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Instrumentation Report No. 3: Performance and Reliability of Instrumentation Deployed for the Spent Fuel Test—Climax

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Abstract

A demonstration of the short-term storage and subsequent retrieval of spent nuclear fuel assemblies was successfully completed at the U.S. Department of Energy's Nevada Test Site. Nearly 1000 instruments were deployed to monitor the temperature of rock, air, and metallic components of the test; displacements and stress changes within the rock mass; radiation dosage to personnel and to the rock; thermal energy input; characteristics of the ventilation airstream; and the operational status of the test. Careful selection, installation, calibration, and maintenance of these instruments ensured the acquisition of about 15.3×10^6 high-quality data points. With few exceptions, the performance and reliability of the instrumentation and associated data acquisition system (DAS) were within specified acceptable limits. Details of the performance and reliability of the instrumentation are discussed in this report.

Introduction

A suite of instrumentation was deployed and operated for a period of 3-1/2 years to monitor the Spent Fuel Test—Climax (SFT—C). This test was conducted under the technical direction of the Lawrence Livermore National Laboratory (LLNL) for the U.S. Department of Energy as part of the Nevada Nuclear Waste Storage Investigations (NNWSI).

The SFT—C consists of three parallel drifts connected at their ends (Fig. 1), and is located 420 m below the surface in a granitic intrusive. Although the facility is about 150 m above the regional water table, water seeps into the underground workings along geologic fractures, shears, and faults (Wilder and Yow, 1981). As a result of the test, the temperatures of a large volume of the rock and various test components were increased to as high as 85 and 145°C, respectively. The remote location of the SFT—C in the northeast corner of the Nevada Test Site placed it at the end of the power distribution grid where significant fluctuations in line voltage were common. These conditions provided additional challenges to the task of long-term monitoring of the facility.

The objectives of this report are to document the performance, reliability, and errors associated with the instrumentation deployed on the SFT—C and to assess its adequacy in meeting the overall

objectives of the SFT—C. This is being done for three reasons. First, the performance and reliability statistics, together with error analyses, will be used directly in analyses and interpretations of the data acquired with the instruments described in this report. Second, our experiences provide an important data base for the performance of various types of instruments in a simulated repository environment. Researchers who are responsible for obtaining field data at future repository sites or at generic underground research facilities can use this data base to guide specification and modification of their instrumentation. Third, we present certain advances in instrumentation technology that should prove useful to other researchers. Included are development of a microprocessor-controlled rod extensometer calibration device, design and deployment of a strain-gauged proving-ring assembly for measuring displacements in large diameter boreholes in rock, and application of optical absorbance and thermoluminescent dosimetry techniques to *in situ* measurement of radiation dose to rock.

This report presents performance and reliability data for each of the types of instruments deployed on the SFT—C. Objective measures of performance and reliability and rigorous error analyses are used to the extent possible. The

Figure 1. Plan view of the Spent Fuel Test—Climax showing location of spent fuel and related heat sources.

breadth of discussion is in proportion to the complexity of the particular instrument or problems associated with it. For example, those instruments requiring sophisticated temperature correction schemes and individual calibration coefficients are discussed in greater detail. The depth of discussion is uniform to the extent practical. The objectives of the SFT—C and of the instrumentation plan as well as an evaluation of the data acquisition system are summarized to provide a context for the instrumentation evaluations.

Test Objectives

The principal objective of the SFT—C was demonstration of the feasibility of short-term storage and subsequent retrieval of spent nuclear-fuel assemblies in a deep geologic environment (Ramspott et al., 1979). Technical objectives focused on the response of the rock mass to excavation processes and to the heat generated by radioactive decay. Specific objectives included:

- Documentation of displacements and stress changes in the rock comprising the pillars between the central and side drifts caused by the mechanical disturbance of mining the central drift.
- Comparison of that response to the results of existing computational modeling to assess the

To keep this document within a reasonable size, we have not included detailed descriptions of the various instruments, their specifications and design, or the techniques used to install them. The reader is assumed to have available and to be familiar with the two previous reports in this series (Patrick et al., 1981, and Brough and Patrick, 1982), which present these items of information.

validity of those models in terms of mechanical effects alone.

- Documentation of the temperature and radiation dose in the close-in heated zone to infer both the total power level of the spent-fuel assemblies and the proportion of that power transported out of the canisters by nuclear radiation, as opposed to thermal processes.
- Documentation of displacement and stress effects in the intermediate heated zone caused by the thermal disturbance from the fuel and heaters.
- Comparison of measured thermomechanical responses with computational modeling to assess the validity of those thermomechanical models.

- Documentation of the amount of heat removed by ventilation.
- Documentation of the thermal field (both close-in and intermediate) and comparison with calculational models.
- Documentation of the relative effect of existing fractures on rock response by duplicating all mechanical measurements in either fractured or

relatively unfractured regions, and by direct instrumentation of selected, prominent geologic fractures.

- Evaluation of displacement and stress instrumentation under simulated repository conditions. Note that this objective was added because of instrumentation failures early in the test (Patrick et al., 1981).

Instrumentation Objectives

The objective of the instrumentation program was to ensure that the appropriate quantity and quality of data were obtained for three purposes. First, instrumentation had to provide data to meet the technical objectives of the SFT—C. Second, it had to ensure radiation safety. Third, it was required to monitor the status of the test, including

measurements of the ventilation airstream, the power distribution system, and the data acquisition system. The instrumentation plan led to the successful specification, design, calibration, and installation of the instrumentation required to meet these three objectives (Brough and Patrick, 1982).

Data Acquisition System

The DAS has a profound, direct effect on the quality and quantity of test data produced by the instrumentation. The effect on data quality is primarily a function of the precision and accuracy of the digital multimeters and the resolution provided by the digital system. The effect on data quantity is a function of the system failure characteristics.

System Description

The DAS deployed in support of the SFT—C is based on two Hewlett-Packard 21MX E-Series (HP1000) minicomputers. Specifications and documentation of the DAS are provided by Nyholm et al. (1982) and by Nyholm (1983).

The DAS hardware configuration is shown in Fig. 2. In the normal operational mode, the two computers (Node 100 and Node 200) share the task of acquiring, processing, and archiving about 500 data points per hour from nearly 1000 individual channels of instrumentation. An HP-IB bus extender switching network was designed to minimize the adverse effect of a malfunction of one computer node. When a malfunction occurs on one node, the other node switches the bus extenders by means of an HP-3495 scanner so that no loss of data occurs.

The two major subsystems of the DAS are separated by about 650 m. The surface portion of the system includes the two computers, disc

drives, magnetic tape units, system terminals, and related peripherals, and is located in an air conditioned room of a trailer complex. The subsurface portion includes the scanners and digital multimeters and is located 420 m below ground surface in an air conditioned alcove. In operation, one of the computers commands appropriate scanner relays to close via the HP-IB bus. The HP-3455 digital multimeter converts the analog signal from the instrument to digital format and sends it up the bus. The data packet is processed and written to a disc buffer from which it is written to magnetic tape for archiving and subsequent data analysis. By digitizing data at the subsurface location, we were able to limit the length of cables carrying the relatively small analog signals to about 60 m.

System Performance and Reliability

Although the digital multimeters (DMM) are capable of making measurements over a broad range, most of the data is represented by dc voltage readings in the millivolt range and four-wire resistance readings in the 125- Ω range. In these ranges, the DMMs provide measurements accurate to 1 μ V and 0.0042 Ω with 90-day drifts not to exceed 4 μ V and 0.005 Ω , respectively. Resolutions of 1 μ V and 0.001 Ω are specified. Long-term accuracy of the measurement system was achieved by performing regular (90-day interval)

Figure 2. Data acquisition system hardware configuration.

calibrations of the DMMs, by operating them in a controlled environment at about 23°C and 50% relative humidity, and by providing for continuous secondary calibrations of the DMMs between calibrations. The secondary calibrations were accomplished by measuring the following four types of "standards" at intervals ranging from five minutes to one hour:

- A precision 1-mV source accurate to 1 μ V.
- Two precision 120- Ω resistors accurate to 0.00018 Ω .
- One thermocouple and one resistance temperature device (RTD) in a 0°C Kaye ice bath.
- Three thermocouples and one RTD located deep in a borehole away from the effects of the test.

The alarm function of the DAS was used throughout the test to alert us when these "system standard" data values deviated outside acceptable limits. Based on measurements of the 1-mV precision voltage source, Patrick et al. (1984) concluded that the DMMs operated inside an envelope of 0.996 to 1.004 mV at all times. Several periods were noted when four-wire resistance measurements deviated

outside the ± 0.0092 - Ω specification. When such deviations occurred, the malfunctioning DMM was replaced and returned for recalibration or maintenance, as necessary.

System availability may be expressed in terms of a "functionally disabled index" (FDI) (Nyholm et al., 1982). The FDI is a measure of the probability that data cannot be properly acquired and archived when desired. The average FDIs for Node 100 and Node 200 were 14.98 and 8.79%, respectively. The bus extender switching network described above reduced the system FDI to 4.06%. Thus, the DAS was able to acquire data when requested 96% of the time for the 41-month acquisition period.

A total of 15.3×10^6 data values were recorded during this period of data acquisition. About 6.6×10^6 (43%) of these represent radiation dosimetry data that were archived but not entered into the scientific data base for detailed analysis. Only 2.5×10^5 (1.6%) of the data records were unreadable or sufficiently flawed as to be unusable in the analyses.

Radiation Monitors

Radiation monitors were deployed to measure ionizing radiation as well as airborne gaseous and particulate forms of radioactive materials. Monitoring was provided continuously during the three year spent-fuel storage period. Results and discussion of these measurements are provided by Raschke et al. (1983).

Remote area monitors (RAMs) were used to measure gamma radiation levels in the SFT—C underground complex and at the surface where the spent fuel assemblies were received and lowered to the storage level (Figs. 3 and 4). RAMs were in place at the surface locations only during handling operations. Eleven Nuclear Measurements Corp. Model GA-3M RAMs were procured for this purpose (Brough and Patrick, 1982); manufacturer's specifications indicate a precision of $\pm 15\%$.

Continuous air monitors (CAMs) were emplaced to sample for potential release of ^3H and ^{85}Kr , gaseous products that would be released if the spent fuel assembly canisters and zircalloy cladding were breached by corrosion or an accident. In addition to the continuously monitored locations (Fig. 3), ports were also provided to permit sampling from the canister/liner and liner/

rock annuli of each canister emplacement borehole. Two Overhoff and Associates, Inc., Betatec Model 210 CAMs were procured for this purpose (Brough and Patrick, 1982). The use of two CAM chambers permitted redundant sampling from each port. These units have a specified sensitivity of $0.6 \mu\text{Ci}/\text{m}^3$.

Calibration

The RAMs are provided with a pulsed light-emitting diode (LED) as an internal calibration source that can be turned on and off at the control module. More meaningful and accurate calibrations were performed *in situ* before each spent-fuel handling operation by using a ^{226}Ra source up to 100 mR/h and a ^{60}Co source up to 1000 mR/h. In addition, laboratory calibration of the high-level RAMs was performed with a ^{225}Ac ^{137}Cs source. Accuracy is not as critical as with the scientific instrumentation being used, the main concern being adequate sensitivity.

The purpose of the *in situ* calibrations was to determine that the units were functioning properly and that they were performing at the same

Figure 3. Underground radiation monitor locations.

Figure 4. Surface radiation monitor locations.

A = Fixed CAM sampling ports.
 B = Low-level RAM detectors (B* = normal mode).
 D = High-level RAM detectors.
 E = Particulate sampling port.

level of accuracy as when they were procured from the manufacturer. The high sensitivity of these units, which is required to measure low levels of radioactivity, makes it very difficult to achieve accuracy better than the specified $\pm 15\%$ of reading. Changes in calibration coefficient "K" are listed in Table 1. Note that the RAMs were adjusted when the K factors exceeded by 0.50 the nominal 2.00 value used in the data conversion algorithms.

Calibration of the CAM units used an internal radiation source. The chambers for the Betatec 210 CAM units (CAMs 101-107 and 201-207) were modified to include a ^{90}Sr calibration source for this purpose. When placed in the calibrate mode, a $0.4\text{-}\mu\text{Ci}$ source is exposed at the chamber, producing a reading equivalent to $\sim 180\text{ }\mu\text{Ci/m}^3$. The NMC ^{85}Kr CAM (CAM 108 and 208) and the portable CAM units were calibrated at LLNL using radioactive sources. Minor adjustments were made to compensate for instrument drift. Changes in calibration coefficients are noted in Table 2.

Error Analysis

The role of the radiation instrumentation was to detect and monitor for the presence of radiation and radioactive materials rather than to provide high-accuracy measurements for analysis. Higher accuracy data were obtained using portable detectors and personnel dosimetry, as reported by Raschke et al. (1983). Therefore, detailed error analyses were not performed for the RAMs and CAMs.

The relationship between output voltage readings and converted value is of the form

$$R = A \cdot 10^{V/K} - B \quad (1)$$

where

- A = 0.1 for RAMs 101-108, 110-111, 201-208, and 210-211,
- = 10 for RAMs 109 and 209,
- = 0.1 for CAMs 101-107 and 201-207,
- = 0.28 for CAMs 108 and 208;

- B = -0.2 for RAMs 101-108, 110-111, 201-208, and 210-211,
- = -20 for RAMs 109 and 209,
- = 0 for all CAMs;

- K = 2.0 for all RAMs and CAMs 108 and 208,
- = 2.5 for CAMs 101-107 and 201-207;

V is in volts;

R is in R/h for RAMs and in $\mu\text{Ci/m}^3$ for CAMs.

Table 1. Low-level RAM "K" values at various times since deployment of the instruments.

RAM	K value at calibration and time				
	6/26/80	7/1/81	10/6/81	7/29/82	2/16/83
1	2.06	2.23	2.13	2.19	2.04 ^a
2	2.02	2.32	2.35	2.29	2.36
3	2.06	2.41	2.40	2.38	2.49
4	1.95	2.11	2.28	2.30	2.03 ^a
5	1.93	2.09	2.19	2.18	2.12 ^a
6	1.99	2.28	2.24	2.29	2.23
7	1.99	2.24	2.26	2.25	2.26
8	2.03	2.37	2.39	Replaced	2.03
9	—	2.20	2.13	2.21	2.22
10	—	2.16	2.13	2.17	2.13

^a Readjusted RAM unit.

Table 2. CAM "K" values at various times during the SFT—C.

Instrument	K value at calibration time			
	1/16/81	10/6/81	7/29/82	2/16/83
CAM 101	2.48	2.48	2.48	2.45
CAM 201	2.46	2.53	2.46	2.51
CAM 102	2.51	2.55	2.52	2.56
CAM 202	2.50	2.53	—	2.48
CAM 103	2.48	2.46	2.47	2.51
CAM 203	2.45	2.48	2.46	2.49
CAM 104	2.47	2.49	2.46	2.48
CAM 204	2.41	2.46	2.47	2.49
CAM 105	2.61	2.46	2.61	2.46
CAM 205	2.48	2.52	2.45	2.45
CAM 106	2.45	2.42	2.45	2.52
CAM 206	2.49	2.42	2.42	2.42
CAM 007	—	2.23	2.23	2.23
CAM 008	—	2.03	2.05	1.96

Reliability

The RAM and CAM units performed satisfactorily throughout the spent-fuel storage period. Specific problems and associated corrective actions are noted in Table 3. Aging of the RAM photomultipliers and CAM circuitry caused the DAS to generate spurious alarms (on the low side of the alarm limit). Because of the high single-unit reliability of the RAMs and the application of redundancy in the CAMs, radiation monitoring was provided continuously without a significant period of downtime.

Table 3. Occurrence of problems with radiation monitors deployed at the SFT—C.

Effected units	Problem description	Corrective action
All RAMs	Photomultiplier aging	Performed periodic calibrations, adjusted for change in "K"
RAM 108	Noisy output	Photomultiplier circuit replaced
All CAMs	Minor circuit drift	Adjusted circuit (7/28/82) and performed periodic calibrations
All CAMs	Noisy	Resoldered bad electric connections.
CAM 108 & 208	Sensitivity to transient noise	Located and repaired break in a trace of the count-rate-meter printed circuit

Radiation Dosimeters

Radiation-dose-to-granite measurements were made to document the exposure of the granite to ionizing radiation and for comparison with radiation transport calculations (Wilcox and Van Konynenburg, 1981). These measurements were obtained under subcontract to LLNL by EG&G-Santa Barbara Operations.

Four types of passive dosimeters were deployed at the SFT—C to obtain the required data. Long-term gamma dosimetry used optical grade ^7LiF detectors that operate on the principle that optical absorbance of the crystals increases as they are irradiated. Individual ^7LiF chips were enclosed in stainless steel holders that were in turn joined together with sections of braided stainless steel cable to make seven dosimeter assemblies (Fig. 5). These assemblies were installed in 6.35-mm-diam stainless steel tubes. Four tubes were attached to emplacement borehole walls where spent nuclear fuel was stored (Table 4). The fifth and sixth tubes were grouted into boreholes located 508 and 660 mm radially outward from one of the emplacement boreholes, and the seventh was attached to the emplacement borehole wall where an electrical simulator was stored. The latter installation allowed examination of thermal annealing of pre-irradiated dosimeters (Quam and DeVore, 1981). These dosimeters were deployed during three time intervals: April 18, 1980, to January 12, 1981; January 12, 1981, to October 23, 1981; and October 23, 1981, to March 8, 1983.

Long-term neutron dosimetry was performed in conjunction with the long-term gamma dosimetry outlined above. The primary purpose of these measurements was to document the neutron dose for use in corrections if the gamma dosimeters were found to be neutron sensitive. The five dosimeter assemblies located on emplacement

Table 4. Dosimeter locations in the field installation.

CEH No. ^a	Vertical distance of dosimeters from centerline (m) ^b	Lithium fluoride number	Cobalt foil number
1 (wall)	+ 1.22	14	—
	0	15	5,6
	- 1.22	16	—
3 (wall)	+ 1.83	7	—
	+ 1.22	8	—
	+ 0.61	9	—
	0	10	3,4
	- 0.61	11	—
	- 1.22	12	—
3 (20 cm)	+ 1.22	84	—
	0	5	1,2
	- 1.22	6	—
3 (36 cm)	+ 1.22	20	—
	0	21	7,8
	- 1.22	22	—
4 (wall, heater) ^c	+ 1.22	1	—
	0	2	9,10
	- 1.22	3	—
7 (wall)	+ 1.22	17	—
	0	18	—
	- 1.22	19	—
11 (wall)	+ 1.22	23	—
	0	24	—
	- 1.22	25	—

^a CEH denotes canister emplacement hole number. Data in parentheses are used to denote radial locations of dosimeters relative to the borehole wall.

^b The midheight of the spent-fuel assembly is taken as zero, positive numbers are above and negative numbers are below this center position.

^c CEH04 is an electrical simulator used as a nonradiative control.

Figure 5a. Exploded view of dosimeter subassembly.

Figure 5b. Complete dosimeter assembly ready for installation.

borehole walls had provisions for cobalt and silver foils. In addition, the nickel and manganese present in the 303-series stainless steel dosimeter holders were also used to help establish neutron

dose (Quam and DeVore, 1981). The measurement periods were the same as for long-term gamma dosimetry.

Both MgB_2O_7 and CaF_2 short-term thermoluminescent dosimeters were deployed to provide information on the long-term fade characteristics of the ^7LiF dosimeters. Short-term ($\sim$ one hour) measurements were obtained on August 13, 1982, and on March 8, 1983. These measurements were obtained at the borehole wall and at positions 508 and 660 mm radially outward from the spent fuel assembly in canister emplacement borehole (CEH) number CEH03.

Performance, Reliability, and Error Analysis

Long-Term Gamma Dosimeters

One set of long-term gamma dosimeters was deployed for a 9-month period, read in the laboratory, and deployed for a subsequent 17-month period. The other set was deployed for a single 9-month period while the first set was out of service to be read. Temperatures at the dosimeters ranged from about 60 to 80°C, depending on the time

interval and exact location of the dosimeter. The mechanical design and fundamental approach proved to work reliably for the duration of the SFT—C.

Calibrations of the ^7LiF chips were performed at two facilities: the EG&G—Santa Barbara Operations ^{60}Co source range at various controlled temperatures up to 60°C at exposures as high as 10^7 rads-LiF; and at the Sandia Gamma Irradiation Facility at an uncontrolled temperature near 60°C at exposures up to 10^8 rads-LiF. The 247-nm peak in the absorption spectrum was used in the range of 2×10^3 to 9×10^6 rads-LiF, and the 374-nm peak was used in the range of 2×10^6 to 10^8 rads-LiF.

A Beckman 5270 spectrophotometer was used for all the 374-nm data and for the 247-nm data produced by exposures up to about 9×10^5 rad-LiF—about 1.5 absorbance units (AU). An IL 500, modified with a high-pressure mercury vapor light, was used to obtain the 247-nm data for exposures ranging from about 10^4 to 10^7 rads-LiF (about 0.1 to 4.5 AU) because the optical density was so great at these exposures. The data from these two instruments agree very well in the overlapping portion of their ranges.

The high quality of the calibration data is evident in Figs. 6 and 7 for the 374- and 247-nm

peaks, respectively. These calibration curves relate known exposures in rads-LiF to observed AU readings. The AU is the common logarithm of the reciprocal of optical transmission. The calibration coefficients and associated one-standard-deviation error bands are provided in Tables 5 and 6 for the 374- and 247-nm peaks, respectively.

