were made during the early phases of the SFT-C Project to monitor pillar deformations during mining of the canister drift. Analyses of the data indicated that the elastic response of the rock mass was perturbed by the presence of shear zones (Wilder and Patrick, 1981). The thermal phase and cooldown phase monitoring of deformations by the same extensometers allow for consideration of whether the same apparent influence by the shear zones on rock mass deformations was present during these phases of the Project.

Figure 108 shows an anchor-by-anchor comparison of deformations observed during MBI and heated phases of the test. The purpose of this analysis is to determine the agreement between the Mine-By and heated phases of the test. Variation of points from a line through the origin with a slope of unity indicates how much the response at a given anchor point varied between the two test phases. The deformations were caused by different processes so there is no reason to believe that there would be a relationship between the magnitudes of the deformations during the Mine-By and thermal phases. However, it is not unreasonable to expect that the response would remain either elastic or inelastic in nature even though the magnitudes may be different. There is no correlation between the points of the thermal and Mine-By monitoring. The ratios during Mine-By varied widely, from nearly -8 to as much as 18; however, the ratios during the thermal phase monitoring were tightly clustered between approximately 0 and 2. Therefore, the conclusion is that the influence of geologic structure during the Mine-By is not the same during the thermal phase monitoring. The behavior during thermal phase monitoring appears to be more elastic.

Figure 109 is a similar comparison between the cooldown and MBI phase monitoring. This comparison was made because it is possible that during the Mine-By the fractures were opening with stress relief and during the thermal phase they were closing with increasing stresses so that the process is not the same. During cooldown, the

Figure 108. Comparison of measured versus calculated MBI displacements during Mine-By and heating.

Figure 109. Comparison of measured versus calculated MBI displacements during Mine-By and cooling.

stresses are decreasing again so that if the shear zones were preferentially deforming in comparison to the rock mass, the same type of behavior should be observed during cooldown as during mining. There is one major difference—during mining the stresses had already been relieved near the heater drift ribs so that the major changes observed were closer to the canister drift. Although these differences were taken into account in the calculations, if there were influences by the shear zones, those influences would be most pronounced where the total deformations were largest. Therefore, the same ratio of calculated to observed would not be as likely near the heater drift ribs during cooldown as during Mine-By.

The results of the comparison for the cooldown are quite similar to those of the thermal phase. As can be seen in Fig. 109, the ratio during cooldown ranges from 0 to 2, which indicates that the opening of fractures during cooldown did not override the overall elastic response of the rock mass. It is not clear whether the type of response seen during the Mine-By would have occurred if the cooldown had progressed to completion. The data does not seem to indicate that this would have happened, but it cannot be ruled out.

The final comparison, between the thermal and cooldown phases, was made because the curves seen in the two previous comparisons for the thermal and cooldown phases were similar—both with slopes of zero and intercepts of approximately 0.1 mm. However, as can be seen in Fig. 110, the comparison on an anchor-by-anchor basis is not strong, which indicates that the displacements seen are highly variable.

Another factor considered was that the anchor points near the drift were possibly creating erroneous interpretations since many of the larger ratios during the thermal and cooldown phases were near the heater drift ribs. Therefore, the same comparisons were made, excluding the data from the first anchor point (closest to the rib) of each extensometer. Figures 111 through 113 show these comparisons. Although the correlations are slightly improved, the same general patterns are evident. Therefore, the conclusions remain the same for the revised data as for the entire data set.

4.2.6 Ventilation Effects

Late in the heated phase of the SFT—C, a series of brief changes in ventilation rate were implemented to evaluate the effects of the ventilation on heat removal from the facility. Since these changes affected thermal conditions in and around the drifts, they necessarily also affected geomechanical data from the facility. Different parts of the ventilation experiments involved increasing or decreasing the air flow through the facility; in general, a decrease in ventilation had a more profound effect on the measurements than did an increase. This was probably because, within the capability of the ventilation system, it was easier to allow the drifts to become hotter through a decrease in air flow than it was to make the drifts cooler through an increase in flow. During the cooling phase of the SFT—C, the spent fuel was removed, the electrical heaters were turned off, and the ventilation system was augmented with additional fans. All of these heat sources were functioning during the ventilation experiments.

Figure 110. Anchor-by-anchor comparison of heating and cooling MBI displacement.

Figure 111. Anchor-by-anchor comparison of MBI displacement during Mine-By and heating excluding first anchor.

Figure 113. Anchor-by-anchor comparison of heating and cooling MBI displacements excluding first anchor.

