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Spent Fuel Test—Climax: Technical Measurements Interim Report Fiscal Year 83

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Spent Fuel Test—Climax: Technical Measurements Interim Report Fiscal Year 83

Abstract

The Spent Fuel Test—Climax (SFT-C) is located 420 m below surface in the Climax stock granite on the Nevada Test Site. The test is being conducted under the technical direction of the Lawrence Livermore National Laboratory (LLNL) as part of the Nevada Nuclear Waste Storage Investigations (NNWSI) for the U.S. Department of Energy (DOE). Eleven canisters of spent nuclear reactor fuel were emplaced, and six electrical simulators were energized April–May 1980. The spent-fuel canisters were retrieved and the thermal sources were de-energized in March–April 1983 when test data indicated that test objectives were met during the 3-year storage phase.

The SFT-C operational objective of demonstrating the feasibility of packaging, transporting, storing, and retrieving highly radioactive fuel assemblies in a safe and reliable manner has been met. In addition to emplacement and retrieval operations, three exchanges of spent-fuel between the SFT-C and a surface storage facility, conducted during the storage phase, furthered this demonstration.

Technical objectives of the test led to development of a technical measurements program, which is the subject of this and three previous interim reports. Geotechnical, seismological, and test status data have been recorded on a continuing basis for the 3-1/2 year duration of the test on more than 900 channels. Data acquisition from the test is now limited to instrumentation calibration and evaluation activities. Data now available for analysis are presented here. Highlights of activities this year include a campaign of *in situ* stress measurements, mineralogical and petrological studies of pretest core samples, microfracture analyses of laboratory irradiated cores, improved calculations of near-field heat transfer and thermomechanical response during the final months of heating as well as during a six-month cool-down period, metallurgical analyses of selected test components, and further development of the data acquisition and data management systems.

Chapter 1

Summary and Conclusions

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

The SFT-C is located 420 m below surface in the Climax stock granite where facilities were constructed between June 1978 (when funding for the test was initiated) and April 18, 1980 (when spent-fuel emplacement began). Spent-fuel emplacement between April 18 and May 28, 1980, spent-fuel exchanges in January and October 1981 and August 1982, and spent-fuel retrieval between March 3 and April 6, 1983 combined to meet the operational objective of the test: demonstration of safe and reliable packaging, transport, short-term storage, and retrieval of spent nuclear reactor fuel. The storage period corresponds to spent-fuel ages of 2.5 to 5.5 years out of core (YOC).

The technical measurements program is aimed at acquiring data concerning the ultimate qualification of granitic rock as a repository medium, as well as the design and prediction of the response of such a repository in granitic rock. Numerous technical objectives were established at the initiation of the test, as presented in the test Technical Concept (Ramsdottir et al., 1979). Our activities have continued to focus on these stated aims throughout the duration of the test.

Data have been recorded continuously on more than 900 channels during the three year storage phase of the test and continued for six months following retrieval to record thermal and thermomechanical responses during cooling of the simulated repository environment. Most data are acquired through a central data acquisition system (DAS). Periodic displacement measurements and radiation dosimetry data are acquired manually and processed independently of the DAS. Acoustic emissions data are also acquired independently.

This report is the fourth in a series of technical interim reports (Carlson et al., 1980, Patrick et al., 1982, Patrick et al., 1983). It summarizes the data acquired and presents some preliminary analyses and interpretations. For the sake of completeness, we also summarize key results published in topical reports throughout the fiscal year. Some important results that became available in

FY 1984 while this report was in preparation are also included.

1.1. Site Characterization and Geologic Investigations

Site characterization and geologic investigations completed this year focused on measurements of the *in situ* state of stress, mineralogical and petrological studies of the pretest cores obtained near the 17 canister emplacement holes, and microfracture analyses of laboratory irradiated cores. The following are recent observations:

- In the north and south heater drift pillars, the maximum principal stress (σ_1) is essentially vertical, the intermediate principal stress (σ_2) is horizontal and aligned parallel to the long axes of the pillars, and the least principal stress (σ_3) is parallel to the pillar width.