Temperature effects on dosimeter sensitivity were found to be a serious problem with the ^7LiF dosimeters. Two types of sensitivity were observed. First, irradiated chips were found to fade when held at elevated temperatures following irradiation. Fade factors were determined for temperatures of 50, 100, and 150°C (Quam and DeVore, 1981a). Fade at the 374-nm peak was generally less than 5% for temperatures of interest here (up to 85°C). However, fade at the 247-nm peak was nearly 30%, so fade corrections were applied to the 247-nm data. Second, the chips also exhibited a change in sensitivity when simultaneously heated and irradiated. Changes in sensitivity of about $1\%/^\circ\text{C}$ were documented for the 374-nm peak. Changes in sensitivity of the 247-nm peak appear to be about 5% at exposures up to 10^5 rads-LiF over a temperature range of 25 – 60°C . Rather than document sensitivity as a function of temperature and exposure for the 247-nm

Figure 6. Calibration data for the 374-nm peak, polished LiF, 2-mm thickness (after Quam and DeVore, 1984).

Figure 7. Calibration data for the 247-nm peak, polished LiF, 2-mm thickness (after Quam and DeVore, 1984).

Table 5. The 374-nm calibration data at 60°C (after Quam and DeVore, 1984).

Rads-LiF exposure ^a	Holder material	⁶⁰ Co source	Exposure date	Beckman 5270 AU ± 1 sigma	Dosimeters per point
1.55(6)	Al	RS2 ^b	Jun 82	0.018 ± 0.002	10
2.55(6)	Al	RS2	Apr 82	0.045 ± 0.011	2
3.87(6)	Al	RS2	2 Jun 83	0.065 ± 0.008	9
3.87(6)	Al	RS2	Jun 82	0.052 ± 0.003	10
5.90(6)	Al	RS2	6 Jun 83	0.088 ± 0.008	10
6.74(6)	Al	G1F ^c	31 Aug 83	0.099 ± 0.008	5
6.00(6)	SS	RS2	6 Jun 83	0.097 ± 0.011	10
6.77(6)	SS	G1F	31 Aug 83	0.089 ± 0.006	5
7.74(6)	Al	RS2	Apr 82	0.125 ± 0.002	2
7.74(6)	Al	RS2	Jun 82	0.103 ± 0.004	10
7.90(6)	Al	RS2	31 May 83	0.109 ± 0.004	5
7.77(6)	SS	RS2	22 Aug 83	0.163 ± 0.005	5
1.03(7)	Al	RS2	Apr 82	0.178 ± 0.019	2
1.55(7)	Al	RS2	Apr 82	0.236 ± 0.008	2
1.56(7)	Al	RS2	Jun 82	0.199 ± 0.007	10
1.48(7)	SS	G1F	17 Apr 80	0.243 ± 0.008	1
3.71(7)	SS	G1F	17 Apr 80	0.594 ± 0.037	3
7.42(7)	SS	G1F	17 Apr 80	1.398 ± 0.87	1

^a 1.55(6) means 1.55 × 10⁶, etc.

^b EG&G/EM Santa Barbara Operations source array.

^c Sandia Corporation source array.

Table 6. The 247-nm calibration data at 60°C^a (after Quam and DeVore, 1984).

Rade-LiF exposure ^b	⁶⁰ Co source	Beckman 5270 AU ± 1 sigma	IL500 AU ± 1 sigma
1.64(3)	RS1	0.026 ± 0.004	—
3.29(3)	RS1	0.036 ± 0.005	—
6.58(3)	RS1	0.066 ± 0.007	—
7.67(3)	RS2	0.103 ± 0.006	0.080 ± 0.016
1.53(4)	RS2	0.165 ± 0.018	0.155 ± 0.024
2.95(4)	RS1	0.233 ± 0.025	—
3.83(4)	RS2	0.298 ± 0.030	0.280 ± 0.030
7.66(4)	RS2	0.490 ± 0.050	0.500 ± 0.050
1.53(5)	RS2	0.704 ± 0.058	0.780 ± 0.070
3.83(5)	RS2	1.09 ± 0.10	1.14 ± 0.10
7.66(5)	RS2	1.49 ± 0.11	1.55 ± 0.11
1.53(6)	RS2	—	2.06 ± 0.14
3.83(6)	RS2	—	3.28 ± 0.14
7.66(6)	RS2	—	4.41 ± 0.08

^a For all exposures, holder material was aluminum; 10 dosimeters per point used for all data.

^b 1.89(3) means 1.89×10^3 , etc.

peak, Quam and DeVore (1984a) developed a calibration curve at the proper temperature to eliminate the need for such corrections. Quam and DeVore (1984a) report the overall accuracy of the ⁷LiF dosimeters as ±11%.

Neutron Dosimeters

The neutron dosimeters were operated at the lower limit of their usable range of exposures. Quam and DeVore (1982) report that the foil counting rates were very low. Exposure rates were measured to be less than 1.09×10^{-4} rem/s with overall errors of at least ±30%. Since the gamma dosimeters were confirmed to be insensitive to neutrons [as was indicated in the literature (McLaughlin et al., 1978)], accurate knowledge of neutron dose was relatively unimportant. No further efforts were made to reduce the observed errors or to deploy a more accurate neutron dosimetry technique.

Short-Term Gamma Dosimeters

An initial 1-h exposure of both CaF₂ and MgB₄O₇ thermoluminescent dosimeters (TLDs) was conducted on August 13, 1982. Calibrations were made at 60 and 25°C for both types of TLDs. The ratios of these calibration values were 1.01 ± 0.085 for the CaF₂ TLDs and 1.03 ± 0.103 for the MgB₄O₇. Therefore, no temperature corrections to the data were required.

The magnesium borate TLD material was selected because of its low-Z, which should produce

little trouble in terms of low energy response, in contrast to the high-Z calcium fluoride TLD, which has a known response problem to energies in the ~80-keV range (Quam and DeVore, 1984b). In addition, it has a relatively high-temperature trap at 200°C, which should make it more stable at the 60°C irradiation temperature. However, the MgB₄O₇ dosimetry provided data that steadily decreased in quality during this phase of calibrating and initial field measurements. Therefore, only CaF₂ dosimeters were deployed for the second set of short-term measurements. The calibration data and initial field data showed that the stainless steel holders used to encapsulate the dosimeters trimmed the low-energy photons sufficiently so that the response of the two types of TLDs was essentially the same.

The second 1-h exposure used only CaF₂ dosimeters in the same design stainless steel holders as are used for long-term dosimetry. A post-exposure calibration of each individual TLD chip was performed so that average sensitivity values did not have to be relied upon. In addition, this approach to calibration eliminates the need to make corrections for nonlinearity, which occurs at high exposures. This calibration was performed in a thick aluminum holder, the temperature of which was controlled to the field irradiation temperature of 60°C. Exposure rates were controlled to be the same as those calculated to occur in the field. Both ¹³⁷Cs and ⁶⁰Co sources were used in the calibrations to confirm that TLD response was not

energy-dependent. Calibration dose rates were measured with a Keithley Model 616 electrometer and related precision resistors and voltage source. This set of instruments has been shown to be within 1% of the NBS values at one standard deviation. The standards themselves are $\pm 1\text{-}1/2\%$, and Quam and DeVore (1984b) estimate the total system error (including positioning relative to the source) as $\pm 5\%$.

Temperature Sensors

Resistance Temperature Devices

RTDs were selected to measure the temperature of thermocouple reference-junction isothermal blocks and to be used as system standards to verify the quality of four-wire resistance measurements made by DMMs. The reference block RTDs experienced temperatures in the range of 18 to 40°C at relative humidities of 50 to 70%. One RTD was immersed in a Kaye icebath to provide a system standard as noted in the "Data Acquisition System" section. Standard, industrial-grade platinum Degussa Model 2101 RTDs were procured from C. S. Gordon, Co. for these applications (Brough and Patrick, 1982).

Calibration

Pre- and post-test laboratory calibrations of the RTDs were performed using HP3455A digital multimeters, a Kaye Instruments Model 374 temperature probe, a Rosemount Co. Model 911A1 calibration bath, a Kaye Instruments Model UTR-AS isothermal reference block, and a Delta Design Model 6400C environmental chamber. Values of R_0 were established at 0°C, and calibrations were obtained at temperatures of approximately 23 and 38°C. The results of these calibrations are provided in Table 7.

Table 7. Results of pre- and post-test laboratory calibration of RTD's.

Calibration	Number calibrated	Calibration errors (°C)		
		Mean	Std dev	Range
Pretest, ~23°C	19	0.032	0.048	-0.014 to 0.225
Pretest, ~38°C	20	0.039	0.037	-0.016 to 0.172
Post-test, ~23°C	20	0.090	0.011	0.063 to 0.108
Post-test, ~38°C	20	0.112	0.045	-0.008 to 0.191

The short-term gamma dosimeters proved to be an important adjunct to the originally planned long-term dosimeters. The calcium fluoride TLDs exhibited better accuracy and, because exposure times were short, could be post-exposure calibrated in a manner that eliminates the uncertainties associated with the long-term dosimeters.

Error Analysis

The algorithm for calculating temperature from resistance is of the form

$$T = \frac{\left[\left(A^2 - 4B \left(1 - \frac{R}{R_0} \right) \right)^{1/2} - A \right]}{2B}, \quad (2)$$

where

A and B are coefficients provided by the manufacturer,

R_0 is the 0°C resistance of the RTD,

R is the measured resistance of the RTD at temperature T.

The sensitivity factors are calculated by differentiating Eq. (2) with respect to each of the two resistances:

$$\Theta_{R_0} = \frac{dT}{dR_0} = - \frac{R}{R_0^2} \left[A^2 - 4B \left(1 - \frac{R}{R_0} \right) \right]^{-1/2} \quad (3)$$

$$\Theta_R = \frac{dT}{dR} = \frac{\left[A^2 - 4B \left(1 - \frac{R}{R_0} \right) \right]^{-1/2}}{R_0} \quad (4)$$

For an error in resistance R_0 of 0.010 Ω , temperature errors of 0.026°C (at 0°C) and 0.030°C (at 40°C) are calculated using Eq. (3). Likewise, for an error in resistance R of 0.011 Ω , temperature errors of 0.028°C occur in the range of 0 to 40°C. Combining these two sources of error gives a maximum root-sum-square* (RSS) uncertainty in temperature that ranges from 0.038°C (at 0°C) to 0.041°C (at 40°C).

* This calculation squares each individual error, sums these squares, and takes the square root of the resulting sum.

Reliability

All 20 RTDs functioned reliably throughout the period of deployment.

Thermocouples

Type K Chromel-Alumel thermocouples (TCs) were selected as the principal temperature measuring device for the SFT-C and were procured from C. S. Gordon, Co. These devices were sheathed in Inconel 600 with MgO insulation, and each TC junction was grounded to its sheath.

As described by Brough and Patrick (1982), thermocouples were deployed under a variety of operating conditions for periods of up to 3-1/2 years. Temperature environments ranged from an ambient 23°C in far-field applications (Fig. 8) to about 450°C on the electric heaters (Fig. 9). A combination of temperatures up to 145°C and intense ionizing radiation up to 50,000 rad/hour were present near the spent-fuel assemblies (Fig. 10). Depending on location within the test facility, relative humidity ranged from about 50 to 100%. Many TCs were in contact with the chloride- and sulphate-rich groundwater (Ishwood et al., 1982).

Most TCs were installed in guide tubes so that they could be removed for field calibration using the central DAS. Pre- and post-test calibrations of all these units were conducted. A total of 56 TCs were permanently located in borehole extensometers. Therefore, only pretest laboratory calibrations were conducted for these units.

Calibration

Field calibrations were conducted at temperatures appropriate to the application of the individual TC. A Rosemount Model 911A1 ice bath was used for 0°C, a Kaye Model HTR150 temperature reference for 50 and 100°C, and a Proceadyne Model TH050 dry bath for the 150°C measurements. Actual bath temperatures were measured with laboratory-calibrated RTDs that were scanned in sequence with the TCs.

The results of the pre- and post-test calibrations are displayed in Figs. 11 through 14. Three thermocouples were found to operate outside the $\pm 1.1^\circ\text{C}$ ISA special limits of error. Most of the thermocouples were deployed where temperatures were in the range of 20 to 60°C. As indicated by the calibration results, errors in this temperature range are generally limited to $\pm 0.25^\circ\text{C}$ and are symmetrically distributed at around 0°C. However, at higher temperatures, such as those

observed in canisters, liners, and heaters, the errors become somewhat larger and are skewed toward positive values.

Error Analysis

Temperature and TC voltage are related by the equation

$$T = A_0 + A_1V + A_2V^2 + A_3V^3 + A_4V^4 \quad (5)$$

where A_i are constants calculated from the NBS-tabulated values of voltage vs temperature (Powell et al., 1974), and

$$V = V_R + B_1T_R + B_2T_R^2 + B_3T_R^3 \quad (6)$$

where

V_R is the thermocouple voltage at the reference block,

T_R is the reference block temperature recorded by an RTD,

B_i are constants provided by the NBS (Powell et al., 1974).

Equation (6) contains three sources of error. First, the NBS documents (Powell et al., 1974) that the conversion of RTD temperature to equivalent thermocouple voltage is accomplished with an accuracy of -0.06 to $+0.14 \mu\text{V}$ in the range 0 to 50°C. Second, error in the RTD temperature was calculated to be about $\pm 0.04^\circ\text{C}$ in this range (see previous section). The voltage equivalent of this error is $\pm 1.67 \mu\text{V}$. Third, the TC voltage reading at the reference block has an associated error in the range of 4.00 to 4.42 μV for temperatures between 40 and 200°C. The RSS error for these three error sources is at most 4.73 μV .

Equation (5) contains two sources of error, that are due to the total RSS voltage error and residual errors in the temperature vs voltage equation. Differentiating Eq. (5) with respect to voltage, we have

$$\Theta_V = \frac{dT}{dV} = A_1 + 2A_2V + 3A_3V^2 + 4A_4V^3 \quad (7)$$

The higher order terms are very small so the equation may be evaluated using the NBS-tabulated values of A_1 (Powell et al., 1974) and the RSS voltage errors calculated above. The maximum uncertainty in temperature resulting from these errors is calculated to be $\pm 0.12^\circ\text{C}$.

Residual errors in the temperature vs voltage equation were minimized by fitting quartics to four segments of the temperature range of interest. Initial break points were selected at 100, 200,

Figure 8. Intermediate- and far-field thermocouples. Locations in the storage facility are indicated by dots.

Figure 9. Additional intermediate-field thermocouple locations associated with auxiliary heaters.

400, and 1000°C. Best-fit quartics were then obtained for NBS-tabulated paired values of temperature and voltage (Powell et al., 1974). The break points were then adjusted to coincide with the intersections of adjoining quartics, thus providing a smooth transition in the errors. The adjusted break points are 96.49, 200.39, 407.21, and 1000°C. Residual errors for the four segments were calculated to be 0.0004, 0.0023, 0.0102, and 0.02°C, respectively. These are minor contributions to the RSS error calculated above.

Reliability

The TCs performed reliably throughout the measurement period. Performance was evaluated

on a continuing basis during the SFT—C by means of a loop-resistance check and through the DAS alarm system. The resistance checks were conducted on all TCs at about 6-month intervals. Comparison of the current resistance with the pre-test value served as a guide in determining if moisture was invading the TC or if the wire connections at the zone box were degrading. Such problems did occur and were promptly corrected by reterminating and drying the TC or by cleaning and tightening the reference block connections, respectively. The DAS alarm system, which was described previously, also provided for prompt recognition and correction of such problems. Since anticipated temperatures were well known,

Figure 10. Near-field thermocouples. Locations are designated with triangles.

Figure 11. Thermocouple calibration results at 0°C.

Pretest (open) and post-test (stippled) thermocouple calibration

Figure 12. Thermocouple calibration results at 50°C.

Figure 13. Thermocouple calibration results at 100°C.

Figure 14. Thermocouple calibration results at 150°C.

based on thermal calculations, alarm limits were set quite narrow. As a result, problems (which were expressed as temperatures that were out of expected limits) were quickly observed and corrected.

Four thermocouple sheaths were found to be corroded when they were recovered for post-test calibrations. However, none of these units exhibited abnormal behavior in service. All four were located in spent-fuel storage boreholes. Three (SLT 144, SLT 164, and SLT 166)* were located on the outer surface of emplacement borehole liners where temperatures were in the range of 80 to 100°C and radiation doses were about 2×10^8 rad for the 3-year storage period. The fourth TC (CDT 035)[†] was likewise in this environment for three years (as SLT 036), was subsequently deployed for an additional six months to monitor the temperature of a borehole deformation gauge, and was found to be corroded after the second deployment. Temperatures decreased from about 60 to 30°C during this second period.

Metallurgical analyses of the corroded TC sheaths revealed that two were Inconel 600, as specified, but the other two were 304-series stainless steel. We speculate that the latter units were erroneously sheathed in the manufacturing process. The extent of the problem of incorrect sheathing was not confirmed by further sampling and testing because none of the remaining TCs exhibited either corrosion or any other problem.

Thermistors

Two arrays of thermistors were deployed within the canister storage drift to document non-uniformities in the air temperature distribution. Nominal 340-k Ω YSI Model 44014 thermistors were attached to two large crosses that were constructed from sections of 19-mm-diam PVC pipe. The crosses were positioned so that five temperature measurements could be obtained along both vertical and transversely horizontal axes of the drift cross section. Nine thermistors were used at each of two locations in the drift (the center thermistor was common to the vertical and horizontal profiles). In addition, another thermistor was located on the outer surface of a NEMA enclosure containing TC reference blocks to provide

* SLT xxx is the instrument designator for storage borehole liner thermocouples.

[†] CDT xxx is the instrument designator for canister emplacement borehole deformation gauge thermocouple.

a comparison between temperatures recorded by the thermistor and the RTDs. Temperatures in the ventilation airstream varied from about 18 to 40°C during the SFT—C, with temperatures near 30°C most of the time.

Calibration

Pretest calibrations were performed at a nominal 23°C ambient temperature and post-test calibrations were performed at nominal temperatures of 19, 23, and 30°C. All calibrations were performed in the laboratory using an Instrulab Model 841-12 temperature sensor, an Instrulab Model 4202-13-1506 temperature monitor, and a Fluke Model 8860A DMM. Accuracy of the temperature sensor is $\pm 0.02^\circ\text{C}$, and accuracy of the DMM is $\pm 0.014\%$ of reading plus three counts. All calibrations were performed with lead wires and cabling attached to the thermistors. Calibration results, which were obtained using Eq. (8) to calculate temperatures from resistance readings, are shown in Table 8.

The thermistor calibrations show that both the mean errors and the standard deviations of those errors have increased substantially between the time of pretest calibrations in May 1981 and post-test calibrations in December 1983. However, examination of individual calibration records shows that only one thermistor had an error outside the desired $\pm 0.1^\circ\text{C}$ window at 30°C, and none had an error this large at 23°C.

Error Analysis

The algorithm for calculating temperature from resistance is

$$T = A_0 + A_1R + A_2R^2 + A_3R^3 + A_4R^4 \quad (8)$$

where

A_i are coefficients of the polynomial,
 R is the thermistor resistance.

The sensitivity factor is calculated by differentiating Eq. (8) with respect to resistance, such that

$$\Theta_R = \frac{dT}{dR} = A_1 + 2A_2R + 3A_3R^2 + 4A_4R^3 \quad (9)$$

The maximum RSS uncertainty in temperature is calculated by evaluating this equation for appropriate values of R (423.2 k Ω at 18°C to 149.4 k Ω at 40°C) and A_i . The maximum error in resistance reading in this range is about 55 Ω , giving a maximum uncertainty in temperature of 0.022°C.

Table 8. Results of pre- and post-test laboratory calibration of YSI Model 44014 thermistors.

Calibration (°C)	Number calibrated	Calibration errors (°C)		
		Mean	Std dev	Range
Pretest, mean temp. = 22.55	19	0.006	0.005	-0.0087 to 0.0205
Post-test, mean temp. = 19.13	18	0.091	0.036	0.048 to 0.138
Post-test, mean temp. = 22.73	18	0.015	0.032	-0.046 to 0.078
Post-test, mean temp. = 29.58	18	-0.019	0.114	-0.437 to 0.086

Reliability

Nineteen thermistors were deployed in the two arrays. All functioned without failure during the measurement period. One lead wire was broken at the thermistor bead during handling and could not be repaired for post-test calibration.

Convergence Wire Temperature Monitors

Convergence wire extensometers (CWEs) are long-gauge-length, removable instruments capable of accurately measuring relative displacements across mined underground openings. Because the 0.635-mm-diam connecting wire used on this instrument changes length with changes in temperature, it was necessary to develop a technique capable of measuring the average temperature of stainless steel wires 2.9 to 8.0 m long.

The convergence wire temperature monitors (CWTs) operate on the same principal as RTDs. Two small metal clamps attached near the end points of the stainless steel wire are in turn attached to two pairs of lead wires, one of which provides a known pulsed current while the other measures the voltage drop across the wire. Thus, a four-wire resistance measurement is made. Knowing the temperature coefficient of resistance and an initial wire resistance at a known temperature, it is possible to calculate an average wire temperature. Sequential CWT measurements are used to calculate changes in temperature that in turn are used to calculate the thermal expansion of the wire.

Temperature Coefficient of Resistance

To use the four-wire measurement technique, it is necessary to know the relationship between changes in resistance and changes in temperature of the wire material. A search of the literature for available data revealed that the temperature coefficient of resistance varied widely among steel alloys from 0.0001 to 0.005/°C.