Figure 112. Anchor-by-anchor comparison of MBI displacement during Mine-By and cooling excluding first anchor.

ventilation experiments. Interestingly, changes are seen more frequently in the MBI data. The CWE and FMS data reflect ventilation changes only in certain instruments, but the GxE data do not reflect the changes at all. Conceptually, many of these differences can be explained by the proximity of an instrument system to the heat sources below the SFT—C drifts, e.g., the GxE instruments were too close to the spent fuel to be affected by short-term drift cooling or heating. The MBI instruments were located in pillars that could be affected thermally by the ventilation rate from two sides, but the ventilation changes often involved opening the doors so that increased ventilation was greater in canister drifts than in heater drifts. Therefore, an increase in heating caused by a drop in ventilation rate caused a predictable, associated increase in displacement magnitude. The response of the CWE and FMS systems, though, is puzzling because only some of the vertical CWE instruments and some of the FMS systems appear to be influenced by the ventilation experiments.

Time series plots of MBI, GxE, CWE, and FMS data (presented in Section 4.1) were examined for changes in data trends that reflect changes in the thermal regime caused by the

5. Conclusions

Several basic conclusions can be drawn from the analysis of geomechanics data. The first and possibly overall conclusion is that during the thermal phase the rock behaved essentially elastically for sections with shear zones or faults as well as for the overall facility with ubiquitous jointing. Therefore, during the thermal phase the fractures have relatively little impact or have a uniform influence on the rock mass response. Also for thermal phase, rock mass behavior can be properly analyzed as elastic continuum.

During the cooling phase, there was a generally elastic response during the early phases of cooling. Therefore, fractures that had closed during the thermal loading had not yet unloaded to the extent that they behaved inelastically. In a few cases, an inelastic response was observed where the monitored deformations were asymptotically approaching a value other than full recovery. In addition, responses that were recorded in shear zone areas versus unsheared areas had different magnitudes but similar shapes. Therefore, during cooling, fractures began to open up (or there was a stress decrease so that joints were not as tightly closed) and were responding in a fundamentally different mode than did the rock mass itself.

Another overall conclusion is that modulus differences, which were associated with the weathering, alteration, and fracturing of the shear zones, caused greater deformations for the same stress change. Therefore, displacement magnitudes were larger in these zones than elsewhere within the rock, even for the thermal and early cooling phases, which were essentially elastic responses. This phenomenon was particularly true near the fault zone, where there was considerably more alteration than elsewhere within the rock mass (Wilder and Yow, 1984).

Comparison of thermal phase and cooldown phase deformations with the Mine-By excavation deformations showed that the response during the Mine-By was fundamentally different than the responses during the thermal heating and cool-

down loading. There is no correlation in the response on an anchor-by-anchor basis between the Mine-By and the thermal phase deformations. The lack of correlation during cooldown is a result of incomplete cooling, and fractures once closed by the thermal stresses do not entirely recover their original conditions. The deformations during Mine-By, which were caused by the unloading phenomenon of excavation, result from fundamentally different processes than those experienced during the thermal phase when stresses on fractures increased. The incomplete response during cooldown is similar to that seen by Barton et al. (1985) and many other investigators during laboratory investigations. Conceptually, the response documented by these investigators for laboratory specimens is applicable to large rock masses. The work by Barton and others often addressed normal stress cycles. The fracture monitors indicate that much of the inelastic response seen at Climax was a result of nonrecovered shear deformations. In general, the FMS monitors indicate nearly complete recovery of normal displacements across fractures.

The data were inconclusive in terms of the stick-slip behavior of fractures; therefore, no conclusions relative to this type of response are made.

There is consistently an influence on stress changes during both thermal and cooldown phases that is caused by the presence of shear and fault zones. In the floor of the canister drift, this possibly results from erroneous stiffness assumptions used in formulas for gauge data reduction. However, for the pillar, the influence seems to be caused by actual block isolation that results from fracture bounding. The stresses that were monitored in the pillar show a much greater magnitude of stress decrease near the ribs of the canister drift (compared with midpillar) than can be accounted for by modulus changes, which is important since the presence of fractures had been suggested as one of a number of possible influences (Creveling et al., 1984) on *in situ* stress measurements.