- "Free field" state of stress measurements indicate that the maximum principal stress is oriented toward the east-northeast and is nearly horizontal, the intermediate principal stress is nearly vertical, and the nearly horizontal least principal stress is oriented north-northwest. These results are consistent with the conclusions of previous investigators and the motions of active faults at the NTS. The USBM and CSIRO gauge results are in reasonable agreement with each other.

- There appears to be a systematic difference in the maximum secondary principal stress levels measured in boreholes ISS-9 and ISS-10, which at this time does not appear to be related to any geologic structural anomaly. An additional stress measurement borehole will be drilled in the near future to attempt to determine the reason for this result.

- Significant chemical, petrographic, and modal variations occur in the Climax record cores. These variations result from both igneous and hydrothermal processes.

- The microfracture structure of Climax granite is highly heterogeneous on the scale of 0.1 to 10 mm, making it difficult if not impossible, to discern damage produced by elevated stress, temperature, and/or gamma irradiation. No statistically significant evidence of changes in microfracturing caused by laboratory gamma irradiation was observed.

1.2. Thermal Sources

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

- Total thermal energy input to the SFT-C was 1041 MW·h during the three-year storage phase of the test, with an additional 19 MW·h added during post-retrieval activities.
- The input energy partition was 25.3% from the spent fuel, 14.2% from the electrical simulators, 57.7% from the peripheral guard heaters, and 2.8% from the facility lights.
- Electrical sources of heat, associated controllers, and instrumentation, displayed a high degree of reliability.

1.3. Data Acquisition System

The data acquisition system functioned with a high degree of accuracy and reliability throughout the 3-1/2 year storage and cool-down phases of the test. System statistics show that:

- System availability averaged about 96% (Functionally Disabled Index is 4%).
- The accuracy of dc voltage measurements was maintained within a $\pm 4\text{-}\mu\text{V}$ envelope.
- The accuracy of 4-wire resistance measurements was occasionally outside the anticipated $\pm 0.0092\text{-}\Omega$ envelope because of digital voltmeter (DVM) failures which occurred periodically and were repaired.

1.4. Near-Field and Intermediate-Field Temperature Measurements

Heat transfer measurements continued through the remaining heated phase and six-month cooling phase of the SFT-C. Post-test thermocouple calibrations have confirmed that these transducers have functioned with a high degree of reliability, producing excellent quality data for the duration of the SFT-C. Comparison of measured and calculated temperatures shows:

- Agreement continued to be excellent during the heated phase.
- Agreement during the cooling phase was not as good. Measured temperatures were consistently 1 to 5°C cooler than calculated temperatures. We hypothesize that this discrepancy occurs because the model utilized to calculate energy removal in the ventilation airstream is inadequate.

1.5. Ventilation and Dew-Point Measurements

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

- All associated measurement systems have functioned reliably.
- Total energy removal from the SFT-C was about 148 MW·h during the spent-fuel storage phase of the test. Of this, 76.7% was removed as sensible heat and 23.3% as latent heat of vaporization. Our ability to calculate this energy removal is limited, as noted in previous Interim Reports. Additional models of this aspect of heat flow are being considered.
- About 20 tonnes of water are removed from the facility each year in the ventilation airstream.

1.6. Radiation-Dose-to-Granite Measurements

Radiation-dose-to-granite measurements with lithium fluoride dosimeters were completed with the retrieval of spent fuel from the SFT-C. These measurements are made at the emplacement hole wall and at distances of 200 and 360 mm into the rock at selected emplacement holes. Additional calibration data were obtained at elevated temperature to compensate for the effects of simultaneous heating and irradiation on the response of the dosimeters. A second series of short-term dose measurements were obtained using calcium fluoride and magnesium borate TLDs to investigate the effects of post-irradiation annealing over extended times. In general, data and calculations of radiation-dose-to-granite agree within about $\pm 25\%$.

1.7. Measurements of Radiation Dosage to Man

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

1.8. Displacement Measurements

Measurement of displacements continued through the heated phase and for six months following retrieval of the spent-fuel assemblies. Significant results include:

- Rock response to cool-down was calculated to be very small. Tape extensometer measurements could not resolve the effect of cool down.
- Extensometers utilizing carbon steel connecting rods record very little displacement since the expansion coefficients of the rock and rods are nearly identical. This effect is compensated for by correcting the rod extensometer data for thermal effects.
- A device was designed and fabricated to monitor displacements within selected canister emplacement holes following spent-fuel retrieval. Calculations indicate diametral changes of less than 0.1 mm. Data are not yet available for comparison with calculations.