Given this high variability, we developed a simple test fixture to determine the temperature vs resistance relationship for the 304 stainless steel wire used for the CWEs (Fig. 15). A 5.5-m-long section of the wire was wrapped in loops over two plastic spools mounted on opposite ends of a flat plate. The wire was arranged in a spiral so that the loops did not contact each other, and provision was made to dead-weight-load the wire. Thermistors were attached in three locations on the wire and the entire assembly was placed in a muffle oven where temperatures were cycled between 18 and 40°C with simultaneous thermistor and wire resistance readings at selected temperatures. The process was repeated for both the unloaded and dead-weight-loaded configurations. After normalizing the resistance readings with respect to wire length, the slope of the resulting line through the data was 480 m·°C/Ω.

To determine average wire temperature, the following equation is applied:

$$T = \left[T_0 - \frac{R_0}{L} \right] + \frac{\dot{T}}{L} R \quad (10)$$

where

- T is the present wire temperature, °C,
- T_0 is the reference temperature at which R_0 is measured, °C,
- $\dot{T}$ is the slope of the temperature-resistance line, 480 m·°C/Ω,
- R_0 is the reference resistance at temperature T_0 , Ω,
- R is the present wire resistance as determined by a four-wire measurement, Ω, and
- L is the wire length between the current/voltage probes, m.

Calibration

The individual wires were calibrated in isothermal containers constructed of two overlapping cardboard boxes lined with low-density styrofoam blocks about 70 mm thick. The wires

Figure 15. Sketch of calibration fixture for the convergence wire temperature monitor.

coiled naturally into circles about 0.2 m in diameter when removed from the CWE and the individual loops of each coil were insulated, using either plastic sheets or tubing, to prevent shorting during the calibration process. Two YSI Model 44014 thermistors were placed at diametrically opposite positions on the coil, and the insulated box was closed and sealed for about 12 hours. Once the temperature within the box became uniform and stable, the thermistors and CWT resistance were recorded. An equilibrium value of R_0 was thus obtained at a single known temperature T_0 .

Since the values of $\bar{T}$ and L in Eq. (10) may be assumed to be constants for a given wire (at least for the short duration of a calibration), determination of only the first term of the equation was required, and the single-temperature calibration

procedure outlined above was adequate. This approach thus assumes the slope $\bar{T}/L$ to be constant and checks for changes in the offset constant (intercept), $T_0 - \bar{T}R_0/L$. Table 9 provides the measured changes in offset constant that occurred between the pre-installation February 1982 calibration and the post-test February 1984 calibration. Because errors are a function of wire length, the CWTs are treated in three groups. Note that while the average errors are acceptably small, individual errors in some cases approached or exceeded 0.5°C .

Error Analysis

Four potential sources were identified that together produce the calibration errors reported above: the coefficient $\bar{T}$, wire length, thermistor

Table 9. Measured errors resulting from changes in offset constant during the two-year period of deployment of convergence wire temperature monitors.

Wire length (m)	Number calibrated	Errors (°C)		
		Mean	Std dev	Range
2.9 to 3.5	18	-0.101	0.354	-0.814 to 0.429
4.6 to 5.9	11	-0.090	0.219	-0.426 to 0.164
8.0	1	-0.248	NMF ^a	NMF ^a

^a No meaningful figure.

temperature reading, and the resistance reading. The coefficient $\dot{T}$ is first analyzed separately because it is itself a function of several sources of error:

$$\dot{T} = \frac{T^* L^*}{R^*}, \quad (11)$$

where

T^* is the calibration temperature, °C,

L^* is the length of the calibrated wire, m, and

R^* is the calibration resistance, Ω .

The sensitivity factors for $\dot{T}$ are calculated by differentiating Eq. (11) with respect to its three components

$$\Theta_L = \frac{d\dot{T}}{dL} = \frac{T^*}{R^*}, \quad (12)$$

for errors in wire length,

$$\Theta_T = \frac{d\dot{T}}{dT} = \frac{L^*}{R^*}, \quad (13)$$

for errors in temperature measured by the thermistor,

$$\Theta_R = \frac{d\dot{T}}{dR} = -\frac{T^* L^*}{R^{*2}}, \quad (14)$$

for errors in wire resistance.

The maximum RSS uncertainty of the value of $\dot{T}$ is calculated to be $8.836 \times 10^{-2} \text{ } ^\circ\text{C} \cdot \text{m}/\Omega$. Maximum individual sources of error were (a) wire length, $\pm 1.5 \text{ mm}$, (b) temperature $\pm 0.2^\circ\text{C}$, and (c) resistance, $\pm 5 \text{ m}\Omega$.

Sensitivity factors for T may be calculated by differentiating Eq. (10) with respect to each of the four error sources. Ignoring the slope term for reasons outlined above, we calculate

$$\Theta_{\dot{T}} = \frac{dT}{d\dot{T}} = -\frac{R_0}{L}, \quad (15)$$

for errors in the coefficient;

$$\Theta_L = \frac{dT}{dL} = \frac{\dot{T} R_0}{L^2}, \quad (16)$$

for errors in the wire length;

$$\Theta_{T_0} = \frac{dT}{dT_0} = 1, \quad (17)$$

for errors in temperature measured by the thermistor;

$$\Theta_{R_0} = \frac{dT}{dR_0} = -\frac{\dot{T}}{L}, \quad (18)$$

for errors in wire resistance.

The maximum uncertainty of the calibration is calculated for each of the three classes of CWTs by obtaining the product of the sensitivity factor and its associated maximum error. Maximum errors were (a) coefficient determination, $\pm 8.84 \times 10^{-2} \text{ } ^\circ\text{C} \cdot \text{m}/\Omega$; (b) length measurement, $\pm 1.5 \text{ mm}$; (c) temperature measurement, $\pm 0.2^\circ\text{C}$ (see the section entitled "Thermistors"); and (d) resistance measurement, $\pm 5 \text{ m}\Omega$.

Table 10 presents the uncertainty for each source of error and the resulting composite uncertainty that was calculated as the RSS of the four uncertainties. These calculated errors agree favorably with those observed during calibrations (Table 9).

The error analysis may be extended to operation of the CWTs in the field where the slope term in Eq. (10) becomes operational. The sensitivity factors are now

$$\Theta_{\dot{T}} = \frac{dT}{d\dot{T}} = -\frac{R_0}{L} + \frac{R}{L} = \frac{R - R_0}{L}, \quad (15a)$$

$$\Theta_L = \frac{dT}{dL} = -\frac{\dot{T}}{L^2}(R - R_0), \quad (16a)$$

$$\Theta_{T_0} = \frac{dT}{dT_0} = 1, \quad (17a)$$

$$\Theta_R = \frac{dT}{dR} = \frac{\dot{T}}{L}. \quad (18a)$$

Note that the value of Eq. (18a) differs from Eq. (18) only in sign. This result occurs because R

Table 10. Calculated errors in offset constant associated with calibration of convergence wire temperature monitors.

Wire length (m)	Source and magnitude of error (°C)				RSS
	Coefficient $\dot{T}$	Length measurement	Thermistor temperature	Resistance reading	
2.9 to 3.5	0.200	0.520	0.200	0.824	1.015
4.6 to 5.9	0.200	0.306	0.200	0.506	0.655
8.0	0.200	0.203	0.200	0.354	0.496

Table 11. Calculated total errors associated with field deployment of convergence wire temperature monitors.

Wire length (m)	Source and magnitude of error (°C)				RSS
	Coefficient $\dot{T}$	Length measurement	Thermistor temperature	Resistance reading	
2.9 to 3.5	0.004	0.011	0.200	0.824	0.848
4.6 to 5.9	0.004	0.006	0.200	0.506	0.544
8.0	0.004	0.004	0.200	0.354	0.407

is not present during calibration and R_0 is present but is a constant (the derivative of which is zero) during field deployment of the instruments. Values of $R - R_0$ were calculated using average values of $\dot{T}/L$ over the temperature range of 18 to 40°C observed in the field. Table 11 presents the maximum uncertainty for each error source and for the RSS error. Note that the RSS errors during field deployment of the CWTs are less than the RSS errors associated with calibration because the errors associated with the coefficient $\dot{T}$ and wire length are partially self-compensating.

Reliability

The 32 CWT units deployed at the SFT—C functioned reliably throughout the monitoring period with one exception. CWT011 was located across a fault zone where the rock and clay gouge

were very moist and pyrite was plentiful. These conditions produced a small battery that caused current to pass through the wire. As a result, variations in the apparent resistance of the wire made this CWT unusable. This observation indicates a need to insulate the CWE wire from the rock mass in applications where the rock is an insufficient dielectric medium or where natural "batteries" may be present.

During calibration, one of the metal clamps used to connect electrical lead wires to the stainless steel wire slipped on CWE011 and CWE031, resulting in calibration errors of several degrees. Calculated errors associated with replacing the slipped clamps range from about 0.2 to 0.5°C, assuming that contact resistance remained unchanged or small.

Ventilation System Instrumentation

It was necessary to control the ventilation of the underground space to maintain a safe, habitable working environment while not extracting so much thermal energy that the rock would not attain realistic temperatures. Pretest calculations (Montan and Patrick, 1981) indicated that without ventilation, air temperatures would reach about 60°C during the test. These calculations also showed that a modest air flow would limit air

temperatures to about 40°C and remove about 13% of the total energy deposited during the test.

It was necessary to monitor the energy removal so that the ventilation model could be evaluated and so that the general heat transfer model could be modified as necessary to account for the loss of energy from the test environment. Instrumentation was deployed to measure air temperature, dewpoint, and ventilation flowrate.

During the spent-fuel storage phase of the test, all air flow occurred through a single exhaust port: the canister access shaft. Flow was regulated in the three drifts by means of bulkheads and louvers (Patrick and Mayr, 1981). Following spent-fuel retrieval, an additional exhaust port was added to each heater drift to expedite cooling of the rock mass surrounding the facility. Ventilation system instrumentation was deployed for each of these phases of the test.

Air Temperature

Type K thermocouples sheathed in Inconel 600 were positioned at the trifurcation of the heater drifts and canister drift, at the ventilation-control bulkheads at the far ends of the two heater drifts, at the heater drift midpoints, and at the far end of the canister drift where the canister access shaft intersects the roofline. This last location is where the ventilation air exits the facility. In addition, a thermocouple was located at the inlet of each of two exhaust tubes used to expedite cooling of the facility following spent-fuel retrieval.

Thermocouples measure the so-called dry bulb temperature of the airstream. Changes in temperature between the ventilation inlet and outlet points at a constant water content are thus used to calculate the sensible heat removed from the SFT—C.

Since these thermocouples were from the batch described previously in the section on Temperature Sensors, they are not described further here. The RSS uncertainty in temperatures in the 20 to 40°C range was previously established to be $\pm 0.12^\circ\text{C}$ for the batch of thermocouples, but by using individual calibrations, maximum errors were limited to $\pm 0.005^\circ\text{C}$.

Dewpoint

Dewpoint sensors were located at the ventilation inlet and outlet points to determine changes in water content of the ventilation airstream. These measurements are used to calculate the energy removed as a result of adding water to the airstream through vaporization. This component, together with the sensible heat component noted above, constitutes the total energy removed in the ventilation airstream.

Two Yellow Springs Instrument Co., Inc., (YSI) Model 9400 lithium chloride dewpoint cells were mated with Weather Measure Corp. Model H361-DPYA dewpoint sensor assemblies to pro-

vide the necessary dewpoint measurements during the spent-fuel storage phase of the test. Two additional cells were added to obtain measurements at the two exhaust points added during the cooling phase.

Calibration

Dewpoints ranged from 10 to 22°C during the test with differences between inlet and outlet dewpoints of about 1 to 2°C (relative humidity was about 50% during the test).

The dewpoint cells were calibrated before and after the test to confirm their adherence to YSI-tabulated values. Calibrations were performed at 21 and 49°C pretest and at 21°C posttest. These calibrations were performed under contract at the Sandia Standards Laboratory, Albuquerque, New Mexico. Figures 16 through 19 show the excellent agreement between calibration results and YSI-tabulated relationships between dewpoint cell resistance and dewpoint temperature.

Error Analysis

Comparisons between YSI and calibration resistance readings at dewpoint temperatures between 10 and 22°C show that typical errors in RTD resistance are 0.1 to 0.2% with two extreme errors of 0.4 and 0.9%. Since RTD readings are a linear function of cell temperature in this range, the RTD errors may be expressed as dewpoint errors of about 2.2°C/1% error in RTD reading. Because RTD errors were typically a few tenths of a percent as noted above, the resulting dewpoint errors are well within the YSI-quoted "maximum possible errors," which range from -1.75 to $+0.75^\circ\text{C}$ at a dewpoint of 10°C, to -1.50°C to $+1.25^\circ\text{C}$ at a dewpoint of 20°C.

In the energy balance calculations, vapor pressure (rather than dewpoint temperature) is used directly. Vapor pressure V_p and dewpoint cell resistance R are related by the equation

$$V_p = A_0 + A_1R + A_2R^2 + A_3R^3 + A_4R^4 \quad (19)$$

The sensitivity factor for errors in RTD resistance reading is found by differentiating Eq. (19) with respect to R , such that

$$\Theta_R = \frac{dV_p}{dR} = A_1 + 2A_2R + 3A_3R^2 + 4A_4R^3 \quad (20)$$

Maximum uncertainty in vapor pressure due to errors in resistance readings is ± 0.0187 Torr,

Figure 16. Comparison of dewpoint calibration data with YSI-tabulated data for dewpoint cell DPM001.

based on an error in resistance of $0.011\ \Omega$ (see the section on RTDs). Since the energy calculations are based on differences in vapor pressures, any systematic errors that may exist cancel.

Reliability

All four dewpoint cells functioned reliably throughout their deployment periods. Two of the cells were in use for about three years, while the other two were in service only for the 6-month cooling period following spent-fuel retrieval.

Ventilation Flowrate

An Engineering Measurements Company Model TMP turbine flowmeter was located in the

surface duct-work of the ventilation system to measure air flow. In addition, a Model FTP-812S3700-GJS-12 "Mini-Probe" flowmeter was installed in the duct-work of each heater drift following spent-fuel retrieval to monitor the augmented airflow. These units are referred to as "airflow monitors" and carry designations of the form AFMxxx.

Calibration

Calibrations were performed by REEC Co Industrial Hygiene Section personnel using a hand-held pitot tube that was inserted through a port in the duct-work. Simultaneous readings of the pitot tube and flowmeter were obtained at 10 positions across both the horizontal and vertical diameters of the duct. Measurements were obtained at three

Figure 17. Comparison of dewpoint calibration data with YSI-tabulated data for dewpoint cell DPM002.

flowrates. The pitot tube measurements used a Magnehelic panel consisting of a barometer and Dwyer magnehelics with ranges of 0 to 2 in. H₂O, 0 to 5 in. H₂O, and 0 to 60 in. H₂O. The REEC Standards and Calibration Facility certified an accuracy ±0.1% of reading for the magnehelics. However, the rather poor resolution of the magnehelics limited the actual accuracy to ±3% for the main ventilation system (AFM201) and ±5% for the augmented ventilation system (AFM002 and AFM003).

Average airflow velocities were used to compute volumetric flowrates of standard temperature and pressure air. The volumetric flowrate Q was

in turn related to the flowmeter output voltage using the equation

$$Q = AV + B \quad (21)$$

A comparison of the pre- and post-test calibrations indicates that substantial shifts occurred in the parameter B in Eq. (21). The resulting errors are 0.20 m³/s (17%) for AFM002 (north drift), 0.22 m³/s (18%) for AFM003 (south drift), and 0.50 m³/s (18%) for AFM201. In all cases, the post-test measured flowrates are lower for a given voltage output. Conversely, the voltage output is higher for a given measured flowrate, which is the opposite of what occurs when a turbine fails because of

Figure 18. Comparison of dew-point calibration data with YSI-tabulated data for dewpoint cell DPM003.

increased friction in the bearings or because of dust accumulations on the turbine blades. Examination of the flowrate data recorded during the SFT—C indicates no systematic increase in apparent flow with time. We suspect that this very consistent (~18%) error was introduced in calibration and is not present in the data acquired during the test.

Reliability

The three turbine flowmeters appear to have functioned reliably throughout the test period. The only question concerning reliability relates to the apparent 18% shift in readings discussed

above. AFM201, which was in service for 3.5 years, experienced one turbine failure at about 4.5 YOC* (two years into the test) and was replaced at that time. It also malfunctioned at about 4.72 YOC in August 1982 during the third exchange of spent-fuel assemblies. The turbine was cleaned, reinstalled, and functioned reliably through termination of the test.

* YOC is a time index based on the spent fuel age measured in "years out of core." It is used throughout the SFT—C data acquisition and reporting activities. The first spent-fuel assembly was emplaced on April 18, 1980, with an age of 2.412 YOC.

Figure 19. Comparison of dewpoint calibration data with YSI-tabulated data for dewpoint cell DPM004.

Energy Removal Calculation

The sources of error described above propagate to the calculation of energy removal from the SFT—C. The algorithm for determining the power removed as sensible heat is

$$P_s = (T_0 - T_i) V \quad (22)$$

where T_0 and T_i are outlet and inlet temperatures and V is the volumetric flow rate. Differentiating Eq. (22) with respect to each parameter gives

$$\Theta_{T_0} = \frac{dP_s}{dT_0} = V \quad (23)$$

for errors in outlet temperature;

$$\Theta_{T_i} = \frac{dP_s}{dT_i} = -V \quad (24)$$

for errors in inlet temperature;

$$\Theta_V = \frac{dP_s}{dV} = (T_0 - T_i) \quad (25)$$

for errors in volumetric flowrate.

The algorithm for determining the power removed as the latent heat of vaporization is

$$P_L = 2.135(V_{P2} - V_{P1})V, \quad (26)$$

where V_{P2} and V_{P1} are the outlet and inlet vapor pressures and V is the volumetric flowrate. Differentiating Eq. (26) with respect to each parameter gives

$$\Theta_{V_{P2}} = \frac{dP_L}{dV_{P2}} = 2.135 V, \quad (27)$$

for errors in the vapor pressure of the outlet air,

$$\Theta_{V_{P1}} = \frac{dP_L}{dV_{P1}} = -2.135 V, \quad (28)$$

for errors in the vapor pressure of the inlet air,

$$\Theta_V = \frac{dP_L}{dV} = 2.135(V_{P2} - V_{P1}), \quad (29)$$

for errors in the volumetric flowrate.

Maximum errors in temperature were limited to $\pm 0.005^\circ\text{C}$ by using individual thermocouple calibration data, and errors in vapor pressure were ± 0.0187 Torr (see the section entitled "Dewpoint"). The manufacturer's specified error for flowrate of $\pm 0.1\%$ was used because fundamental inaccuracies in the calibration system were so large (see the section entitled "Ventilation Flowrate") that the calibrations were of little value in establishing absolute relationships between flowrate and transducer output. Using Eqs. (23)–(25) and Eqs. (27)–(29), we calculate a total uncertainty in energy removal rate of ± 0.19 kW, or about $\pm 3.4\%$ during the spent-fuel storage phase of the test. This uncertainty increased to ± 0.21 kW, or about $\pm 3.7\%$ during the cooling phase of the test when the auxiliary ventilation system was operating.

Watt Transducers

Watt transducers were selected and deployed to measure the quantity of electrical energy introduced to the rock mass and ventilation airstream during the SFT—C. Three primary sources of electrical heat were present: electrical simulators, auxiliary heaters, and areal lighting. An overall accuracy requirement of 2 kW for the system—1.5 kW with lighting off—was determined to be adequate for the purposes of the SFT—C (Brough and Patrick, 1982).

The thermal output of the six electrical simulators was monitored and controlled on an individual basis. Outputs ranged from about 1.6 to 0.6 kW per simulator. Loyola Industries BPAC-series controllers (SCR-type) delivered power to the simulators. American Aerospace Controls, Inc., Model 413-25-230 watt transducers measured the power output of the controllers.

The power output of the 10 auxiliary heaters located in each of the side drifts ranged from 1.85 to 0.625 kW per heater. Since the heaters were grouped in two sets of three and one set of four in each drift, measured powers ranged from 7.40 to 1.88 kW. Loyola SCRs and American Aerospace Controls, Inc., Model 413-100-115 watt transducers were used.

The power output of the areal lights was monitored with two ranges of transducers. Canister drift lighting was monitored with three American Aerospace Controls, Inc., Model 413-100-115 watt transducers, whereas the heater drift lighting was monitored with a total of four Model 413-25-

115 watt transducers. Electrical lights were connected directly to utility power with no intervening SCRs.

Calibration

Calibrations were performed to examine the accuracy and behavior of the transducers under realistic conditions. The relative complexity and need for precision precluded use of field calibrations so laboratory calibrations were performed. A calibration system was developed that used incandescent lights as electrical loads. Both pre- and post-test calibrations were conducted. Details of the calibration configuration are presented by Brough and Patrick (1982).

Means and standard deviations of errors measured during pre- and post-test calibrations are presented in Table 12 for transducers deployed with SCRs. Similar data are presented in Table 13 for transducers deployed in the continuous ac voltage mode. Error data are given both as absolute watts and as a percentage of reading. A systematic change in transducer response is noted in all cases. Pretest errors were negative (measured power less than power calculated using manufacturer's sensitivity and offset values) in all but one case. On the other hand, post-test errors were positive in all but two cases, and even here the errors became more positive.

The observed systematic changes in transducer response are attributed nonspecifically to

Table 12. Errors measured during pre- and post-test calibration of watt transducers with SCR-controlled voltage.