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References

- Abey, A. E., and J. R. Washington (1980), *Stressmeter Placement at Spent Fuel Test in Climax Granite*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-18629.
- Ballou, L. B., W. C. Patrick, D. N. Montan, and T. R. Butkovich (1982), *Test Completion Plan for Spent Fuel Test—Climax, Nevada Test Site*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53367.
- Barton, N., and V. Choubey (1977), "The Shear Strength of Rock Joints in Theory and Practice," *Rock Mechanics and Rock Engineering*, **10**, 1-54.
- Barton, N., S. L. Bandis, and K. Bakhtar (1985), "Strength, Deformation, and Conductivity Coupling of Rock Joints," *Int. Jour. Rock Mech. Min. Sci.*, **22**(3), 121-140.
- Butkovich, T. (1982), *The Effects of Boundary Conditions on Thermomechanical Calculations: Spent Fuel Test—Climax*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53338.
- Butkovich, T. R., and W. C. Patrick (1985), *Post-Test Thermomechanical Calculations and Preliminary Data Analysis for the Spent Fuel Test—Climax*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53688.
- Butkovich, T., J. Yow, Jr., and D. Montan (1982), "Influence of Heat Flow on Drift Closure During Climax Granite Spent Fuel Test: Measurements and Calculations," *Proceedings of International Conference on Radioactive Waste Management, Winnipeg, Manitoba, Canada*. (Also available as UCRL-87248, Lawrence Livermore National Laboratory, Livermore, CA.)
- Carlson, R. C. (1985), *Spent Fuel Test—Climax: Technical Measurements Data Management System Description and Data Presentation*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20712.
- Carlson, R. C., W. C. Patrick, D. G. Wilder, W. G. Brough, D. N. Montan, P. Harben, L. B. Ballou, and H. C. Heard (1980), *Spent Fuel Test—Climax: Technical Measurements Interim Report, FY 1980*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53064.
- Creveling, J. B., F. S. Shuri, K. M. Foster, and S. V. Mills (1984), *In Situ Stress Measurements at the Spent Fuel Test—Climax Facility*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-15628.
- Ellis, W. L., and J. E. Magner (1982), *Determination of the In Situ State of Stress at the Spent Fuel Test Climax Site, Climax Stock, Nevada Test Site*, U.S. Geological Survey Open File Report 82-458.
- Heuze, F. E., W. C. Patrick, R. V. de la Cruz, and C. F. Voss (1981a), *In Situ Geomechanics, Climax Granite, Nevada Test Site*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53076.
- Heuze, F. E., T. R. Butkovich, and J. C. Peterson (1981b), *An Analysis of the "Mine-by" Experiment, Climax Granite, Nevada Test Site*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53133.
- Mao, N. (1984), *Overcoring and Calibration of IRAD Gauge Stressmeters at the Spent Fuel Test in Climax Granite*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20301.
- Montan, D. N., and W. C. Patrick (1986), *Post-Test Thermal Calculations and Data Analyses for the Spent Fuel Test—Climax*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53728.
- Patrick, W. (1986), *Spent Fuel Test—Climax: An Evaluation of the Technical Feasibility of Geologic Storage of Spent Nuclear Fuel in Granite*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53702.
- Patrick, W., L. Ballou, T. Butkovich, R. Carlson, W. Durham, G. Hage, E. Majer, D. Montan, R. Nyholm, N. Rector, D. Wilder, and J. Yow, Jr. (1982), *Spent Fuel Test—Climax: Technical Measurements Interim Report, Fiscal Year 1981*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53294.
- Patrick, W. C., N. L. Rector, and T. R. Butkovich (1984a), "The Application of Proving-Ring Technology to Measure Thermally Induced Displacements in Large Boreholes in Rock," *Proceedings of the 5th International Congress on Experimental Mechanics, Montreal, Quebec, Canada*, pp. 189-196. (Also available as UCRL-88933, Lawrence Livermore National Laboratory, Livermore, CA.)
- Patrick, W. C., N. L. Rector, and J. J. Scarafioti (1984b), *Instrumentation Report No. 3: Performance and Reliability of Instrumentation Deployed for the Spent Fuel Test—Climax*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53637.
- Patrick, W. C., J. L. Yow, Jr., and M. C. Axelrod (1985a), "Observations of Borehole Deformation Modulus Values Before and After Extensive Heating of a Granitic Rock Mass," *Proceedings of the 26th U.S. Symposium on Rock Mechanics, South Dakota School of Mines and Technology, Rapid City, SD*. (Also available as UCRL-91468, Lawrence Livermore National Laboratory, Livermore, CA.)

- Patrick, W. C., J. L. Yow, Jr., and M. C. Axelrod, (1985b), *Estimates of In Situ Deformability with an NX Borehole Jack, Spent Fuel Test—Climax, Nevada Test Site*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53673.
- Pratt, H., R. Lingle, and T. Schrauf (1979), *Laboratory Measured Material Properties of Quartz Monzonite, Climax Stock, Nevada Test Site*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-15073.
- 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.
- Wilder, D. G. (1979), *Influence of Jointing on Stress and Strain Response During Underground Excavation for Test Storage of Spent Reactor Fuel*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-82742.
- Wilder, D. G., and W. C. Patrick (1981), "Geotechnical Status Report for Test Storage of Spent Reactor Fuel in Climax Granite, Nevada Test Site," *AEG Bulletin*, XVIII(4), 355-367.
- Wilder, D. G., and J. L. Yow, Jr. (1984), *Structural Geology Report, Spent Fuel Test—Climax, Nevada Test Site*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53381.
- Yow, J. L. Jr. (1985), *Field Investigation of Keyblock Stability*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53632.
- Yow, J. Jr., and T. Butkovich (1982), "Calculated and Measured Drift Closure During the Spent Fuel Test in Climax Granite," *Proceedings of the 23rd Symposium on Rock Mechanics*, Chap. 86, pp. 855-863, University of California, Berkeley, CA. (Also available as UCRL-87179, Lawrence Livermore National Laboratory, Livermore, CA.)