1.9. Acoustic Emission and Wave Propagation Measurements

Monitoring of acoustic emission (AE) and wave propagation characteristics was completed this year. Monitoring during the cool-down period produced some of the most interesting results. The principal observations are:

- Changes in AE frequency are closely related to changes in the rate of energy input to the rock. Adjustments to heater power levels and retrieval of single or multiple spent-fuel assemblies or other heat sources produce rapid increases in AE activity.

- Changes in the ratio of S- to P-wave amplitudes qualitatively agree with temperature changes in the rock mass.

- No measurable variations in P- and S-wave velocities occurred during the monitoring period.

1.10. Metallurgical Analyses

Metallurgical analyses were conducted this year to examine failures in two test components. First, the emplacement hole liner welds were determined to have inadequate penetration which led to one of the liners leaking; thus bringing water into contact with the encapsulated spent-fuel assembly. Second, metallurgical analyses of failed Superinvar connecting rods from borehole extensometers indicated that the failures were the result of stress corrosion cracking. Accelerated testing produced failures which have morphologies similar to those observed in the field installations.

1.11. Data Management System

Activities this fiscal year have focussed on development of the computer program responsible for compensating the acquired data for temperature effects. Development of a data base of conversion and calibration parameters was completed. Several trial operations of the program were made on subsets of acquired data (up to a million words) in order to debug and verify operation of the program. Processing of all test data is now in progress with the fully operational version of the code.

Chapter 2

Introduction

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

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

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

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

2.1. Objectives of the SFT-C

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

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

- Documentation of displacements and stress changes in the rock comprising the pillars between the central and side drifts due to the mechanical disturbance of mining the central drift.
- Comparison of that response to the results of existing computational modeling to assess the 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 of 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 duplication of all mechanical measurements in regions which are either fractured or relatively unfractured, and by direct instrumentation of selected, prominent geologic fractures.
- Evaluation of displacement and stress instrumentation under simulated repository conditions.

2.2. Areas of Research in FY 1983

Research continued this year toward meeting the stated test objectives. Investigations were carried out in seven general areas.

Site characterization field activities were resumed following spent-fuel retrieval. *In situ* stress measurements were obtained and preliminary analyses are complete. Measurements of *in situ* deformation modulus are in progress at this time and will be reported next fiscal year.

Laboratory studies included further investigation of the effects of gamma irradiation. A study was conducted of the density and character of microfracturing in laboratory irradiated and unirradiated samples. The mineralogy and petrology of pretest record cores was documented. These studies precede post-test analyses of the effects of heat and heat plus radiation on the rock adjacent to the borehole walls.

Measurement of near-field and intermediate-field temperatures supported heat transfer studies. Rock and air temperature measurements following spent-fuel retrieval allowed assessment of our models under conditions when thermal energy input was essentially zero and ventilation was augmented to rapidly cool the rock mass.

Additional radiation dose-to-granite measurements were made. Dose-to-man monitoring was completed during the spent-fuel retrieval operations.

Displacement and stress monitoring continued with the five types of extensometers and the vibrating-wire stressmeters in use at the SFT-C. To facilitate analysis and comparison with calculated displacements, thermal expansion effects were compensated for in selected data from rod and tape extensometers and the Whittemore gauge. A device was developed to measure diametral displacements in two of the canister emplacement holes following spent-fuel retrieval.

Acoustic emission monitoring was completed this fiscal year. Several interesting AE events were recorded during the period of reduced thermal energy input to the rock which immediately followed spent-fuel retrieval.

Metallurgical investigations were initiated this year to examine corrosion phenomena which have influenced instrumentation reliability and which have affected various metallic components in the canister emplacement hole environment. An examination of the quality of emplacement hole liner welds was also completed.

In addition to these seven areas of investigation, we maintained the test environment, maintained and operated facilities for data acquisition, and continued development of a system for processing and archiving the acquired data.