Instrument license plate	Serial number	Pretest calib. mean (std dev) error		Post-test calib. mean (std dev) error	
		Watts	% reading	Watts	% reading
Auxiliary heater watt transducers					
NHW001	121	- 69.0 (23.7)	- 1.3 (0.3)	137.4 (50.5)	3.2 (0.3)
NHW002	122	- 53.5 (37.1)	- 1.3 (0.8)	119.1 (36.8)	2.8 (0.4)
NHW003	123	18.3 (25.8)	0.3 (0.5)	—	—
SHW001	124	- 221.0 (90.7)	- 3.9 (0.5)	66.6 ^a (17.1)	1.6 ^a (0.4)
SHW002	125	- 43.3 (8.5)	- 1.1 (0.4)	173.6 (60.2)	4.1 (0.4)
SHW003	126	- 13.9 (10.0)	- 0.4 (0.3)	26.7 (12.7)	0.7 (0.4)
Composite	N/A	- 63.7 (86.6)	- 1.3 (1.4)	105.6 (63.5)	2.5 (1.2)
Electrical simulator watt transducers					
CHW021	136	- 80.6 (45.9)	- 3.8 (1.4)	20.9 (6.0)	3.6 (0.9)
CHW041	137	- 69.8 (41.3)	- 3.2 (1.0)	14.8 (4.6)	2.8 (1.0)
CHW061	138	- 74.8 (46.4)	- 3.4 (1.1)	13.5 (5.3)	2.2 (0.9)
CHW131	139	- 63.8 (37.8)	- 2.9 (0.7)	31.6 (9.6)	5.3 (0.9)
CHW151	140	- 85.1 (36.1)	- 4.0 (1.3)	16.9 (6.9)	2.4 (1.0)
CHW171	141	- 83.0 (33.1)	- 4.0 (1.2)	18.9 (5.9)	3.1 (0.6)
Composite	N/A	- 76.2 (38.9)	- 3.5 (1.1)	19.4 (8.6)	3.2 (1.3)

^a Apparently damaged in shipment. See discussion in "Reliability" section.

Table 13. Errors measured during pre- and post-test calibration of watt transducers with continuous alternating current.

Instrument license plate	Serial number	Pretest calib. mean (std dev) error		Post-test calib. mean (std dev) error	
		Watts	% reading	Watts	% reading
Heater drift lighting watt transducers					
NLW001	131	- 36.1 (11.3)	- 2.7 (0.7)	8.5 (5.4)	0.7 (0.5)
NLW002	132	- 33.8 (9.9)	- 2.5 (0.4)	11.8 (6.8)	9.8 (0.4)
SLW001	133	- 37.8 (11.4)	- 2.8 (0.4)	20.0 (10.5)	1.4 (0.3)
SLW002	134	- 38.2 (11.2)	- 2.8 (0.5)	- 9.3 (4.7)	- 0.7 (0.3)
Composite	N/A	- 36.5 (10.5)	- 2.7 (0.4)	7.7 (12.8)	0.5 (0.9)
Canister drift lighting watt transducers					
CLW001	127	- 284.4 (87.7)	- 7.0 (0.8)	- 66.1 (31.9)	- 1.8 (0.9)
CLW002	128	- 86.7 (35.4)	- 2.2 (0.6)	— ^a	— ^a
CLW003	129	- 83.4 (19.9)	- 2.1 (0.5)	— ^a	— ^a
Composite	N/A	- 151.5 (109.0)	- 3.7 (2.4)	- 66.1 (31.9)	- 1.8 (0.9)

^a Apparently damaged in shipment. See discussion in "Reliability" section.

component aging. The same measurement system, calibration standards, and procedures were used in both calibrations so there is little likelihood that a different error source was introduced at this point. Furthermore, it is clear that the offset, while systematic in design, varies quite widely in terms of both absolute power and percentage of reading. We are confident that these differences in pre- and post-test errors represent actual changes in transducer responses.

Error Analysis

Changes such as those identified above present a real challenge in determining how to utilize calibration results in the data conversion algorithms. This observation may also suggest a need to perform additional periodic calibrations or to obtain additional information on the aging of these transducers.

In the absence of such information, we performed an error analysis using the calibration results directly, ignoring the lighting transducers since the contribution of input energy from lighting was only 4.8% of the total (Patrick et al., 1984). The approach is based on the calibration data presented above with the power calculated from the manufacturer's specification taken as the "true" value. This analysis indicates that at the start of the SFT—C, 1.3% less energy than planned was being deposited by the auxiliary heaters and 3.5% less energy than planned was being deposited by the electrical simulators. By the end of the test, 2.5 and 3.2% more energy than planned was being deposited, respectively, from these two heat sources. Since there was a period when the average error was negative and then positive, it follows that the cumulative error was less than either of these extremes.

Reliability

With one exception, the watt transducers deployed on the six electrical simulators functioned reliably throughout the 2.8-yr heating phase of the SFT—C. The SCR for the CEH17 simulator failed and was out of service for 12 days between 2.83 and 2.86 YOC. Examination of the individual plots of power output shows no other periods of erratic behavior. The sensitivity of the partial duty cycle controllers to variations in line voltage became excessive as the power level was reduced below about 1 kW (Patrick et al., 1982). A set of process controllers with power-sensing feedback was installed at about 5.0 YOC to reduce the variability in output power. A markedly more stable power output resulted (Fig. 20).

Several component malfunctions were observed in the auxiliary heater control system. The performance of each system is noted in Table 14. Figure 21 shows the failure mode for the heater controller. The power level fluctuates, fairly repeatedly, between the setpoint and some higher power level that is less than the full power of the controller. Note that the problems were identified with the controller, not with the watt transducers themselves. Auxiliary heater power levels were set too low on February 19, 1982; beginning on March 1, 1982 they were adjusted upward in power to balance out the period of low power input. In addition, one watt transducer was apparently damaged in shipment so a valid post-test calibration was not obtained (Table 12).

Individual data records indicate that the canister-drift and heater-drift-lighting watt transducers functioned reliably throughout the measurement period. As noted in Table 13, two of the seven were apparently damaged in shipment, which precluded obtaining a valid post-test calibration.

Figure 20. Electrical simulator power history showing effect of loop controller addition at 5.0 YOC.

Table 14. Performance history of the auxiliary heater controller systems.

Associated wall transducer	Mode of failure	Period of failure
NHW001	—	None
NHW002	Erratic controller output, changed controller	10/22/81–10/30/81
	Erratic controller output, changed controller	11/11/81–11/19/81
	Erratic controller output, changed controller	1/23/82–2/9/82
NHW003	Erratic controller output, checked connections, some loose	2/21/82–3/2/82
	Erratic controller output, changed controller	3/11/82–3/25/82
	Erratic controller output, changed controller, also changed wall transducer 11/8/82 with no improvement	10/7/82–11/10/82
SHW001	Erratic controller output, changed controller	3/8/82–3/25/82
SHW002	—	None
SHW003	—	None

Figure 21. Guard heater power history for north heater drift group showing effect of controller malfunctions.

Stressmeters

Vibrating-wire stressmeters were deployed at the SFT—C to measure stress changes that occurred as a result of heating the rock mass. Three IRAD Gage Co. Model VBS-1HR (hard rock) stressmeters were used in the pillars during the Mine-by experiment (Wilder and Patrick, 1981). During the heated phase of testing, 18 Model VBS-1HT[HR] (high-temperature hard rock) stressmeters were used in the pillars and at positions 1.2 m radially outward from the spent-fuel assemblies (Brough and Patrick, 1982) (Figs. 22 and 23). The principal differences in the latter units were the use of Teflon-sheathed electrical wire and higher temperature potting and O-ring seals.

Three steps were taken to reduce the likelihood of corrosion of the stressmeters during the heated phase. These actions were taken based on observed corrosion of the three stressmeters deployed for the Mine-by experiment (Carlson et al., 1980). First, the stressmeter bodies and platens were plated before assembly with a 0.127-mm-thick electroless nickel containing 7 to 10% phosphorus. Second, the stressmeters were coated with a 0.167-mm-thick film of Pyrolene-N. Third, following installation, the borehole void was filled with inert high-density foam.

Twelve stressmeters were deployed in two sets of three in each of two 38-mm-diam horizontal boreholes in the north pillar of the SFT—C. Vertical, 60-degree clockwise and 60-degree counterclockwise orientations were used in each set of three to form a rosette with 150-mm spacings between gauges (Carlson et al., 1980). Two sets were positioned near the center of the pillar and two sets were located within 1 m of the canister drift rib. In addition, six stressmeters were deployed in two rosettes in vertical boreholes adjacent to canister emplacement boreholes CEH03 and CEH09. Details concerning the positioning and installation of all stressmeters are reported by Abey and Washington (1980). A single Type K thermocouple was positioned with each set of three stressmeters to provide temperature data to compensate for the effects of thermal expansion.

The initial set of 18 stressmeters failed in service and were replaced with units featuring a new seal design (Patrick et al., 1981). Stainless steel end-caps were electron-beam welded in place to hermetically seal the center cavity of the stressmeters, which houses the vibrating wire. Details concerning the positioning and installation of the replacement units are provided in Patrick et al. (1982 and 1983) and Patrick et al. (1981).

Figure 22. Location of thermal phase instrumentation.

Figure 23. Cross section showing thermal-phase and Mine-by instrumentation arrays.

Calibration

Three special investigations were conducted on the calibration characteristics of the IRAD vibrating-wire stressmeters. An in-house study by Abey and Washington (1980) focused on techniques to reliably install a stressmeter in such a way that its calibration coefficient was known. Depending on borehole conditions, the initial preload decreased varying amounts when the installation tool was released. This study found that the calibration coefficient was directly related to the preload on the stressmeter.

IRAD Gage, Inc., was contracted to perform a second, broader series of laboratory calibration studies that focused on the behavior of the vibrating-wire stressmeter in Climax granite at elevated temperatures (Dutta et al., 1981). A test program was developed to study nine important factors that influence stressmeter response: test block size, stressmeter stiffness, gauge reproducibility and hysteresis, gauge preload, initial stress field, platen geometry, platen orientation, elevated temperature, and rock anisotropy. Many of these tests were conducted under uniaxial, biaxial, and triaxial loading conditions. In addition to improving our basic understanding of the stressmeter response to a variety of test conditions, the results of these studies were used to develop the algorithm for data reduction and interpretation. These results are summarized below.

1. Blocks of aluminum, Barre granite, and lucite were used in this study to examine the effect of sample size. While sample width was constant at 250 mm, the height-to-width ratio was varied from 1.0 to 1.5 or 2.0. For the three materials tested, the influence of sample size on stressmeter sensitivity was 7.3, 3.1, and 1.1%, respectively.

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

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

4. Gauge preload effects were observed at low preload values, but the sensitivity of the gauge is nearly constant for preloads of 175 units or more.

5. The influence of initial stress field on gauge response was determined to be negligible.

6. Tests in lucite and aluminum indicated that the hard rock (HK) platen results in markedly smaller (in fact, negligible) variations in the sensitivity factor as a function of stress than when soft rock and modified soft rock (SR and MSR) platens are used.

7. Theory shows that the ratio of gauge sensitivity to loading parallel to the wire compared with loading perpendicular to the wire should be -3.00 . However, test results indicated that the actual ratio varies from -2.84 to -3.28 , depending on stress level.

8. The influence of temperature is probably the most critical aspect of gauge response as it relates to the SFT—C. Changes in temperature were found to simply cause an offset in stressmeter reading by a factor $1.55 \Delta t$. For the range of temperatures experienced at the SFT—C, changes in stressmeter sensitivity with increasing temperature are negligible.

9. Tests in three slabs of Climax granite revealed that fairly significant anisotropy exists (11 to 27%) for different stressmeter orientations. This may be the result of preferential orientation of healed geologic fractures and feldspar phenocrysts in the rock slabs.

The first two calibration studies made it clear that the response of a stressmeter was a unique function of the local rock conditions and installation process. Since the stressmeters have no provision for *in situ* calibration, we developed an experimental approach to retrieve the gauges while they were still encased in a core of rock for subsequent laboratory calibration (Mao, 1984).

Each rosette of three stressmeters was retrieved by overcoring with a nominal 0.25-m-diam diamond-impregnated bit. Only 6 of the 18 stressmeters were successfully retrieved because of problems associated with the geological structure and the drilling technique. Once the large-diameter core was received at the laboratory, it was overcored with a nominal 0.15-m-diam bit to obtain concentricity with the 38-mm borehole containing the stressmeters.

The retrieved stressmeters, still encased in the section of rock in which they were installed, were calibrated under uniform biaxial compression. Mao (1984) shows that the sensitivity factor for a particular stressmeter installation may vary widely from the nominal value obtained during

conventional laboratory calibration. The importance of accurately knowing the sensitivity factor is discussed below.

Error Analysis

The basic equation for determining changes in stress is

$$S = 1.7842 \times 10^{14} A \left[\frac{1}{(T_1')^2} - \frac{1}{(T_2)^2} \right] \quad (30)$$

where

- S = is the stress change in pascals,
- $T_1' = T_1 + 1.55 \Delta t$, where T_1 is the initial stressmeter reading and Δt is the change in temperature that occurred between the readings T_1 and T_2 ,
- T_2 = the current gauge reading,
- A = assumed to be a constant.

Note that the values of T_1 are obtained from the IRAD MB-6 readout box (or its equivalent) and are equal to $10^7/f$, where f is the frequency of the vibrating wire. Based on the early studies by Abey and Washington (1980), the following values were used in our data conversion algorithm:

- $A = 1.6$ for gauges with a stable preload.
- $A = 1.8$ for gauges showing a 5 to 10% decrease in preload.
- $A = 2.0$ for gauges showing a greater than 10% decreased in preload.

The study by Mao (1984) indicates that variations in A , which are caused by unique gauge-rock interactions, are the most significant source of error in the stressmeters. Gauge-to-gauge variations have been shown to be small (when the gauge is tested independent of the rock) and gauge sensitivity and stability are excellent (0.1 to 1.0%) (Patrick et al., 1982).

Error sensitivity factors are determined by differentiating Eq. (30) with respect to temperature and the gauge factor A , such that

$$\Theta_T = \frac{dS}{dT} = -5.531 \times 10^{14} \frac{A}{(T_1')^3} \quad (31)$$

$$\Theta_A = \frac{dS}{dA} = 1.7842 \times 10^{14} \left[\frac{1}{(T_1')^2} - \frac{1}{(T_2)^2} \right] \quad (32)$$

Evaluating Eq. (31) for errors in temperature readings of 0.14°C , as developed in the section on thermocouples, we calculate an error of 0.019 MPa, a trivial quantity compared with anticipated

Table 15. Errors introduced by differences between assumed and measured calibration constants for six vibrating-wire stressmeters.

Instrument license plate	Assumed "A" value ^a	Measured "A" value ^b	Percentage error
NSG231	1.6	0.99	+38
232	1.6	1.30	+19
233	1.8	2.85	-58
NSG244	1.6	2.42	-51
245	1.6	2.34	-46
246	1.8	2.51	-39

^a Based on data from Patrick, Carlson, and Fector (1981).

^b Based on data from Mao (1984).

magnitudes of stress changes on the order of several MPa. Likewise, Eq. (32) may be evaluated using differences between the assumed A values and those reported by Mao (1984). Table 15 shows the observed range of differences in A values and the resulting errors in calculated stress changes.

This analysis highlights the need to obtain reliable post-test calibrations of the stressmeters while they are still encased in the same volume of rock as in the field.

Reliability

The original set of vibrating-wire stressmeters began failing a few months after their installation in March 1980 with the onset of failure marked by an erratic output signal (Fig. 24). The earliest failures were noted in the CSG-series instruments, which experienced the thermal pulse that accompanied spent fuel emplacement much sooner than the NSG-series instruments (Table 16). Thermal time constants for these positions are 12.5 and 240 days and the mean times to failure are 114 and 352 days, respectively.

Although we have defined failure here in terms of erratic gauge behavior, it is quite possible that the stressmeter data were incorrect by some amount for an unknown time period before the onset of erratic behavior. Direct inspection of the wires determined the failures to be caused by rusting of the vibrating wires (Patrick et al., 1981). The erratic output signal was apparently generated when rust particles on the wire critically damped the vibrations. Before the critical damping, however, the wire was increasing in mass due to the rust (Patrick et al., 1981). This mass loading would tend to decrease the vibrational frequency

Figure 24. Data from selected vibrating-wire stressmeters showing signatures of normal and failing units.

of the wire, which would be interpreted as an increase in rock stress. Since an actual increase in

Table 16. Time-to-failure data for vibrating-wire stressmeters.

Instrument license plate	Serial number	Failure date (YOC)	Time to failure (days) ^a
CSG011	07	2.86	161
012	Q15	2.84	153
013	05	2.63	77
CSG021	Q1	2.70	102
022	Q27	2.66	88
023	Q4	2.70	102
NSG031	Q9	3.72	476
032	Q13	3.72	477
033	Q18	3.27	310
NSG034	Q17	4.50	760
035	Q22	3.52	402
036	Q26	3.27	310
NSG041	011	3.20	285
042	020	3.14	264
043	03	3.05	230
NSG044	012	3.29	318
045	023	3.13	260
046	024	2.80	139

^a "Failure" is based on the onset of erratic data. The data received prior to "failure" may or may not be reliable.

stress was anticipated based on rock response calculations, it is impossible to discern what portion of the observed gauge response is due to actual stress change in the rock and what is due to mass loading of the wire.

Under independent funding, IRAD subsequently designed and tested a hermetically sealed version of the gauge. In the new version, sealing is accomplished by thin, stainless-steel cups welded to the gauge body around the perimeter of the hole at the ends of the gauge (Fig. 25). Since the welding is done by electron beam, the interior of the gauge is a hard vacuum, thereby eliminating any moisture entry during assembly.

Nine of these new gauges were installed at the SFT—C on June 16 and 17, 1981, and the remaining nine were installed on October 15–27, 1982. With the assistance of a borescope, the location and orientation of each gauge was precisely selected to avoid rough spots, fractures, and residual foam on the wall contact areas. Locations and initial readings of the replacement gauges are provided by Patrick et al. (1981) and Patrick et al. (1983).

With two exceptions, the 18 replacement stressmeters functioned reliably. Stressmeter number NSG242 occasionally returned erratic output signals for about 3.5 months following its installation in October 1982, and NSG243 exhibited similar behavior throughout its 1-year deployment period. Most readings were reliable for both gauges. The cause of the erratic readings was not determined.

Figure 25. Use of thin stainless cups in the new-design vibrating-wire stressmeters.

Rod Extensometers

Commercially available multiple-point borehole extensometers (MPBX) were used as the principal instrument to measure relative displacements within the rock mass at the SFT—C. Two series of extensometers were deployed, both of which were manufactured by Terrametrix Co., Golden, Colorado.

The Mine-by instrument (MBI) series consisted of four sets of three- and six-anchor units that were installed from the north and south heater drifts of the SFT—C (Figs. 22 and 23) and were originally used to measure relative displacements that took place as the canister drift was excavated (Wilder and Patrick, 1980 and Heuze et al., 1981). The MBI-series extensometers were hydraulically anchored in 76-mm-diam (NX)* boreholes using a standard burst tube and check valve inflation system. Only the collar stabilizer tube was grouted; the rest of the borehole remained open. The connecting rods were carbon steel and were enclosed as a group in a silicone-rubber-sheathed flexible metal conduit. Following the Mine-by experiment, the head assemblies were refurbished, the associated linear potentiometers were recalibrated, and the MBI-series extensometers were returned to service for the heated phase of the SFT—C.

During the heated phase, the MBI-series extensometers were augmented by a second series that was grouped in four sets to measure near-field thermal effects in the canister storage drift. These units are called the GxE-series, where the "x" is A, B, C, or D depending on which set is being described (Figs. 22 and 23). The GAE and GDE units each comprise one four-anchor MPBX, whereas the GBE and GCE units each comprise two subsets of three four-anchor MPBXs located on either side of the drift centerline. The GxE-series extensometers were also hydraulically anchored but used a nitrogen-over-hydraulic-oil-pressure maintenance system to ensure adequate initial inflation and subsequent pressures during the heated phase of the test (Brough and Patrick, 1982). These units were grouted along their entire length using a grout formulated to expand slightly as it cured. To allow for differential expansion and shear between extensometer components, grout, and rock, a ring of closed-cell foam was attached about 0.3 m above and below each hydraulic anchor. Because temperatures would reach 60 to

65°C, Superinvar connecting rods were used on the GxE-series extensometers. The connecting rods were enclosed as a group in a silicone-rubber-sheathed flexible metal conduit.

For their initial deployments, both the MBI- and GxE-series extensometer transducers were Bourns Model 5184 rectilinear potentiometers. The refurbished MBI units also used these transducers. The potentiometer shafts were attached to the extensometer connecting rods with threaded fittings and lock nuts.

The GxE-series extensometers experienced severe transducer failures shortly after deployment for the heated phase (Patrick et al., 1981). As a result, four types of transducers were installed to evaluate how each type performed. Three extensometers were equipped with each type for a total of 12 of each transducer type. The transducers used in this evaluation were the Bourns Model 5184 rectilinear potentiometer, Vernitron Model 113 rectilinear potentiometer, Schaevitz Model 250 HCD LVDT, and Kaman Sciences Model KD-2310-6U electromagnetic proximeter. With the exception of the proximeter, which is a noncontacting device, the transducers were coupled to the connecting rods through a spring-loaded ball resting on a machined flat surface. Each set of four transducers of each type was subjected to one of three environments: sealed head assembly connected to sealed borehole; head assembly continuously flushed with a small flow of dry nitrogen; and head assembly ventilated of potentially harmful vapors with a slight vacuum.

Calibrations

Laboratory Calibrations

All transducers were laboratory-calibrated before installation to establish that the individual transducer was operating within specifications. Post-test laboratory calibrations were used to establish changes in transducer sensitivity, linearity, and hysteresis characteristics. Because there was no means to reliably establish a "mechanical zero" for the transducer, from which one could determine the theoretical electrical zero position, changes in the offset constant of the transducer could not be determined.

Significant changes occurred in the sensitivity of each type of transducer, with the performance of the electromagnetic proximeters clearly being

* NX is a standard borehole size, nominally 76 mm (3 in.).

poorer than that of the potentiometers and the LVDTs. The errors in displacement readings generated by these changes in sensitivity are shown in the top half of Table 17. These errors were calculated for an assumed displacement of 5 mm, somewhat larger than anticipated from calculations of rock mass response and thermal expansion of the rods. This approach is conservative for two reasons. First, it focuses the error analysis on the range of interest and does not smooth out the errors in this range by including data from the entire range of the transducer (a common problem with error analyses that are expressed as a percentage of full-scale output). Second, we have observed that this approach tends to highlight the detrimental effects of nonlinearities in the range of interest.

The distribution of errors resulting from changes in transducer sensitivity is shown in histogram form in Fig. 26. Note that the distribution is fairly symmetric at about zero, and about 80% of all errors fall within a $\pm 50\text{-}\mu\text{m}$ range. Errors of

this magnitude are a relatively small contribution to the total system errors for the extensometers, as discussed below in "Error Analysis."

Although it is easy to understand how drift in the relatively complex electronics of the LVDTs and proximeters could produce the observed changes in sensitivity, we did not foresee such changes in the linear potentiometers. A plausible mechanism for such changes is an increase or decrease in resistance near either end of the resistive element. A debonding or flaking of the resistive material near either terminal would increase the resistance over that segment of the potentiometer, thus decreasing the sensitivity over the remainder of the potentiometer. If this occurred outside the calibration range, the potentiometer would remain linear, as we observed in most cases. On the other hand, introducing a parallel resistance near a terminal would have the opposite effect of increasing the sensitivity over the remainder of the potentiometer. A conductive oxide film or accumulation of chemical residue and moisture could

Table 17. Summary of laboratory and *in situ* calibration errors for borehole rod extensometers.

Transducer	Calibration	Number	Magnitude of error (μm) ^a		
			Mean	Std dev	Range
MBI-series, potentiometers	Laboratory	58	-3.8	67.4	-281.2 to +348.1
GxE-series, potentiometers	Laboratory	29	-30.8	104.3	-539.6 to +115.4
GxE-series, LVDTs	Laboratory	12	-22.8	59.7	-207.2 to +13.9
GxE-series, proximeters	Laboratory	12	+190.8	308.1	-398.0 to +586.9
MBI-series, potentiometers	<i>in situ</i>	59	-222.5	603.7	-3440.3 to +29.4
GxE-series, potentiometers	<i>in situ</i>	29	-105.9	168.0	-938.6 to +45.1
GxE-series, LVDTs	<i>in situ</i>	11	-94.1	31.0	-136.3 to -45.5
GxE-series, proximeters	<i>in situ</i>	11	-746.8	895.2	-2651.2 to 580.9

^a Errors result from differences between pre- and post-test sensitivities. A positive sign indicates that the post-test transducer sensitivity was greater than the pretest value.

Figure 26. Distribution of errors measured in laboratory calibration of GxE- and MBI-series extensometer transducers. Errors result from changes in transducer sensitivity between pre- and post-test calibrations.

produce this effect. Both of these mechanisms are consistent with our observations concerning failure of linear potentiometers, as discussed below in "Reliability."

***In Situ* Calibrations**

Because MPBXs are relatively complex mechanical systems, we also performed field calibrations. The manufacturer's recommended procedure was followed for all pretest field calibrations of MBI- and GxE-series units. This procedure calls for displacing the head assembly relative to the anchors by means of machined steel blocks. To perform this calibration, the head assembly is displaced upward relative to the collar stabilizer tube by means of three bolts. Three calibration blocks are then positioned 120 degrees apart and the head assembly is lowered onto the appropriate steps of the blocks. Thus, whether the gross displacements are increasing or decreasing, the head assembly is always moved down relative to the collar stabilizer tube before each calibration reading is obtained. These calibrations were performed in 1-mm steps over a range of 5 mm for the potentiometers, and in 0.5-mm steps over a range of 4 mm for the electromagnetic proximeters and the LVDTs (Brough and Patrick, 1982; and Patrick et al., 1981).

A new device was developed to facilitate field calibration of borehole rod extensometers. Based on a concept developed by researchers at the Lawrence Berkeley National Laboratory for studies at the Stripa Mine in Sweden (DuBois et al.,

1981), our calibrator incorporates several improvements, including a motor drive, microprocessor control, and independent transducers that provide reference data for the calibrations. The calibrator both automates the calibration process and circumvents the need for lowering the head assembly onto step blocks. Automation is achieved through an HP85B microprocessor, interfaced to the central DAS, which actuates a stepping motor to drive a gear train and screw jacks to raise or lower the extensometer head assembly (Fig. 27). At appropriate displacements, the motor stops and voltage readings are obtained for the extensometer transducers and the three LVDTs on the microadjuster. Note that the three LVDTs, rather than step blocks, constitute the "standard" against which the extensometer transducers are calibrated. Hysteresis and stick-slip behavior are more readily studied with the system's truly bidirectional calibration capability.

Two types of error analyses were performed using the field calibration data. First, an end-point (terminal-point) analysis was used to determine the range of errors that occurred during the pre- and post-test calibrations. Second, pre- and post-test calibration results were examined to detect changes in transducer sensitivity that would introduce errors in displacement readings.

The end-point analysis is a convenient technique for examining the extreme errors that occurred over the range of the field calibration. Note that this calibration range corresponds to the range of actual displacements recorded in the field

Figure 27. Photograph of the microprocessor-controlled "microadjuster" calibration device.

rather than the full range of the transducer. While the laboratory calibrations measure only transducer errors, errors measured in the field calibrations propagate as a result of nonlinearities and hysteresis in the entire extensometer system. We distinguish between nonlinearity and hysteresis by defining the former as deviation from a straight line for either the ascending or descending portion of the calibration cycle. On the other hand, hysteresis is the offset in apparent displacement observed between the ascending and descending segments of the calibration. Table 18 summarizes the pertinent end-point error data for each transducer and extensometer type as well as for the entire set of instruments. While all transducers performed quite well in the calibrations, it is clear that the LVDTs exhibited less variability than the potentiometers during both the pre- and post-test calibrations. It is equally clear that the electromagnetic proximeters are more variable from unit to unit and also have a larger mean error. The distributions of the pre- and post-test calibration errors show a tight grouping near the zero point and are rather flat but symmetric beyond $\pm 5 \mu\text{m}$ (Fig. 28). Only subtle changes are evident between the pre- and post-test distributions of errors. About 74% of the pretest errors and 75% of the post-test errors fall within a $\pm 50 \mu\text{m}$ window.

As was the case for laboratory calibrations, it is not possible to determine changes in the offset constant because there is no way to establish a

zero value for the transducers. However, the errors in displacement readings generated by changes in transducer sensitivity can be determined. Once again, these errors are evaluated from changes in slope over a range of 5 mm. The measured changes in extensometer sensitivities and the errors associated with those changes are dramatic (Table 17, lower half). The distribution of field calibration errors arising from changes in transducer sensitivity is shown in Fig. 29. After removing six outliers, the mean errors caused by sensitivity changes are reduced to -110.9 , -76.1 , -94.1 , and $-305.1 \mu\text{m}$, respectively. The errors are observed to cluster about the first three of these means, giving the frequency histogram a bimodal shape with a central plateau (Fig. 29). This is different from the results obtained in the laboratory where the errors resulting from changes in sensitivity are normally distributed about a mean value near zero (Fig. 26).

It appears, then, that the errors associated with changes in extensometer sensitivity observed in the field calibrations are not solely the result of changes in transducer sensitivity. Nor are they the result of a difference in the errors generated during the pre- and post-test calibrations, since these error distributions are nearly identical (Fig. 28). We hypothesize two plausible sources of the observed changes in sensitivity. First, rust on the extensometer connecting rods may have prevented them from moving freely through the collar stabilizer tube and head assembly during the

Table 18. Summary of pre- and post-test *in situ* calibration errors for borehole rod extensometers.

Transducer	Calibration	Number ^a	Magnitude of error (μm) ^b		
			Mean	Std dev	Range
MBI-series potentiometers	Pretest	120	9.5	60.6	-173.1 to $+234.0$
	Post-test	116	-5.6	55.3	-261.0 to $+186.4$
GxE-series potentiometers	Pretest	180	1.4	51.8	-212.4 to $+170.2$
	Post-test	58	-8.6	36.3	-136.0 to $+97.3$
GxE-series LVDTs	Pretest	24	1.2	17.3	-31.2 to $+32.1$
	Post-test	22	-3.6	7.6	-18.3 to $+6.8$
GxE-series proximeters	Pretest	24	31.2	51.4	-65.6 to $+130.2$
	Post-test	20	176.9	309.0	-226.6 to $+1072.8$
All instruments	Pretest	348	6.2	53.9	-212.4 to $+234.0$
	Post-test	216	10.7	115.2	-226.6 to $+1072.8$

^a The "number" is twice the actual number of transducers because a two-sided error band is used.

^b Errors result from the characteristics of the transducer and extensometer as a system. Data represent extreme errors calculated from an end-point error analysis.

Figure 28. Distribution of errors measured in pre- and post-test field calibrations of borehole extensometer transducers. Data represent extreme errors calculated from an endpoint error analysis.

Figure 29. Distribution of errors measured in field calibrations of GxE- and MBI-series borehole extensometers. Errors result from changes in transducer sensitivity between pre- and post-test calibrations.

post-test calibration. The net result would be a smaller transducer output for a given (apparent) displacement. The transducer would appear to decrease in sensitivity, as was observed (Table 17). The potential for this problem was recognized and all extensometers were exercised over the range of the calibration before any data were acquired. However, minor problems may still have occurred. Second, the differences in extensometer sensitivity may be an accurate reflection of the differences between the two calibration procedures. No explicit cause of such differences has been identified to date, however.

It is also important to realize that the two sources of errors discussed above are not completely independent of each other. Since the first represents errors propagated in a single calibration, it is a component of the second that measures average changes that occurred in the time

interval between the pre- and post-test calibrations. Therefore, the two errors should not be root-sum-square added. On the other hand, the former errors, which are based on all calibration positions, are not a strict subset of the latter, which are based only on the two endpoints.

Error Analysis

Three types of transducers, each with different operating characteristics, were deployed on borehole rod extensometers: potentiometers, LVDTs, and electromagnetic proximeters. Connecting rods were fabricated from Superinvar for near-field GxE-series units, or carbon steel for MBI-series units. These variations were present in four combinations. An error analysis for each type is presented below.

GxE-series with Potentiometers

Seven sources of error were identified for the rod extensometers where rectilinear potentiometers were used: the calibration coefficient, excitation and signal voltages, the coefficient of thermal expansion, rod length, and initial and current rod temperatures. The calibration coefficient is determined to be

$$K = \frac{E}{S} \cdot D^* \quad (33)$$

where

D^* is the displacement recorded at calibration, m,

E is the excitation, V,

S is the recorded signal, V.

Sensitivity factors are calculated by differentiating Eq. (33), such that

$$\Theta_E = \frac{dK}{dE} = \frac{D^*}{S} \quad (34)$$

for errors in excitation voltage;

$$\Theta_S = \frac{dK}{dS} = -\frac{D^*E}{S^2} \quad (35)$$

for errors in signal voltage;

$$\Theta_D = \frac{dK}{dD} = \frac{E}{S} \quad (36)$$

for errors in displacement. Maximum individual errors over an operational range of 5 mm are (a) signal, 7.48×10^{-5} V, (b) excitation, 5.3×10^{-4} V, and (c) displacement, 2.54×10^{-6} m. The maximum RSS uncertainty in the value of K is calculated to be 1.28×10^{-5} V·m/V.

In field use, displacements are calculated using the equation

$$D = K \cdot \frac{S}{E} + \alpha L (T - T_0) \quad (37)$$

where

L = the rod length, m;

α = the coefficient of thermal expansion, m/m·°C. In this case, $\alpha = aT + b$ (Patrick et al., 1983), where $a = 0.33 \times 10^{-8}/^\circ\text{C}^2$, and $b = -54.95 \times 10^{-8}/^\circ\text{C}$

$T - T_0$ = the change in temperature since installation, °C.

Differentiating Eq. (37) we obtain the following seven sensitivity factors:

$$\Theta_K = \frac{dD}{dK} = \frac{S}{E} \quad (38)$$

for errors in calibration coefficient;

$$\Theta_E = \frac{dD}{dE} = \frac{-KS}{E^2} \quad (39)$$

for errors in excitation voltages;

$$\Theta_S = \frac{dD}{dS} = \frac{K}{E} \quad (40)$$

for errors in signal voltages;

$$\Theta_\alpha = \frac{dD}{d\alpha} = L(T - T_0) \quad (41)$$

for errors in coefficient of thermal expansion;

$$\Theta_L = \frac{dD}{dL} = \alpha(T - T_0) \quad (42)$$

for errors in rod length;

$$\Theta_T = \frac{dD}{dT} = (2aT + b - \alpha T_0)L \quad (43)$$

for errors in current rod temperature;

$$\Theta_{T_0} = \frac{dD}{dT_0} = -(aT + b)L \quad (44)$$

for errors in initial rod temperature.

GxE-series with LVDTs

Seven error sources were also identified for these units. Because a dc-to-dc converter that is insensitive to input voltage was used on the LVDTs, excitation was not a source of error in normal operation, as it was with potentiometers. However, the LVDTs had a temperature sensitivity that introduced errors of not more than 4.8×10^{-6} m/°C. The LVDT calibration coefficient is determined to be

$$K = \frac{D^*}{S} \quad (45)$$

Sensitivity factors are calculated by differentiating Eq. (45).

$$\Theta_s = \frac{dK}{dS} = \frac{-D^*}{S^2}, \quad (46)$$

for errors in signal voltage;

$$\Theta_D = \frac{dK}{dD} = \frac{1}{S}, \quad (47)$$

for errors in displacement. Maximum individual errors over an operational range of ± 2.5 mm are (a) signal, 2×10^{-4} V, and (b) displacement, 2.54×10^{-6} m. The maximum RSS uncertainty in the value of K is calculated to be 6.36×10^{-7} m/V.

In field use, displacements are calculated using the equation

$$D = KS + \alpha L (T - T_0). \quad (48)$$

Differentiating Eq. (48), we obtain

$$\Theta_S = \frac{dD}{dS} = K, \quad (49)$$

for errors in signal voltage;

$$\Theta_K = \frac{dD}{dK} = S, \quad (50)$$

for errors in calibration coefficient. Note that $\Theta_E = 0$ for LVDTs, and all other Θ values are as expressed in Eqs. (41) through (44) above.

GxE-series with Proximometers

The error sources for electromagnetic proximometers are the same as for LVDTs. The temperature sensitivity of these units introduces errors of not more than 2.4×10^{-6} m/ $^{\circ}$ C. Maximum individual errors during calibration over a ± 2.5 -mm range are (a) signal, 1.55×10^{-4} V and (b) displacement, 2.54×10^{-6} m. The maximum RSS uncertainty in the value of K is calculated to be 1.02×10^{-6} m/V.

In field use, displacements are calculated using an equation of the form of Eq. (48). Sensitivity factors are as indicated by Eqs. (41) through (44), (49) and (50).

MBI-series with Potentiometers

Calibration errors associated with MBI-series units are the same in form and magnitude as for GxE-series extensometers.

In field use, displacements are calculated using an equation of the form of Eq. (37). Thus, the sensitivity factors Θ_K , Θ_E , Θ_S , Θ_α , and Θ_{T_0} can be applied as given in Eqs. (38) through (42). Because

α is essentially constant over the range of temperatures of interest here (18 to 35 $^{\circ}$ C), Θ_T and Θ_{T_0} take on a simpler form:

$$\Theta_T = \frac{dD}{dT} = \alpha L, \quad (51)$$

for errors in current rod temperature;

$$\Theta_{T_0} = \frac{dD}{dT_0} = -\alpha L, \quad (52)$$

for errors in initial rod temperature.

Calculation of Errors

The unit values for the various sources of error are tabulated in Table 19. These values are used in conjunction with the sensitivity factors derived above to calculate the errors in displacement readings.

Table 20 displays maximum calculated errors for each of the four combinations of transducers and rod materials, and for three typical rod lengths for each of these four combinations. The effects of time-varying temperatures directly and indirectly introduce the most significant errors. Our relatively poor knowledge of and the high variability in the coefficient of thermal expansion of the rod materials introduces errors for all four combinations. Where carbon steel rods were used, significant errors are also generated as a result of the scheme used to approximate rod temperatures. In addition, the thermal sensitivity of LVDTs and proximometers is a major contributor to the total error. Note that the "calibration coefficient" errors shown in this table do not include the errors associated with changes in transducer sensitivity recorded during field calibrations (see the "Calibrations" section) but, rather, are the values calculated from Eq. (38) or (50).

Reliability

Three classes of problems were identified with the borehole rod extensometers: (1) transducers on the GxE series units deployed in the canister storage drift failed during use; (2) the GxE Superinvar connecting rods experienced stress-corrosion fracturing; (3) the stability of some of the MBI-series extensometer anchors was determined to be inadequate or marginally adequate. These units were inflated with the burst-line technique. In addition, a variety of minor miscellaneous problems occurred during the test period. These problems are summarized below.

Table 19. Unit errors from various sources for borehole rod extensometers.

Extensometer type	Cal. coeff.	Error source and magnitude					Length ($\times 10^{-3}$ m)
		Excit. ($\times 10^{-4}$ V)	Signal ($\times 10^{-5}$ V)	Initial temp ^a (°C·m)	Current temp ^a (°C·m)	Coeff. exp. ^{b,c} ($\times 10^{-7}/^{\circ}\text{C}$)	
GxE Bourns	1.28×10^{-5} V·m/V	5.30	7.43	3.0	3.0	3.0	3.05
GxE Vernitec	1.28×10^{-5} V·m/V	5.30	7.43	3.0	3.0	3.0	3.05
GxE LVDT	6.36×10^{-7} m/V	—	20.0	3.0	3.0	3.0	3.05
GxE Prox.	1.02×10^{-6} m/V	—	15.5	3.0	3.0	3.0	3.05
GxE original Bourns	1.28×10^{-5} V·m/V	5.30	7.43	3.0	3.0	3.0	3.05
MBI Bourns	1.28×10^{-5} V·m/V	5.30	7.43	3.0	3.0	5.85	3.05

^a $3.0^{\circ}\text{C}\cdot\text{m}$ is maximum error introduced by trapezoidal approximation of the temperature distribution. Total temperature error is the RSS of $[3.0/(\text{rod length})]$ and 0.17°C , the error in thermocouple readings.

^b a for GxE = $aT + b$, where $a = 0.33 \times 10^{-8}/^{\circ}\text{C}^2$ and $b = -54.95 \times 10^{-5}/^{\circ}\text{C}$; error obtained from LLNL measurements (Patrick et al., 1983).

^c a for MBI = $11.7 \times 10^{-6}/^{\circ}\text{C}$; error assumed as $\pm 5\%$ ($5.85 \times 10^{-7}/^{\circ}\text{C}$).

Table 20. Calculated maximum errors for borehole rod extensometers.

Extensometer series, transducer type, and rod length (m)	Error source and magnitude (μm)						
	Calib. coeff.	Excit. and signal	Component temp.	Coeff. of expansion	Temp. coeff. of transducer	Component length	RSS
GxE, potentiometer,	2	1.3	0.02	1.9	13.2	0	13.4
	5	1.3	0.02	1.9	33.0	0	33.1
	13.5	1.3	0.02	1.9	89.1	0	89.1
GxE, LVDT,	2	2.5	0.01	1.9	13.2	106	107.3
	5	2.5	0.01	1.9	33.0	106	111.5
	13.5	2.5	0.01	1.9	89.1	106	138.8
GxE, proximeter,	2	2.6	0.02	1.9	13.2	53	54.7
	5	2.6	0.02	1.9	33.0	53	62.5
	13.5	2.6	0.02	1.9	89.1	53	103.7
MBI, potentiometer,	1	1.3	0.02	24.8	9.9	0	26.8
	5	1.3	0.02	24.8	49.7	0	55.6
	15	1.3	0.02	24.8	149.2	0	151.3

Transducer Failures

Several episodes of failures of GxE-series transducers took place. Each is discussed in chronological order.

Initial deployment. This series of transducers is designated by instrument license plates of the form GxE-0yz where "x" is A, B, C, or D (as described previously), the leading "0" of the numeric code indicates the original set of transducers, "y" is the borehole number (1 through 6), and "z" is the anchor number (1 through 4).

The onset of failures was observed when computer-recorded readings of relative displacement

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

Early in September 1980, routine monitoring showed other units (GCE014, GBE013, GCE033, and GCE063) responding in similar fashion. Apparent displacements became large enough (over 5 mm) to cause concern, and a field inspection of these units took place. Although the data acquisition system was recording voltages that indicated displacements of several millimetres, this inspection revealed that the potentiometer shaft had not moved relative to the potentiometer body. Thus, these voltage measurements at the instrument head revealed that the problem was located there and not in the DAS hardware or software. A further set of voltage and confirming resistance measurements indicated that the resistance of the potentiometers was changing in a nonlinear manner with time.

A series of field and laboratory tests undertaken at that point indicated the possibility of chemical vapor action on the potentiometer resistive element. Details of these evaluations were reported by Patrick et al. (1981). Based on this assessment, the head assembly covers were removed to vent such vapors.