The results of these activities are summarized in Chapter 1 and detailed in Chapters 3 through 12.

Chapter 3 Site Characterization and Geologic Investigations

3.1. Summary of *In Situ* Stress Measurements

A major activity at the SFT-C during FY 88 was directed toward measuring the *in situ* stress states within two distinct regions of the facility. The first of these areas includes the two relatively long pillars located between the central canister drift and the north and south heater drifts (see Fig. 3-1). In these pillars, four relatively short test bor-

ings designated ISS-4 through ISS-7 were drilled to measure stress profiles. The second measurement area is located in relatively virgin rock that is reached by a test borehole extending outward from the south heater drift (ISS-8), and by two boreholes drilled from the tail drift extension (ISS-9 and ISS-10) as shown in Fig. 3-1. Tests in these boreholes were intended to measure the "free field" state of stress which existed in advance of excavation and heating of the rock mass. Borehole

Plan view

Note:

ISS-10 is inclined upward about 45° and is on the same bearing as ISS-9. Other boreholes horizontal

Figure 3-1. Map view of the spent fuel test site showing the locations of the *in situ* state of stress measurement boreholes ISS-4 through ISS-10.

ISS-8 was also used to obtain a profile of stresses outward from the SFT-C facility.

Two different types of stress measurement instruments were used during this study. Both are based on the stress relief or "overcoring" technique described below. The first device is the U.S. Bureau of Mines gauge that has been used in the geotechnical community for several years. The second gauge is the CSIRO gauge (Commonwealth Scientific and Industrial Research Organization) that has been under active research and development in this Australian research laboratory for the last several years. Both of these gauges were modified to include a thermistor heat-sensing element through which direct measurement of ambient rock temperature, at the actual test location, was made. Standard test procedures were also extensively modified to maintain, to the maximum extent possible, a constant temperature during the test itself. A total of 45 USBM-gauge and 31 CSIRO-gauge tests were attempted of which 37 (82%) and 20 (65%) tests were successful, respectively.

The stress measurements performed in the Climax Stock were done with the aid of Foundation Sciences, Inc. (FSI). They supplied the USBM and CSIRO gauges, calibration and readout apparatus, and various support equipment, along with three staff members, needed to conduct these tests. LLNL supplied a project monitor who also assisted during actual tests as a fourth crew member. The data presented here are taken from the draft FSI report by Creveling et al. (1983) which is currently being revised. Therefore, the following data should be considered preliminary, and subsequent revisions are likely to occur.

3.1.1. Test Methods

Both the USBM and CSIRO gauges use the strain relief by overcoring method of measuring the magnitude and orientation of the stress regime. During the test, one of the gauges is inserted in a nominally EX size (38-mm-diameter) borehole at the desired test location. A nominally 6-in. (150-mm) diameter core barrel is then used to coaxially "overcore" the gauge location thereby allowing the rock to strain relieve. This causes the small central borehole to slightly change its size and shape which is the deformation measured by these highly sensitive gauges. After the overcoring is complete, the core is recovered, carefully measured, described, and then placed, with the gauge in the central borehole, in a hydraulic "biaxial" test cell where it is subjected to cyclicly-applied confining pressures. The results of this

test are used to calculate a Young's Modulus using thick-walled cylinder theory, and this value is in turn used to calculate the rock stresses at the test location.

The USBM and CSIRO gauges are fundamentally different in the manner in which they measure borehole wall deformation. The USBM gauge uses six strain gauged Be-Cu cantilevers mounted so that they measure three equally spaced borehole diameters in a single transverse plane (Fig. 3-2). This reusable instrument cannot measure borehole axial deformation and therefore, cannot measure all the strain components necessary to determine the complete state of stress. The information obtained is sufficient to derive the two secondary principal stresses (P and Q) that exist perpendicular to the borehole axis. These values must be combined with similar measurements obtained in at least two other non-parallel boreholes to obtain directions and magnitudes for the true principal stresses.