The principal means of detecting malfunctions of the linear potentiometers were checks for changes in total resistance and erratic output voltage readings as a function of time. Total resistance was outside the manufacturer's specification of $5\text{ k}\Omega \pm 10\%$ for 23 of the 56 transducers (Patrick et al., 1981). Inspection of the recorded data provides additional information. Figure 30 displays typical output voltages as a function of time for two transducers located within the same head assembly. Several features of these plots are worth noting. First, the output voltage of GCE051 shows a definite break in trend at 2.8 YOC, followed by a period of erratic behavior between 2.9 and 3.0 YOC (0.5 to 0.6 years into the test). This behavior is distinctly absent for GCE052, which is located in the same head assembly. Second, the erratic behavior is confirmed by measurements of total resistance. At 3.0 YOC, unit GCE051 was out of specification with respect to total resistance but GCE052 was not. Third, beginning at about 3.0 YOC, there is a definite recovery in GCE051 and a slight upturn in the GCE052 output voltage. This change is associated with removing the O-ring-sealed head assembly cover. Fourth, these displacements (up to the break in trend) agree in form and magnitude with anticipated values.

The break in trend exhibited by GCE051 is not but ubiquitous, for the GxE0yz transducers. This indicates that transducer failure is an "event" rather than a "process." If we could

Figure 30. Voltage signatures for two typical Bourns linear potentiometers. (a) Unit GCE051 displays both an erratic output voltage and total resistance out of specification. (b) Unit GCE052 displays a smooth output signal and is still within specification with respect to total resistance.

establish that the break in trend could be used as a failure indicator, we would be confident in accepting data collected before the break. This is particularly tempting because the data agree in form and magnitude with our expectations. However, there is no known mechanism to support the hypothesis that failure is an "event" rather than a "process." Therefore, we have used the break in trend or erratic signal as indicators of the latest date at which acceptable data may have been acquired, and conditionally accepted data up to that time. Table 21 displays the pertinent time periods for all GxE0yz units. The mean and standard deviation of time to failure using this criterion are 223 and 259 days, respectively.

We considered seven failure hypotheses in evaluating these failures (Patrick et al., 1981):

1. The failed units were from a bad batch.
2. The cause of failure was introduced in the calibration laboratory.

3. Electrical damage was caused by over-powering the units.

4. Dithering produced excessive wear to the resistive element.

5. Shock-loading by explosives damaged the units.

6. Higher downhole temperatures caused the sealing agents to cure, producing chemical vapors that damaged the resistive elements.

7. Hygroscopy of the resistive element produced the observed changes in resistance.

The evaluation of the observed failures included field resistance measurements, gas sampling, hygroscopy studies at low pressure and elevated temperature, microscopic textural inspections, and chemical interaction tests. These evaluations are documented in Patrick et al. (1981). Although these investigations led us to eliminate several possible causes of failure, we have not found a totally satisfactory answer to the problem to date. Hypothesis 6 remains the most plausible. As noted above, venting the potentiometers by removing the head assembly cover appeared to curtail and possibly reverse the observed degradation.

Replacement Bourns Potentiometers. Following the laboratory and field evaluations noted

above, replacement Bourns potentiometers were procured and calibrated at the EG&G-Atlas facility. About two weeks later, before fielding, a sample of the replacement units was checked for total resistance and found to be out of specification. In all, 21 of the 64 replacement units (33%) failed. Testing showed that these transducers remained linear, contrary to the nonlinear mode of failure observed in the units deployed in the field. Since none of these transducers were fielded, their failures resulted in no direct loss of data.

Deployment for transducer evaluation.

We decided to revise our original decision to install only "off-the-shelf" instrumentation (Brough and Patrick, 1982) to correct the problem of the failed potentiometers. A period of instrument evaluation was planned for the remaining life of the SFT-C. We based our changed philosophy on three facts. First, since the cause of the potentiometer failures had not been definitively established, it seemed prudent to install several transducer types to minimize further loss of data if the failure mode was peculiar to one transducer type. Second, installation of several types would allow us to evaluate the relative performance of the selected transducers. Third, judicious choice of alternative transducers would not degrade the quality

Table 21. Failure dates for Bourns linear potentiometers deployed on borehole extensometers in the spent-fuel canister storage drift.

License plate	Failure date (YOC)	License plate	Failure date (YOC)	License plate	Failure date (YOC)
GAE011	4.38	GBE051	2.68	GCE041	— ^a
012	4.38	052	2.72	042	— ^a
013	4.38	053	3.24	043	— ^a
014	4.38	054	2.69	044	2.76
GBE011	— ^a	GBE061	2.60	GCE051	2.82
012	— ^a	062	3.21	052	2.79
013	2.75	063	— ^a	053	2.79
014	2.82	064	2.98	054	— ^a
GBE021	2.64	GCE011	2.92	GCE061	— ^a
022	2.70	012	2.89	062	— ^a
023	2.62	013	2.67	063	2.77
024	2.76	014	2.65	064	2.60
GBE031	2.60	GCE021	— ^a	GDE011	5.68
032	2.65	022	2.73	012	4.85
033	2.78	023	2.70	013	— ^a
034	2.65	024	2.77	014	— ^a
GBE041	2.63	GCE031	2.66	—	—
042	2.71	032	2.73	—	—
043	— ^a	033	2.69	—	—
044	2.66	034	2.77	—	—

^a Not observed before removal at 3.84 YOC.

of acquired data and might even improve the quality.

These three considerations led us to select four transducers to replace the 48 GBE- and GCE-series units, where all failures had occurred to date. The leading digit of the numeric code was changed to "2" to denote the second series of transducers. Each group of three extensometers received one type of transducer. Schaevitz Model 250HCD linear variable differential transformers (LVDTs) were installed in GBE21x, GBE22x, and GBE23x; Bourns Model 5184 rectilinear potentiometers were reinstalled in GBE24x, GBE25x, and GBE26x; Kaman Model KD-2310-6U electromagnetic proximeters were installed in GCE21x, GCE22x, and GCE23x; and Vernitron Model 113 rectilinear potentiometers were installed in GCE24x, GCE25x, and GCE26x. The characteristics of the selected transducers are summarized by Patrick et al. (1981). Although each of the three alternates compares favorably in several ways with the original Bourns potentiometers, both the LVDTs and proximeters are temperature-sensitive, as discussed previously in "Error Analysis."

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

Another modification was to subject each of the head assemblies associated with the Bourns, Vernitron, Schaevitz, and Kaman transducers to three different environments. To produce the three test environments, the head assemblies were either (1) sealed with an O-ring on the cover of the head assembly; (2) sealed and flushed with

dry nitrogen; or (3) sealed and ventilated of potentially harmful vapors using a small vacuum.

As an added precaution, all Vishay precision bridge completion resistors associated with linear potentiometers were replaced with hermetically sealed units. This change was implemented in response to two observed resistor failures (Patrick et al., 1981).

Before installation, all transducers were laboratory-calibrated, and all refurbished rod extensometers were calibrated *in situ* in accordance with the established procedures described above in "Calibration." Because of the shorter range of the Kaman and Schaevitz transducers, these units were calibrated in 0.5-mm steps over a range of 4.0 mm rather than in 1.0-mm steps over a range of 5.0 mm.

A few months after the second deployment, the Vernitron linear potentiometers began to fail. Two failure modes were exhibited. Whereas most units showed a slight rise in signal as a function of time followed by a precipitous fall (Fig. 31), the

Figure 31. Failure signature of Vernitron linear potentiometers.

Table 22. Failure dates for Vernitron linear potentiometers deployed on borehole extensometers in the spent-fuel canister storage drift.

License plate	Installation (YOC)	Failure (YOC)
GCE241	3.95	4.46
242	3.95	4.46
243	3.95	4.46
244	3.95	4.47
GCE251	3.95	4.95
252	3.95	5.01
253	3.95	4.97
254	3.95	5.08
GCE261	3.95	4.12
262	3.95	4.02
263	3.95	4.14
264	3.95	4.13

others showed an abrupt rise, typically to full scale positive voltage, followed by a precipitous fall to a voltage of -2 to -4 V. For the latter cases, the signal was generally erratic. Table 22 displays the interval during which data from these transducers are conditionally acceptable. The mean and standard deviations of time to failure are 210 and 141 days, respectively. As with the original failures, we cannot be certain that data are reliable before the break in trend, which was used as the failure criterion.

Failure analysis for these units was more limited than for the first sequence of failures. Optical and electron microscopy revealed that the resistive elements were severely fractured. In general, these fractures were transverse to the length of the resistive element and appeared to originate on the outer edge of the element and propagate inward. Fracturing was most intense opposite the shaft end of the potentiometer and decreased to none near the center (wiper) location.

Following failure of the Vernitron potentiometers, they were replaced with Bourne potentiometers. The leading digit of the numeric code was changed to 4 to denote this series of transducers.

Rod and Anchorage Integrity Tests

Both the MBI- and GxE-series borehole extensometers used hydraulic bladder anchors that consist of sections of flattened copper tube that have been welded along the ends and formed around a cylindrical mandrel. To ensure that the anchors were properly fabricated, leak tests were performed before installation. A connecting rod is attached to the mandrel to provide a reference for displacement measurements. In the case of the MBI units, the anchors had an integral check

valve that was used in conjunction with a hydraulic burst-line to inflate the anchors and, presumably, maintain anchor pressure following the bursting of the inflation line. These units were not grouted in place. The initial inflation pressure was provided to the GxE anchors through high-pressure Bundiwell tubing, and the pressure was maintained with a nitrogen-over-hydraulic system (Brough and Patrick, 1982). As previously noted, these units were full-column-grouted.

Anchor pressures. Schrauf and Board (1979) reported problems associated with inflating the MBI anchors. The MBI-105 and -106 anchors could not be installed to the planned depth because of "... pinching (jamming) of the hydraulic lines. ..." In addition, they report that the hydraulic lines burst prematurely for the MBI11z, MBI12z, and MBI13z units (a total of 15 anchors). The hydraulic lines typically burst at ~1000 psi (6.9 MPa), but the line associated with MBI136 burst at ~500 psi (3.4 MPa). The effect of inadequate inflation pressures is discussed below.

As noted above, the near-field (GxE-series) rod extensometers used a nitrogen-over-hydraulic fluid system in an effort to maintain stable anchor pressure. At approximately 1-month intervals, the pressure of each anchor was checked for conformance to a 1750- ± 50-psi (12.1- ± 0.3-MPa) criterion. Nitrogen was added or vented to adjust the observed pressure to the acceptable range. Both pressure decreases and increases were observed. Pressure decreases may be due to system leaks, continued deformation of the anchor in the borehole, or differential expansion of the borehole relative to the anchor. Pressure increases are generally thought to be due to thermal expansion of the hydraulic fluid and differential contraction of the borehole relative to the anchor.

Although all GxE unit anchors were successfully inflated to the 1750-psi (12.1-MPa) anchoring pressure, 27 of the 56 (48%) exhibited pressure losses as the test progressed. Table 23 documents the first occurrence of these leakages and the typical pressure recorded at the time of pressure adjustment (monthly). These represent irreparable leaks that occurred in the downhole components of the extensometer. Nearly 80% of the leaks occurred during the first year of the test when significant heating of the rock mass was in progress (Fig. 32). As discussed below, there is no evidence that these pressure losses adversely effected data quality. This is attributed to the fact that all anchors were subjected to proper inflation pressures for a minimum of two months before leaks occurred.

Table 23. Loss-of-pressure record for GxE-series borehole rod extensometer anchors that used a nitrogen-over-hydraulic inflation and pressure-maintenance system.

Instrument license	First occurrence of leakage ^a	Typical pressure [psi (MPa)]
GAE011	7/80	0 (0)
012	10/80	200 (1.4)
013	7/80	0 (0)
014	7/80	500 (3.4)
GBE013	12/81	0 (0)
021	10/80	1425 (9.8)
023	4/80	0 (0)
031	6/80	700 (4.8)
034	10/80	1100 (7.6)
044	12/81	1200 (8.3)
053	2/81	650 (4.5)
054	12/80	1050 (7.2)
061	6/80	200 (1.4)
GCE012	4/80	250 (1.7)
013	4/80	0 (0)
021	10/80	1610 (11.1)
022	7/80	550 (3.8)
023	10/80	1100 (7.6)
032	12/82	1600 (11.0)
033	6/80	0 (0)
034	10/80	0 (0)
052	3/82	1250 (8.6)
054	2/82	950 (6.6)
061	6/80	200 (1.4)
063	6/80	1050 (7.2)
064	4/83	0 (0)
GDE014	6/80	475 (3.3)

^a First leakage below 1650 psi (11.4 MPa). Date is month and year of pressure check when leakage was observed.

In situ tests of anchor integrity. A positive-displacement hydraulic system was designed, fabricated, and deployed to pull-test each individual rod of the MBI- and GxE-series extensometers after the post-test calibrations were completed (Fig. 33). These pull-test results were used to confirm that the anchors were stable during the SFT—C. To provide an average displacement value at each load increment, three linear potentiometers were positioned at 120-degree azimuthal orientations at a common radial distance from the rod axis. The reference for the potentiometers was attached directly to the individual rod, so slip of the coupling, which was being pulled by the hydraulic ram, would not be measured. Load was measured by a calibrated load

cell located between the hollow hydraulic ram and the reaction plate of the test fixture. Each rod and anchor assembly was subjected to four cycles of loading and unloading. The test plan required a minimum load of 300 lb (1.3 kN) [~ 6100 psi (42.1 MPa) rod stress], but most tests on GxE-series extensometers were conducted to 900 lb (4.0 kN) to examine anchor and rod integrity at higher loads.

Anchor slip was interpreted by comparing the measured stiffness of the system K_a with the calculated rod stiffness K . Because of uncertainties in material properties, we established a criterion that K_a be within 10% of K . The value of K_a was obtained graphically as the slope of the load vs displacement plot at the nominal rod tension of 100 lb (0.4 kN) for the first loading of the rod and anchor system. The value of K was calculated as $K = EA/L$, where E is the Young's modulus of the rod, A is the rod cross-sectional area, and L is the rod length. Nominal values of E and A and measured values of L were used in these calculations.

Table 24 shows the values of K_a and K as well as the ratio K_a/K for the MBI-series extensometers. The ratio of K_a/K is near unity for most anchors, and load-vs-displacement curves are linear (Fig. 34), indicating that the anchors are stable under the nominal force exerted on the rods during the active phases of testing at the SFT—C. Furthermore, the load at which the anchors slipped (as noted by a change in slope of the load-vs-displacement curve) is typically several times the nominal force. Only units MBI-103, -105, -113, -135, and -136 exhibited nonlinear behavior at loads less than 100 lb (0.4 kN). An example is provided in Fig. 35. Even these displayed linear behavior (but low stiffness) near 100 lb (0.4 kN). In addition, units MBI-022, -036, -131, and -132 showed anchor slip at loads less than 200 lb (0.9 kN), twice the nominal load. We judge that these nine anchors were stable during the heated phase of the SFT—C, but may have slipped during the excavation phase (Mine-by) when they were subjected to high explosive shocks.

Similar data for the GxE-series extensometers are shown in Table 25. Most ratios of K_a/K are near unity, and the load-vs-displacement curves are linear (Fig. 36). Note that the longest rod of each set exhibited nonlinear behavior in most cases (Fig. 37). In general, the nonlinear behavior resulted in a lower value of K_a . We believe that nonlinear behavior at low loads is caused by the rods being straightened from their relaxed position. In the relaxed position, the 13.2-m-long rods, which are oriented vertically downward, flex

Figure 32. History of pressure loss for GxE-series rod extensometers that had pressure maintenance systems.

Figure 33. Photograph of the borehole extensometer rod- and anchorage-integrity tester.

Table 24. Comparison of measured and calculated rod stiffness of the MBI-series extensometers as a measure of anchor stability.

Instrument license	K_s [10 ³ lb/in (MN/m)] ^a	K [10 ³ lb/in (MN/m)] ^b	K_s/K	Comments ^c [lb (kN)]
MBI 011	20.99 (3.68)	20.72 (3.63)	1.01	—
012	8.49 (1.49)	9.08 (1.59)	0.94	560 (2.5)
013	6.67 (1.17)	6.36 (1.11)	1.05	520 (2.3)
MBI 021	19.93 (3.49)	19.98 (3.50)	1.00	—
022	9.50 (1.66)	9.26 (1.62)	1.03	160 (0.7)
023	6.28 (1.10)	5.95 (1.04)	1.06	720 (3.2)
024	4.74 (0.83)	4.46 (0.78)	1.06	750 (3.3)
025	4.09 (0.72)	3.96 (0.69)	1.03	580 (2.6)
026	3.62 (0.63)	3.42 (0.60)	1.06	570 (2.5)
MBI 031	18.33 (3.21)	18.29 (3.20)	1.00	—
032	7.33 (1.28)	7.34 (1.29)	1.00	—
033	4.73 (0.83)	4.59 (0.80)	1.03	740 (3.3)
034	3.87 (0.68)	3.59 (0.63)	1.08	920 (4.1)
035	3.12 (0.55)	2.96 (0.52)	1.05	690 (3.1)
036	2.59 (0.45)	2.56 (0.45)	1.01	190 (0.8)
MBI 041	20.83 (3.65)	20.28 (3.55)	1.03	—
042	8.87 (1.55)	9.85 (1.72)	0.90	770 (3.4)
043	6.89 (1.21)	6.76 (1.18)	1.02	—
MBI 051	20.68 (3.62)	20.88 (3.66)	0.99	—
052	10.13 (1.77)	9.72 (1.70)	1.04	—
053	6.64 (1.16)	6.45 (1.13)	1.03	400 (1.8)
054	5.21 (0.91)	5.10 (0.89)	1.02	390 (1.7)
055	4.30 (0.75)	4.13 (0.72)	1.04	510 (2.3)
056	3.51 (0.61)	3.49 (0.61)	1.01	290 (1.3)
MBI 061	21.83 (3.82)	19.57 (3.43)	1.12	—
062	7.39 (1.29)	6.58 (1.15)	1.12	630 (2.8)
063	4.69 (0.82)	4.61 (0.81)	1.02	260 (1.2)
064	3.68 (0.64)	3.48 (0.61)	1.06	490 (2.2)
065	2.99 (0.52)	2.95 (0.52)	1.01	610 (2.7)
066	2.56 (0.45)	2.54 (0.44)	1.01	550 (2.4)
MBI 081	16.27 (2.85)	15.72 (2.75)	1.03	—
082	8.65 (1.51)	9.02 (1.58)	0.96	—
083	6.67 (1.17)	6.46 (1.13)	1.03	610 (2.7)
MBI 091	20.68 (3.62)	19.30 (3.38)	1.07	—
092	9.65 (1.69)	9.75 (1.71)	0.99	390 (1.7)
093	6.77 (1.19)	6.69 (1.17)	1.01	550 (2.4)
094	5.19 (0.91)	4.98 (0.87)	1.04	270 (1.2)
095	4.24 (0.74)	4.01 (0.70)	1.06	590 (2.6)
096	3.80 (0.67)	3.49 (0.61)	1.09	660 (2.9)

Table 24. (Continued)

Instrument license	K_a [10 ³ lb/in (MN/m)] ^a	K [10 ³ lb/in (MN/m)] ^b	K_a/K	Comments ^c [lb (kN)]
MBI 101	19.64 (3.44)	19.03 (3.33)	1.03	—
102	8.30 (1.45)	7.73 (1.35)	1.07	—
103	0.81 (0.14)	4.56 (0.80)	0.18	20, 120 (0.09, 0.5)
104	3.87 (0.68)	3.65 (0.64)	1.06	—
105	0.71 (0.12)	2.97 (0.52)	0.24	10, 190 (0.04, 0.8)
106	2.71 (0.47)	2.60 (0.46)	1.04	320 (1.4)
MBI 111	17.86 (3.13)	16.75 (2.93)	1.07	—
112	9.24 (1.62)	9.17 (1.61)	1.01	—
113	6.96 (1.22)	6.86 (1.20)	1.01	35, 190 (0.2, 0.8)
MBI 121	19.71 (3.45)	19.70 (3.45)	1.00	—
122	8.13 (1.42)	8.69 (1.52)	0.94	570 (2.5)
123	6.16 (1.08)	6.32 (1.11)	0.97	230 (1.0)
124	5.24 (0.92)	4.97 (0.87)	1.05	520 (2.3)
125	4.17 (0.73)	4.13 (0.72)	1.01	400 (1.8)
126	3.38 (0.59)	3.70 (0.65)	0.91	300 (1.3)
MBI 131	12.93 (2.26)	19.84 (3.47)	0.65	150 (0.7)
132	7.20 (1.26)	7.50 (1.31)	0.96	130 (0.6)
133	3.99 (0.70)	4.57 (0.80)	0.87	390 (1.7)
134	3.74 (0.65)	3.71 (0.65)	1.01	290 (1.3)
135	2.76 (0.48)	3.00 (0.53)	0.92	100, 210 (0.4, 0.9)
136	2.99 (0.52)	2.66 (0.47)	1.12	50, 450 (0.2, 2.0)

^a Stiffness of the extensometer system at the nominal rod tension of 100 lb (0.4 kN). Determined as the slope of the load-vs-displacement curve.

^b Calculated stiffness of the extensometer system, $K = EA/L$. Where $E = 28.5 \times 10^6$ psi (197 GPa), rod 0.25 in. (6.35 mm) in diameter, length varies.

^c Rod load at which an anchor slipped was noted by a change in slope of the load-vs-displacement curve. Where two loads are given, they delineate the linear portion of the curve.

(buckle) elastically under their own weight of about 3.5 kg. In addition, during assembly of the extensometers, the rods were noted to have a permanent curvature that was introduced in manufacturing and shipping the rods. This curvature was straightened as the load on the rods increased, producing a linear curve at higher loads (Fig. 37). Since the nominal 100-lb rod tension was essentially constant with time, this behavior does not adversely affect data quality.

As previously discussed, we were unable to maintain anchor pressure on 27 of the GxE-series extensometers (Table 23). Of those, only GAE011, GBE044, and GDE014 have K_a/K ratios which are less than 0.90, that is they have a measured stiffness at least 10% less than the calculated stiffness. Furthermore, GCE041, GCE043, and GDE013 have K_a/K ratios less than 0.90, yet anchor pressures were maintained throughout the

test. Neither the nonlinearities in the load-vs-displacement curves nor the occurrence of K_a/K less than unity are believed to have adversely affected the test data.

In situ test of rod integrity. The Superinvar connecting rods of the GxE-series borehole extensometers began failing about three years into the test, shortly before the heated phase of the test concluded. Seven rods failed in service as noted in Table 26. The rod and anchorage integrity tester was used to determine which rods were approaching failure by subjecting them to load. Three additional rods failed during testing, bringing the total to 10 of the 56 (18%) Superinvar rods deployed on the test. The failure loads indicate that the rod cross sections at failure were about 15% of the nominal value.

Rod failure analysis. Metallographic sections of the rod failure surfaces revealed classic

Figure 34. Typical example of linear load vs displacement response of an MBI-series extensometer.

Figure 35. Typical example of load vs displacement response of an MBI-series extensometer where anchor slip was encountered.

Table 25. Comparison of measured and calculated rod stiffness of the GxE-series extensometers as a measure of anchor stability.

Instrument license	K_a [10 ³ lb/in (MN/m)] ^a	K [10 ³ lb/in (MN/m)] ^b	K_a/K	Comments
GAE 011	10.46 (1.83)	11.88 (2.08)	0.88	
012	6.55 (1.15)	6.91 (1.21)	0.95	
013	4.74 (0.83)	4.84 (0.85)	0.98	
014	1.73 (0.30)	1.86 (0.33)	0.93	Nonlinear
GBE 011	12.41 (2.17)	12.13 (2.12)	1.02	
012	6.98 (1.22)	6.97 (1.22)	1.00	
013	4.85 (0.85)	4.85 (0.85)	1.00	
014	1.82 (0.32)	1.86 (0.33)	0.98	
GBE 021	11.84 (2.07)	11.93 (2.09)	0.99	
022	7.14 (1.25)	6.89 (1.21)	1.04	
023	4.30 (0.79)	4.83 (0.85)	0.93	
024	1.64 (0.29)	1.83 (0.32)	0.90	
GBE 031	12.10 (2.12)	12.07 (2.11)	1.00	
032	7.23 (1.27)	6.89 (1.21)	1.05	
033	4.87 (0.85)	4.83 (0.85)	1.01	
034	N/A	1.83 (0.32)	N/A	Rod broken
GBE 041	12.10 (2.12)	12.00 (2.10)	1.01	
042	6.72 (1.18)	6.89 (1.21)	0.98	
043	4.66 (0.82)	4.83 (0.85)	0.96	
044	1.39 (0.24)	1.91 (0.33)	0.73	Nonlinear
GBE 051	12.53 (2.19)	12.06 (2.11)	1.04	
052	7.06 (1.24)	6.95 (1.22)	1.02	
053	4.76 (0.83)	4.86 (0.85)	0.98	
054	1.78 (0.31)	1.88 (0.33)	0.95	Nonlinear
GBE 061	12.23 (2.14)	12.11 (2.12)	1.01	
062	6.81 (1.19)	6.94 (1.22)	0.98	Rod failed in testing
063	4.64 (0.81)	4.86 (0.85)	0.95	
064	1.79 (0.31)	1.86 (0.33)	0.96	Nonlinear
GCE 011	12.56 (2.20)	12.44 (2.18)	1.01	
012	7.13 (1.25)	7.05 (1.23)	1.01	
013	4.98 (0.87)	4.93 (0.86)	1.01	
014	1.81 (0.32)	1.83 (0.32)	0.99	Nonlinear
GCE 021	N/A	12.41 (2.17)	N/A	Rod broken
022	7.22 (1.26)	6.86 (1.20)	1.05	
023	N/A	4.83 (0.85)	N/A	Rod broken
024	1.80 (0.32)	1.82 (0.32)	0.99	Nonlinear
GCE 031	10.42 (1.82)	11.35 (1.99)	0.92	Nonlinear
032	7.00 (1.23)	6.92 (1.21)	1.01	
033	5.00 (0.88)	4.84 (0.85)	1.03	
034	1.71 (0.30)	1.82 (0.32)	0.94	Nonlinear

Table 25. (Continued)

Instrument license	K_s [10 ³ lb/in (MN/m)] ^a	K [10 ³ lb/in (MN/m)] ^b	K_s/K	Comments
GCE 041	9.36 (1.64)	12.02 (2.11)	0.78	Rod failed in testing
042	N/A	7.25 (1.27)	N/A	Rod broken
043	4.07 (0.71)	4.85 (0.85)	0.84	Nonlinear
044	1.74 (0.30)	1.82 (0.32)	0.96	Nonlinear
GCE 051	N/A	12.06 (2.11)	N/A	Rod broken
052	N/A	6.90 (1.21)	N/A	Rod broken
053	4.83 (0.85)	4.79 (0.84)	1.01	Nonlinear
054	1.85 (0.32)	1.82 (0.32)	1.02	Nonlinear
GCE 061	12.82 (2.25)	12.26 (2.15)	1.05	
062	N/A	6.96 (1.22)	N/A	Rod broken
063	4.46 (0.78)	4.88 (0.85)	0.91	Nonlinear
064	1.83 (0.32)	1.83 (0.32)	1.00	Nonlinear
GDE 011	12.50 (2.19)	12.20 (2.14)	1.02	
012	6.27 (1.10)	6.95 (1.22)	0.90	Nonlinear
013	3.44 (0.60)	4.87 (0.85)	0.71	Very nonlinear
014	1.12 (0.20)	1.80 (0.32)	0.62	Very nonlinear

^a Stiffness of the extensometer system at the nominal rod tension of 100 lb (0.4 kN). Determined as the slope of the load-vs-displacement curve.

^b Calculated stiffness of the extensometer system, $K = EA/L$. Where $E = 19.8 \times 10^6$ psi (136 GPa), rod = 0.25 in. (6.35 mm) in diameter, length varies.

Figure 36. Typical example of linear load displacement response of a GxE-series extensometer.

Figure 37. Typical example of nonlinear load displacement response. Nonlinearity is due to straightening a rod that had permanent curvature.

Table 26. Time of failure and failure load for Superinvar connecting rods that experienced stress-corrosion cracking.

License plate	Failure date (YOC)	Time to failure (days)	Failure load [lb (kN)]
GBE034	5.30	1130	100 (0.4) ^a
062	6.50	1570	520 (2.3) ^b
GCE021	5.90 ^c	1350 ^c	100 (0.4) ^a
023	5.03	1030	100 (0.4) ^a
041	6.50	1570	469 (2.1) ^b
042	5.42	1180	100 (0.4) ^a
051	4.94	1000	100 (0.4) ^a
052	5.90 ^c	1350 ^c	100 (0.4) ^a
062	4.36	790	100 (0.4) ^a
064	6.50	1570	470 (2.1) ^b

^a Nominal load due to spring tension. Failed in service.

^b Failed in testing above nominal spring tension.

^c Failed at nominal load after data acquisition was complete. Exact date of failure unknown.

stress-corrosion cracking to be the mechanism of failure. The presence of a small amount of calcium carbonate at the root of the corrosion cracks leads us to believe that the extensometer seals leaked at some point during the test. This allowed groundwater to contact the rods, and possibly caused galvanic coupling with the copper hydraulic anchors and zinc-plated hardware that was also present in the borehole.

To determine the conditions that contributed to the failures, we attempted to reproduce in the laboratory the type of failure observed in the field

instrumentation. We conducted two series of experiments using virgin Superinvar obtained from the same lot as was used in the field instrumentation. Although we evaluated a variety of couplings and specimen surface preparations, all specimens had in common exposure to Climax groundwater and a temperature of 50°C (Patrick et al., 1983).

Failures were observed in the first series of tests, where coupling to either copper or copper and carbon steel was present, but the observed fracture morphology indicated ductile fracture rather than stress corrosion cracking, as was observed in the field. The second test series was accelerated by adding 94 g/L $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$. Corrosion progressed rapidly and two failures occurred. The surface morphology of these specimens included both transgranular and intergranular fracture, and thus was similar to the fractures observed in the field. In addition, pitting of the rod surface was evident as a result of the chloride ion.

The classic corrosion cracking curve of Copson (1959)—Fig. 38—indicates that Superinvar (31.5% nickel content) is a poor choice of material to use where chloride ion is present, as is the case for typical granite groundwaters. There is obviously a trade-off between the excellent thermal expansion properties of the Superinvar and its relatively poor corrosion behavior.

Miscellaneous Problems

A variety of relatively minor problems arose and were corrected during the SFT—C. Since each of these adversely affected the data for several

days, they are enumerated here to assist analysts in interpreting the measurements.

Two of the 2.5-k Ω bridge completion resistors used in the potentiometer circuit (Brough and Patrick, 1982) failed. The precision resistors were replaced on September 16, 1980, for GCE03z, and October 14, 1980, for GBE03z. In addition, electrical shorts were observed at various times during the test. These resulted when the resistive element of the potentiometer became "dirty," typically with an oxidation film or a speck of metallic or other resistive debris. Such problems were corrected by cleaning and lubricating units GBE26x (February 5, 1982); GBE011 (July 1, 1982); GAE014 (December 8, 1982); and GBE263 (September 8, 1983).

Two MBI-series rectilinear potentiometers malfunctioned during the test. First, MBI081 became nonlinear while maintaining total resistance within specifications (5.4 k Ω). It was replaced and renamed MBI084 on October 28, 1980. Second, MBI063 displayed erratic output. After several attempts to correct the problem by cleaning and lubricating the potentiometer, it was removed from service for repair on November 10, 1982. Details concerning these and other problems are documented in SFT—C project records.

Figure 38. Relationship between breaking time and nickel content (after Copson, 1959).

Convergence Monitors

Convergence wire extensometers (CWEs) were designed and deployed to monitor relative displacements across the three drifts of the SFT—C facility. The design of the CWE units is such that they may be oriented to measure displacements across horizontal, vertical, or angled spans. One end of each CWE is a machined steel pin to which a length of 0.635-mm-diam stainless-steel connecting wire is permanently attached (Fig. 39). The pin is slipped into a mating machined block permanently affixed to the drift surface. The opposite, active end of each CWE consists of a linear potentiometer housed in a brass weight that is attached to the opposite end of the stainless-steel connecting wire with a second machined pin (Fig. 40). The potentiometer shaft, which is also dead-weight-loaded, rests on a machined plate that is part of the second reference point. The connecting wire passes over a threaded pulley, which allows the CWE to be used in a variety of orientations while maintaining the vertical attitude of the dead weight system. Sixteen pairs of horizontally and vertically oriented CWEs were deployed (Figs. 22 and 23).

Figure 39. Inactive end of convergence wire extensometer showing spherical mount for tape extensometer.

One of the important features of the CWE design is that it may be readily removed and replaced to allow free access in the storage drifts for such activities as emplacement and retrieval of the spent fuel. Removal and replacement without loss of reference point were accommodated by the machined attachment pin at the inactive end of the CWE on horizontally oriented units. On vertical units, stainless steel reference tabs at the active end of the CWE were also required so that the CWE could be removed from the floor. The reference tabs were simply 25-mm square stainless steel plate stock with a washer attached. Three such tabs were glued to the concrete floor or a steel plate at each instrument location. Three adjustable leveling "feet" on each vertical CWE unit were mated with these tabs (Fig. 40).

A second feature of the CWE is the development of a four-wire resistance-temperature measurement system. This feature, referred to as a convergence wire temperature (CWT) monitor, is discussed in detail in the "Temperature Sensors" section. The relatively large coefficient of thermal expansion and length of the stainless-steel connecting wire made this feature essential.

The third feature is provision for tape extensometer measurements between the CWE reference points (Figs. 39 and 40). Tape extensometer readings provided a straightforward measurement of relative displacements independent of the DAS. In addition to being available for analysis before CWE data reduction algorithms were in place, the tape extensometer data also provided a check on the CWE electronically acquired data.

Calibration

Pre- and post-test laboratory calibrations of the linear potentiometers were performed using the same procedure as described for laboratory calibration of rod extensometer transducers. These calibrations examined the transducers for possible changes in slope (sensitivity).

At the start of the SFT-C, there was considerable uncertainty with regard to expected displacements. Therefore, the data reduction algorithm and associated sensitivity values were based on the average slope over the entire 25.4-mm range of the transducer. We now know that actual displacements were less than 5 mm. The top two rows of Table 27 present errors caused by using the slope over the full 25.4-mm range of the potentiometers rather than the limited ± 2.54 -mm range. Both pre- and post-test errors are pre-

sented. Since the errors generated are quite small (compared with other sources of errors described in "Error Analysis," below), we decided to continue to use individual full-scale slopes in the data reduction algorithms.

However, if the magnitude of the other sources of error can be reduced in future experiments, it may be worthwhile to use calibration data that was obtained over a more limited range of displacements. In that case, it would be preferable to use a slope that was determined over the smallest possible range, assuming that the expected range of displacements could be determined *a priori*.

The bottom two lines in Table 27 present errors caused by using pretest rather than post-test transducer sensitivities. Whereas the mean errors are negligible, errors for individual instruments are quite large. It is interesting that the errors for full-scale and ± 2.54 -mm ranges are nearly identical, indicating that the changes in sensitivity were fairly uniform over the entire range. Since only

Figure 40. Typical canister drift vertical convergence wire extensometer installation.

the initial and final sensitivities were measured, we do not know how the sensitivities changed as a function of time. If the change was linear, the mean errors would not exceed one half the values noted in Table 27.

Error Analysis

Seven sources of error were identified for the CWE units: (1) the calibration coefficient; (2 and 3) excitation and signal voltages; (4) the coefficient of thermal expansion; (5) wire length; (6 and 7) initial and current average wire temperatures. Equations (34) through (36) are used to evaluate errors in the calibration coefficient. Maximum individual errors in the calibration coefficient over the operational range of 3 mm are (a) signal, 7.48×10^{-5} V; (b) excitation, 5.3×10^{-4} V; and (c) displacement, 2.54×10^{-6} m. The maximum RSS uncertainty in the value of K is calculated to be 2.16×10^{-5} V·m/V.

In field use, CWE displacements are calculated using Eq. (37) as noted in the previous section. Errors are then calculated using Eqs. (38)

through (42) and Eqs. (51) and (52). Maximum individual errors are (a) calibration coefficient, 2.16×10^{-5} V·m/V; (b) excitation, 5.30×10^{-4} V; (c) signal, 7.48×10^{-5} V; (d) coefficient of thermal expansion (assumed $\pm 5\%$ due to lack of data), 8.3×10^{-7} m/m·°C; (e) wire length, 1.5 mm; and (f) wire temperature (from CWT analysis), 0.848°C for short wires, 0.544°C for medium length wires, and 0.407°C for the long wire. The products of appropriate sensitivity factors and individual errors are provided in Table 28 for each range of CWE wire lengths. In addition, the error introduced by removing and replacing the canister drift CWE units is also shown. The mean error associated with removing and replacing the CWEs was -27×10^{-6} m. Errors ranged from zero for the short units (which were never removed) to -234×10^{-6} m for the long unit. Maximum composite errors were calculated by the root-sums-of-squares (RSS) approach.

Because we used pretest sensitivities that were determined over the full range of the transducer and did not account for changes in transducer sensitivities, an additional mean error of 3.8×10^{-6} m and maximum error of 43.3×10^{-6} m

Table 27. Measured errors resulting from changes in transducer sensitivity for CWEs.

Comparison	Number calibrated	Magnitude of error (μ m)		
		Mean	Std dev	Range
Pretest full-scale vs pretest ± 2.54 mm	32	-1.7	11.1	-27.6 to 21.31
Post-test full-scale vs post-test ± 2.54 mm	26	-1.5	12.7	-32.9 to 32.8
Pretest full-scale vs post-test full-scale	26	3.8	8.9	-6.6 to 35.7
Pretest ± 2.54 mm vs post-test ± 2.54 mm	26	3.6	9.0	-6.6 to 43.3

Table 28. Calculated maximum total errors associated with field deployment of convergence wire extensometers.

Wire length (m)	Source and magnitude of error (μ m)						RSS
	Calib. coeff.	Voltage	Thermal coeff.	Length	Temp.	Removal/ replacement	
2.9 to 3.5	2.54	0.26	56.9	0.548	62.0	0	84.2
4.6 to 5.9	2.54	0.26	97.0	0.548	67.8	282	306
8.0	2.54	0.26	146.0	0.548	76.4	234	286

exist. The maximum error value causes the calculated RSS uncertainties shown in the right-hand column to increase slightly to 94.7×10^{-6} m, 309×10^{-6} m, and 289×10^{-6} m, respectively.

Reliability

Of the 32 linear potentiometers deployed on the CWEs, 6 did not meet the post-test calibration acceptance criteria, as noted by their absence from Table 27. Units CWE031 and CWE131 exhibited erratic, unstable readings during calibration. In addition, CWE041, CWE051, and CWE112 were found to operate outside the specified 100-mV

band for hysteresis and repeatability. Physical damage was evident on CWE071, which had a damaged case that impeded the free movement of the shaft and wiper of the potentiometer. An examination of the data plots for each of these six transducers shows no erratic behavior during the period of data acquisition for the SFT—C. Furthermore, CWE071 was responsive to the cooling phase of the SFT—C. Thus, we conclude that only units CWE041, CWE051, and CWE112 (the ones showing hysteresis and lack of repeatability) may have had problems while in service, which, undetected, degraded the quality of their data. All other units functioned reliably during the 3.5-yr monitoring period.

Fracture Monitors

An instrument known as a fracture monitor system (FMS) was designed and deployed to measure three orthogonal components of motion along existing fractures and faults. Where the CWE units measure an integrated elastic and inelastic rock mass response over a long gauge length, the FMS focuses the measurement on a single, discrete geologic discontinuity or a closely spaced set of such discontinuities. The simple rug-

ged design consists of two anchorages on opposite sides of the geologic discontinuity: one houses the three transducers and the other supports a bracket that transfers the motions across the discontinuity to the transducers (Fig. 41). Since the transducer body moves with the first anchorage and the transducer shaft moves with the second anchorage, displacements of the two sides of the discontinuity are sensed relative to each other.

Figure 41. Typical fracture monitor system installation.

The FMS units were installed at seven selected locations to monitor faults or zones of intense jointing (Fig. 22). These units were mounted so that strike-slip, dip-slip, and normal displacements were sensed.

Mechanical components were fabricated from electroless-nickel-plated carbon steel. Although these components were short, thermal expansion was still important because anticipated rock displacements were also small. A single type-K thermocouple was attached to each FMS to provide for compensation of thermal expansion. The transducers were Bourns Model 5184 rectilinear potentiometers.

Calibration

No provision was made in the FMS design for field calibration. Instead, the linear potentiometers were calibrated in the laboratory before and after the measurement period. Calibrations were performed over the full 25.4-mm range of the transducers in 2.54-mm steps.

These calibrations examine the transducer for possible changes in slope (sensitivity). At the start of the SFT—C, there was considerable uncertainty with regard to expected displacements. Therefore, the data reduction algorithm and associated sensitivity values were based on the average slope over the entire 25.4-mm range of the transducer. We now know that actual displacements were less than 1 mm. The top two rows of Table 29 present

errors caused by using the slope over the full 25.4-mm range of the potentiometers rather than the limited ± 2.54 -mm range. Both pre- and post-test errors are presented. Individual full-scale slopes are used in the data reduction algorithms.

Note that while the mean error introduced by this approach is negligible, errors for individual instruments can be quite large. It follows that it is preferable to use a slope that was determined over the smallest possible range if the expected range of displacements is known *a priori*.

The bottom two lines in Table 29 present errors caused by using pretest rather than post-test transducer sensitivities. Once again, the errors for full-scale and ± 2.54 -mm ranges are nearly identical, indicating that the changes in sensitivity were fairly uniform over the entire range. Since only the initial and final sensitivities were measured, we do not know how the sensitivities changed as a function of time. If the change was linear, the errors would not exceed one half the values noted in Table 29. The changes in sensitivity between pre- and post-test calibrations are negligible for the FMS transducers.

Error Analysis

The linear potentiometers were calibrated using the same procedure as for the CWE units. Equations (34) through (36) may be evaluated using maximum individual errors over the operational range of 1 mm: (a) signal, 2.76×10^{-5} V;

Table 29. Measured errors resulting from differences in transducer sensitivity for fracture monitor systems.

Comparison	Number calibrated	Magnitude of error (μm)		
		Mean	Std dev	Range
Pretest full-scale vs pretest ± 2.54 mm	21	-1.4	12.4	-24.8 to 34.4
Post-test full-scale vs post-test ± 2.54 mm	19	-1.5	12.4	-18.2 to 31.8
Pretest full-scale vs post-test full-scale	19	0.6	3.2	-4.0 to 7.2
Pretest ± 2.54 mm vs post-test ± 2.54 mm	19	0.8	4.0	-9.3 to 6.6

(b) excitation, 5.3×10^{-4} V; and (c) displacement, 2.54×10^{-6} m. The maximum RSS uncertainty in the value of K is calculated to be 6.45×10^{-5} V·m/V.