The CSIRO gauge consists of nine variously oriented electrical resistance type strain gauges encased in a thin plastic cylinder (Fig. 3-3). This unit is then irretrievably bonded to the borehole wall using a special epoxy-based adhesive. The nine strain gauges are arranged in such a manner that all three principal strain components are measured which allows, with the modulus value and thick-walled cylinder theory, a direct calculation of the principal stresses. Clearly, a very high quality gauge-to-borehole bond is required if one is to measure correct strain relief values with this gauge.

For tests within the induced thermal field at the Climax stock, several USBM gauge probes were modified to include thermistors for direct temperature measurement. All CSIRO gauges were modified during manufacture to include a similar thermistor within the unit's plastic shell. Both devices required electrical cables with additional conductors for the thermistor signal. Following gauge insertion and thermal equilibration, the temperature value measured was used as a reference for the initial drilling water temperature. During actual overcoring, cold run-of-mine water was added to compensate for the thermal energy deposited in the rock by the drilling process. Following the test, the circulating water was warmed by electrical heaters to reestablish the same initial temperature. The total strain relief values obtained after thermal equilibration were the ones used to calculate the secondary or true principal state-of-stress values, as appropriate.

Figure 3-2. Three views of the modern Reverse Case U.S. Bureau of Mines Borehole Deformation Gauge (modified after drawing by Rogers Arms and Machine Company).

	A	B	C
θ	30°	270°	150°
β	0° 90° 45°	45° 90° 135°	0° 90° 45°

Figure 3-3. Oblique view showing the orientations of the nine electrical strain gauge elements of the CSIRO thin-walled borehole deformation gauge (after Worotnicki and Walton, 1979).

3.1.2. Pillar Stress Measurements

Four test boreholes, designated ISS-4 through ISS-7, were drilled through and perpendicular to the two long slender rock pillars that separate the central canister drift from the north and south heater drifts (Fig. 3-1). Fifteen USBM gauge and three CSIRO gauge tests were successfully conducted in these boreholes. The purpose of these tests was to:

- determine the magnitudes and orientations of the secondary principal stresses (USBM gauge) and total principal stresses (CSIRO gauge),
- observe the stress distribution along the boreholes with respect to the heater drift and canister drift ribs, and

- determine whether the USBM and CSIRO gauges would yield similar values for these stresses.

The preliminary results of these tests are shown in Figs. 3-4, 3-5, and 3-6 which are taken from the report by Creveling et al. (1983). Figure 3-4 shows the magnitude of the major "P" and minor "Q" secondary principal stresses (those stresses that exist in a plane perpendicular to the borehole axis) from USBM gauge tests. These values were calculated assuming a zero axial deformation occurred during overcoring. Synthetic (back calculated) secondary principal stresses are also shown for the three CSIRO gauge tests. These data generally indicate that the P value ranges from about 2000 to 700 psi, and that maximum values are located near the inner heater drift ribs and decrease to a minimum at the canister drift ribs. The Q-value ranges from about 700 to -200 psi (tension) and shows a similar, although weaker, trend.

Figure 3-5 shows these same data plotted in a graphical form along the borehole such that both their orientations and relative magnitudes can be studied. Recall that the "P" and "Q" stresses actually exist on planes transverse to the borehole axis and are portrayed as though one were looking into the borehole collar. From these diagrams it is clear that the maximum secondary stress is nominally within 20 to 30 degrees of vertical; therefore, "Q" is nearly horizontal. In general, the data between the boreholes is quite similar in form with the possible exception of tests 1, 2, and 3 in ISS-6. These measurements are quite consistently inclined to the upper left to lower right (NW). This internal consistency suggests these measurements are correct. This orientation change may reflect the influence of nearby prominent joints and shears (Wilder and Yow, 1982).

The orientations of the principal stresses obtained from the CSIRO tests in pillar boreholes are shown in the upper hemisphere polar stereo net plot in Fig. 3-6. These data generally confirm the previous statements and, along with the tabulated stress magnitudes, provide additional information. The maximum principal stress (sigma 1) is mainly vertical, but is also systematically inclined toward the NNE. The intermediate principal stress (sigma 2) is nearly horizontal and aligned parallel to the pillar axis, and the least principal stress (sigma 3) is also essentially horizontal and oriented parallel to the minimum pillar width. These findings are quite consistent with the long, thin geometry of the pillars.