In field use, FMS displacements are calculated using Eq. (37), the same equation as for the CWE units. Errors may be calculated using the sensitivity factors given by Eqs. (38) through (42) and Eqs. (51) and (52) with proper values of the various parameters inserted in the equations. Maximum individual errors are (a) calibration coefficient, 6.45×10^{-5} V·m/V; (b) excitation, 5.3×10^{-4} V; (c) signal, 2.76×10^{-5} V; (d) coefficient of thermal expansion (assumed 5% due to lack of data), 8.3×10^{-7} m/m·°C; (e) component length, 1.5 mm; and (f) FMS temperature, 0.2°C. The maximum RSS uncertainty in the value of displacement measurements is calculated to be 9.63×10^{-6} m. Because we used pretest sensitivities that were determined over the full range of the transducer and did not account for changes in transducer sensitivities, an additional mean error of 1.5×10^{-6} m and maximum error of 34.4×10^{-6} m exist. These errors cause the calculated RSS uncertainty to increase to mean and maxi-

mum values of 9.75×10^{-6} m and 35.7×10^{-6} m, respectively.

Reliability

Two of the 21 linear potentiometers deployed on FMSs did not pass the post-test calibration acceptance criteria, as noted by their absence from Table 29. The shaft of FMS023 was sticking and it was found to operate outside the specified 100-mV band for hysteresis and repeatability. In addition, physical damage to the case of FMS052 precluded movement of the shaft and wiper so this unit could not be calibrated. Individual data plots for these units revealed no problems with FMS023. However, FMS052 began malfunctioning at 4.85 YOC (September 26, 1982) and was cleaned, lubricated, and returned to service at 5.36 YOC (March 31, 1983). It was functioning reliably when removed for recalibration. It appears that the malfunctions of both these units may be related to events that took place after the SFT—C, possibly during disassembly of the instruments or shipment of the components to the calibration laboratory.

Borehole Closure Monitor

A strain-gauged proving-ring transducer was designed and deployed to measure small diametrical displacements in the 0.61-m-diam by 4.9-m-deep canister emplacement boreholes after the spent fuel was retrieved (Patrick and Rector, 1984). This instrument has been dubbed the canister borehole deformation gauge (CDG). The basic instrument consists of a steel proving ring with a 203.2-mm outside diam, 190.5-mm inside diameter, and 25.4-mm ring width (Fig. 42). Sections of 25.4-mm-diameter bar stock and machined bearing surfaces are connected to the ring to transmit displacements from the borehole to the gauge. The proving ring is prestressed at the time of installation so both positive and negative borehole displacements may be sensed.

Micro-Measurements' SK-06-125AD-350 "Karma" foil strain gauges were used to measure strains in the proving ring resulting from changes in borehole diameter. Gauges were applied in a full bridge configuration at positions 90° from the load axis. The test environment was at 100% relative humidity with temperatures decreasing from 60 to 30°C during the planned 6-month deployment period. Four layers of protective coating

were applied in accordance with manufacturer's suggestions to combat this environment. These consisted of M-Coat D (toulene-thinned acrylic), M-Coat W1 (microcrystalline wax), M-Coat FB (butyl rubber sealant), and M-Coat FN (Neoprene rubber sheet).

A single type-K thermocouple was mounted to each set of three proving rings to provide data to compensate for the effects of thermal expansion of the transducer components.

Two sets of three proving-ring assemblies were installed in each of two canister emplacement boreholes for a total of 12 transducers. Each set of three transducers was arranged on its support brackets in a 60-degree rosette. In addition, two transducers were installed in a third borehole: one in an unloaded configuration and one in a dead-weight-loaded configuration. Since neither of these transducers interacted with the borehole, their output signals were used to monitor transducer drift and zero offset while the experiment was in progress. These data thus provided a degree of confidence (before post-test calibrations were performed) that the data from the other 12 transducers were reliable.

Figure 42. Schematic of canister deformation gauge showing strain-gauged proving-ring concept.

Calibration

Laboratory calibrations were performed on the CDG units before installation and on all units that survived the 6-month deployment. The rings were calibrated on an Ormond beam-balance calibrator. A Bourns Model 141 rectilinear potentiometer was installed diametrically across the ring to measure ring displacements, and the ring was exercised 10 times through the 0.51-mm (0.02-in.) range to ensure that all mechanical interfaces were stable, that the test frame hardware alignments were correct, and that the related hysteresis was minimized. Since the CDGs would be deployed in an elevated-temperature environment, both ambient-temperature (23°C) and elevated-temperature calibrations were conducted. To perform the elevated-temperature calibration, a styrofoam box was constructed around the ring, and the temperature of the proving-ring was raised to 49°C by means of a heat lamp and a small stirring fan. Following the elevated temperature calibration, a third calibration was performed at the ambient temperature to determine if the operation at an elevated temperature produced any changes in ambient temperature calibration characteristics. In general, errors associated with operating the CDGs at elevated temperatures were less than

0.4% of full scale and in no case exceeded 0.7% of full scale. Furthermore, no significant permanent changes were detected by the third calibration. The mean transducer sensitivity was determined to be 8.811 mV/mm with a standard deviation of 0.0988 mV/mm (1.1%). Despite the small variability in transducer sensitivity, individual calibration coefficients were used for each CDG unit.

Post-test calibrations were performed using the same technique outlined above but only ambient temperature calibrations were performed.

Error Analysis

Five potential sources of error were identified: calibration coefficient K , gauge length, temperature, excitation voltage, and signal voltage. Examining first the calibration coefficient K , we have

$$K = \frac{E}{S} D^* \quad (53)$$

where

D^* is the displacement sensed by the transducer in m,

E is the excitation voltage,

S is the signal voltage.

The sensitivity factors are calculated by differentiating Eq. (53), such that

$$\Theta_D = \frac{dK}{dD} = \frac{E}{S} \quad (54)$$

for displacement errors;

$$\Theta_E = \frac{dK}{dE} = \frac{D^*}{S} \quad (55)$$

for excitation voltage errors;

$$\Theta_S = \frac{dK}{dS} = -\frac{D^*E}{S^2} \quad (56)$$

for signal voltage errors. Maximum individual sources of error are (a) displacement, 2.54×10^{-6} m; (b) excitation voltage, 5.3×10^{-4} V; and (c) signal voltage, 4.35×10^{-6} V. The maximum RSS uncertainty in K is calculated to be 5.08×10^{-3} V·m/V.

For field use, the equation for calculating displacement from bridge voltage readings is

$$D = K \frac{S}{E} - \alpha L (T - T_0) \quad (57)$$

where

- D is the borehole displacement, m,
- K is the calibration factor, V·m/V,
- E is the excitation voltage, V,
- S is the signal voltage, V,
- α is the coefficient of expansion, m/m·°C,
- L is the gauge length, m,
- T is the current temperature, °C,
- T_0 is the initial temperature, a constant, °C.

Sensitivity factors are calculated by differentiating Eq. (57) with respect to each of the sources of error:

$$\Theta_K = \frac{dD}{dK} = \frac{S}{E} \quad (58)$$

for errors in calibration coefficient;

$$\Theta_E = \frac{dD}{dE} = \frac{-KS}{E^2} \quad (59)$$

for errors in excitation voltage;

$$\Theta_S = \frac{dD}{dS} = \frac{K}{E} \quad (60)$$

for errors in signal voltage;

$$\Theta_\alpha = \frac{dD}{d\alpha} = -L(T - T_0) \quad (61)$$

for errors in coefficient of expansion;

$$\Theta_L = \frac{dD}{dL} = -\alpha(T - T_0) \quad (62)$$

for errors in gauge length;

$$\Theta_T = \frac{dD}{dT} = -\alpha L \quad (63)$$

for errors in current temperature;

$$\Theta_{T_0} = \frac{dD}{dT_0} = \alpha L \quad (64)$$

for errors in initial temperature. The maximum uncertainty for each source of error is calculated as the product of the sensitivity factor and the associated maximum unit error. Maximum unit errors are (a) calibration coefficient, 5.08×10^{-3} V·m/V; (b) excitation voltage, 8.0×10^{-4} V; (c) signal voltage, 4.9×10^{-6} V; (d) coefficient of thermal expansion, assumed $\pm 5\%$; (e) length, 6.35 mm; and (f) temperature, 0.2°C. The composite RSS error is 1.51×10^{-5} m.

Reliability

Two criteria were applied in judging the reliability of the CDGs. First, the output signals of the devices were carefully examined to determine if there was any erratic behavior. The useful life of the transducer ended when erratic signals began. In general, such changes in transducer response were quickly followed by a complete loss of signal. Table 30 documents transducer reliability judged by this criterion.

Second, post-test calibrations were made to evaluate transducers which survived the 189-day test period. Table 31 summarizes changes between the pre- and post-test calibration characteristics of these transducers. Changes in sensitivity ranged from -0.751 to -1.498% with an average of -1.172%. Shifts in zero offset ranged from 0.001 to 1.007 mV, with an average of 0.867 mV, with two exceptions. The two exceptions are CDG034 and CDG091 which, as noted in Tables 30 and 31, were determined to have failed based on erratic output signals. Also note that CDG095

Table 30. Time periods of acceptable data from canister deformation gauges.

Instrument license plate	Transducer serial number	Start of data (YOC)	End of data (YOC)	Operating life (days) ^a
CDG 031	01	5.30	5.67	135.1
032	02	5.30	5.55	91.3
033	03	5.30	5.52	81.2
034	04	5.30	5.63	120.3
035	05	5.30	5.50	73.0
036	06	5.30	5.63	120.3
091	07	5.34	5.60	95.0
092	08	5.34	5.86	188.9
093	09	5.34	5.86	188.9
094	10	5.34	5.86	188.9
095	11	5.34	5.86	188.9
096	12	5.34	5.86	188.9
072	13	5.34	5.86	188.9
071	14	5.34	5.86	188.9

^a Test duration was 188.9 days.

Table 31. Changes in calibration characteristics of strain-gauged proving-ring transducers.^a

Instrument license plate	Transducer serial number	Calibration characteristics				
		Sensitivity (% change)	Zero offset (mV change)	Span (% change)	Pretest error band (%)	Post-test error band (%)
CDG 034	04	+0.023	20.449	+0.056	+0.50, -0.71	+0.15, -0.17
091	07	-0.598	3.210	-0.511	+0.30, -0.18	+0.16, -0.15
092	08	-1.498	0.309	-1.411	+0.24, -0.29	+0.07, -0.13
093	09	-1.497	0.817	-1.401	+0.34, -0.19	+0.11, -0.13
094	10	-1.009	0.083	-0.919	+0.34, -0.25	+0.13, -0.16
096	12	-1.442	0.001	-1.357	+0.30, -0.40	+0.12, -0.14
072	13	-0.835	1.007	-2.092	+0.21, -0.29	+0.09, -0.13
071	14	-0.751	0.628	-0.827	+0.22, -0.26	+0.37, -0.33

^a Calibration performed over a span of 0.51 mm, nominal 10-V excitation, average transducer sensitivity is 0.881105 mV/V·mm.

provided reliable readings throughout the test period but malfunctioned at the time of calibration.

All failures were judged to be the direct result of moisture leaking into the strain gauge or, more

commonly, into the area where the gauge leads were connected to terminal strips. In future applications, additional environmental protection should correct this problem.

Summary and Conclusions

The objective of the instrumentation program developed for the SFT-C was to ensure that an appropriate quantity and quality of data was obtained for three purposes:

- To meet the technical objectives of the test.

- To provide for radiation safety.

- To monitor the status of the test operating systems such as ventilation, electrical power, and the DAS.

Nearly 1000 instruments were deployed and about 15.3×10^6 data points were automatically

acquired by the DAS. Additional data were acquired from manually recorded instruments such as dosimeters.

The DAS had an availability of 96% during the data collection period of 3.5 years while functioning essentially unattended for most of this period in a remote corner of the Nevada Test Site. This high availability is directly attributable to the redundant design, which utilized two HP1000 mini-computers that were configured to share the data acquisition load in normal operation and to switch so that one computer acquired all data in the event of a malfunction of the other computer.

The three objectives of the instrumentation program were met despite malfunctions and changes in operating characteristics of several types of instrumentation. Stress changes were not adequately determined because the vibrating-wire stressmeters failed too soon after deployment. This is the only data type that we believe was obtained with insufficient accuracy and for an insufficient time period. Although this shortfall precludes using changes in stress as a second independent basis for evaluating the computer code used to model the thermomechanical response of the rock, the availability of a large amount of good quality displacement data will support the evaluation.

Table 32 summarizes the results of error and reliability analyses developed in preceding chapters of this report. We offer several conclusions and suggestions based on our studies.

1. Currently available CAM and RAM systems are adequate for radiation safety purposes when deployed in an underground environment. Provisions for periodic recalibrations must be included in the monitoring plan. The units should be protected from contact with corrosive ground waters.

2. Long-term radiation dosimetry using the optical transmission technique (LiF) should be augmented with short-term TLD measurements using CaF_2 thermoluminescent dosimeters.

3. The foil-type long-term neutron dosimetry used at the SFT-C is inadequate for accurate determinations of dose. Portable dose rate instrumentation provides adequate personnel neutron dosimetry.

4. Commercially available RTDs, thermocouples, and thermistors provide reliable, accurate, long-term temperature data. Sheaths and

environmental sealing materials must be carefully selected for the particular test environment.

5. The four-wire resistance measurement system developed for monitoring CWE temperatures was marginally adequate. Errors in temperature were a significant contributor to total error for the CWEs.

6. More accurate, higher-resolution techniques are needed to calibrate turbine flowmeters. Inadequacy of existing techniques required that we revert to manufacturer's specifications in the error analyses.

7. Systematic changes in watt transducer calibrations (outside of manufacturer's specifications) occurred during the SFT-C. These changes suggest the need for periodic calibrations if an accuracy of better than about 5% is required for the energy balance.

8. Failure of 100% of the original O-ring-sealed vibrating-wire stressmeters led to a hermetically sealed design. These units functioned much more reliably with only 2 of 18 units providing erratic readings. The possibility of filling the stressmeter cavity with fluid should be considered.

9. An attempt at post-test calibrating the vibrating-wire stressmeters after retrieving them by means of an overcoring technique was a limited success. However, the attempt revealed major differences between the actual and assumed gauge sensitivities. Further development of calibration techniques is needed if these gauges are to be used with accuracy.

10. The burst-line technique for inflating hydraulic extensometers was found to be marginally adequate. A nitrogen-over-hydraulic system was deployed on a second set of extensometers to control inflation and maintain adequate anchor pressure. Anchorage was demonstrably better where controlled inflation was used, even when anchorage pressure later decreased to zero due to leakage.

11. Major losses of data resulted from failure of two types of linear potentiometers. These failures are believed to have resulted from degradation of the resistive element, which was brought on by chemical vapor action. Consideration should be given to deploying fluid-filled transducers.

12. Changes in transducer sensitivities occurred in potentiometers, LVDTs, and electromag-

Table 32. Summary error values and reliability statistics for instrumentation deployed at the Spent Fuel Test—Climax.

Instrument type	Number deployed	Error analysis		Reliability analysis			Comments/ recommendations
		Calc. RSS error	Mean calib. error pre- and post-test	Number malfunctions (%)	Mean time to failure	Mode of failure	
1. Remote area radiation monitors	10	—	—	0 (0)	N/A	N/A	Sensitivity changed with time requiring recalibration.
2. Continuous air radiation monitors	14 (2 chambers)	—	—	0 (0)	N/A	N/A	Sensitivity changed with time requiring recalibration.
3. Radiation dosimeters (γ)	25	$\pm 11\%$	—	0 (0)	N/A	N/A	Augment with short-term dosimetry. More study of annealing required.
4. Radiation dosimeters (n)	10	$\pm 30\%$	—	0 (0)	N/A	N/A	Inadequate for low neutron dose measurements.
5. CaF_2 TLD (γ)	18	$\pm 5\%$	—	0 (0)	N/A	N/A	Excellent adjunct to long-term dosimetry.
6. MgB_4O_7 TLD (γ)	18	—	—	18 (100%)	N/A	Erratic readings during calibrations.	Theoretically better than CaF_2 , but unstable in practice.
7. RTD	20	0.038°C @ 0°C 0.041°C @ 40°C	0.032°C, 0.090°C @ 23°C 0.039°C, 0.112°C @ 40°C	0 (0)	N/A	N/A	Flawless performance
8. Thermocouples	515	0.12°C @ 0-200°C 0.13°C @ 200-400°C 0.14°C @ 400-1000°C	See Figs. 11-14 for distr. of errors	4 (0.8%)	Did not fail in service.	Corrosion of 304L stainless or Inconel 600 sheath.	Failure occurred at time of post-test calibration.
9. Thermistors	19	0.022°C	—, 0.091°C @ 19°C 0.006, 0.025°C @ 23°C —, - 0.019 @ 30°C	0 (0)	N/A	N/A	Flawless performance.
10. Convergence wire temperature monitors: 2.9-3.5 m long	18	0.848°C	- 0.101°C	2 (6.2%)	Did not fail in service.	Voltage/current reference moved during post-test calibration.	Loss of post-test calibration does not affect data acquired during tests.
4.6-5.9 m long	11	0.544°C	- 0.090°C				
8.0 m long	1	0.407°C	- 0.248°C				

Table 32. (Continued)

Instrument type	Number deployed	Error analysis		Reliability analysis			Comments/ recommendations
		Calc. RSS error	Mean calib. error pre- and post-test	Number malfunctions (%)	Mean time to failure	Mode of failure	
11. Air temperature TCs	6	$\pm 0.005^{\circ}\text{C}$	$\pm 0.005^{\circ}\text{C}$	0 (0)	N/A	N/A	Used individual TC calibration to minimize errors.
12. Dewpoint cell (LiCl)	4	± 0.0187 Torr	$\pm 0.2\%$ $\pm 0.14^{\circ}\text{C}$	0 (0)	N/A	N/A	Functioned well.
13. Turbine flowmeter	3	$\pm 0.1\%$	—	0 (0)	N/A	Periodic cleaning of turbine was necessary.	Poor resolution of calibration techniques and suspected 18% systematic error led to use of manufacturer's specs for error analysis.
14. Watt transducers (auxiliary heater)	6	—	- 1.3%, + 2.5%	0 (0)	N/A	N/A	One unit damaged in shipping could not be post-test calibrated. Systematic shift in calibration was observed.
15. Watt transducers (electrical simulators)	6	—	- 3.5%, + 3.2%	0 (0)	N/A	N/A	Systematic shift in calibration was observed.
16. Watt transducers: Heater drift lighting	4	—	- 2.7%, + 0.5%	0 (0)	N/A	N/A	—
Can. drift lighting	3	—	- 3.7%, 1.8%	0 (0)	N/A	N/A	Two units damaged in shipping.
17. Vibrating-wire stressmeters: Original	18	—	—	18 (100%)	273 days	Corrosion of vibrating wire. Erratic readings	Resulted in the likely total loss of data.
Replacement	18	—	N/A, 60%	2 (11%)	N/A		Most readings reliable, data are probably ok.
18. Mine-by series extensometers (data for typical 5 m rod)	12 units, 60 anchors	56 μm	Change in sens. produced mean error = - 3.8 μm	9 (15%) 2 (3%)	N/A 580 days	Anchor slip at low loads. Transducer failure	Due to inadequate inflation with burst line system. Erratic output signals.
19. GxE-series extensometer original Bourne potentiometer, 5-m rod	14 units, 56 anchors	33 μm	—	43 (77%) 10 (18%)	223 days 1119 days	Transducer failure; rod fracture.	Resulted in massive loss of early-time displacement data. Stress corrosion cracking.
20. GxE replacement Bourne pot. 5-m rod	6 units 24 anchors	33 μm	Change in sens. produced mean error = - 30.8 μm	0 (0)	N/A	N/A	Transducer sensitivity changed with time.

Table 32. (Continued)

Instrument type	Number deployed	Error analysis		Reliability analysis			Comments/ recommendations
		Calc. RSS error	Mean calib. error pre- and post-test	Number malfunctions (%)	Mean time to failure	Mode of failure	
21. GxE replacement Vernitec pot. 5-m rod	3 units 12 anchors	33 μm	—	12 (100%)	210 days	Transducer failure	Unsealed units failed rapidly after deployment.
22. GxE replacement LVDT 5-m rod	3 units 12 anchors	112 μm	Change in sens. produced mean error = - 22.8 μm	0 (0)	N/A	N/A	Transducer sensitivity changed with time.
23. GxE replacement proximeter 5-m rod	3 units 12 units	63 μm	Change in sens. produced mean error = + 190.8 μm	0 (0)	N/A	N/A	Transducer sensitivity changed with time.
24. Convergence wire extensometers:							
2.9—3.5 m long	20	84 μm	Change in sens. produced mean error = 3.8 μm	3 (9.4%) hysteresis	—	Excessive	Observed in post-test calibration, not evident in data.
4.6—5.9 m long	11	306 μm					
8.0 m long	1	286 μm					
25. Fracture monitor systems	21	10 μm	Change in sens. produced mean error = 0.8 μm	1 (4.8%)	900 days	Erratic readings	A 6-month period of erratic performance corrected 6 months before the end of the test.
26. Borehole closure monitor	14	15 μm	Change in sens. produced mean error = 1.2 μm	7 (50%)	102 days	Electrical shorts due to ingress of water to terminal strips.	Planned test duration 189 days.

netic proximeters. While mean errors produced by these changes were a few tens of micrometres, extreme values were as large as one-half millimetre.

13. The coefficient of thermal expansion of borehole extensometer connecting rods must be better known. Substantial improvements in system accuracy will result.

14. Convergence wire extensometers proved to be reliable instruments for measuring displacements across underground openings. As noted in item 5, errors in temperature readings seriously

degraded the potential accuracy of these units. It is also clear that the coefficient of expansion of the wire must be better known.

15. Fracture monitors functioned with excellent accuracy and reliability.

16. The borehole closure monitors developed for the SFT—C functioned quite well for a prototype instrument. Improvement in environmental sealing should greatly extend the useful life of these specialty instruments.

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