Figure 3-4. Secondary principal stress values of P and Q versus borehole depth for both USBM gage and CSIRO gage pillar stress measurements in boreholes ISS-4, ISS-5, ISS-6, and ISS-7 (after Creveling et al., 1983).

Figure 3-5. Secondary principal stress orientations of P and Q versus borehole depth for both USBM gauge and CSIRO gauge pillar stress measurements in boreholes ISS-4, ISS-5, ISS-6, and ISS-7 (after Creveling et al., 1983).

Test No.	Depth, ft	Principal stresses, psi		
		σ_1	σ_2	σ_3
ISS-5-2	5.3	2,290	836	433
ISS-5-6	14.8	822	674	-294
ISS-7-2	5.5	1,838	668	254

Figure 3-6. Polar stereo net plot showing the principal stress orientations obtained from three CSIRO gauge measurements made in boreholes ISS-5 and ISS-7 (after Creveling et al., 1983).

3.1.3. Free Field Stress Measurements

Three boreholes, designated ISS-8 through ISS-10, were drilled into a relatively undisturbed portion of the stock from the tail drift extension and south heater drift (Fig. 3-1) with the intent of measuring the "free field" state of stress that exists in advance of significant excavation. Many of the experimental objectives were the same as for the pillar study, but with the following additional goals.

- It was desired to measure the stress distribution in an outer heater drift rib for a significant distance into the virgin rock and,
- ISS-8, ISS-9, and ISS-10 provided the three non-parallel boreholes needed to allow true principal stresses to be calculated from the USBM

gauge data, thereby allowing an independent check on the CSIRO gauge results.

Twenty-two USBM gauge tests and seventeen CSIRO gauge tests were successfully conducted in these three boreholes. The preliminary results are shown in Figs. 3-7 through 3-11. Figure 3-7 shows the major "P" and minor "Q" secondary principal stresses for borehole ISS-8 in a manner similar to Fig. 3-4 previously discussed. It appears that the magnitudes of stresses measured by USBM and CSIRO methods are in reasonable agreement. The major secondary stress (P) ranges from about 1000 to 1800 psi, and increases slowly away from the rib (0- to 30-ft region). Both "P" and "Q" values fall to a very low 700 psi and 500 psi, respectively, in the 40- to 45-ft depth range,

Figure 3-7. Secondary principal stress values of P and Q versus borehole depth for both USBM gauge and CSIRO gauge measurements in boreholes ISS-8 (after Creveling et al., 1983).

Figure 3-8. Secondary principal stress orientations of P and Q versus borehole depth for both USBM gauge and CSIRO gauge measurements in borehole ISS-8 (after Creveling et al., 1983).

and there is no obvious explanation for this change. The "P" value then increases from 800 to 1600 psi for the remainder of the borehole. The stress differential is maximum for those tests in the 0- to 30-ft region, and at CSIRO test No. 25 located at the very end of the borehole. The latter may be an anomaly, however.

Figure 3-8 shows the "P" and "Q" stress orientations in a manner similar to Fig. 3-5. The maximum secondary stress tends to be nearly vertical in the 0- to 30-ft portion of ISS-8, which is probably a result of its relatively close proximity to the drifts. Beyond this region, "P" tends to be highly inclined and even approaches horizontal at CSIRO Test No. 25, reflecting the increased influence of the true "free field" state of stress. The extent to which the between-measurement variability and experimental error affects the observed variance of these data is not known.

As shown in Fig. 3-1, boreholes ISS-9 and ISS-10 were drilled along the same bearing and inclined upward 4 and 46 degrees, respectively. Secondary principal stress magnitude data, and orientation data, are shown in Figs. 3-9 and 3-10, respectively. In ISS-9, the stress values appear rel-

atively constant along the borehole length except for the test pair Nos. 7 and 8. Nominally, the "P" and "Q" stress values are 600 to 1200 psi, and 500 to 800 psi, respectively. However, in ISS-10, the "P" value is consistently higher at 1300 to 2500 psi, and the "P" to "Q" stress differential is larger. Although the presence of a shear zone has been suggested as the cause of this disparity, careful examination of the core from both ISS-9 and ISS-10 does not support this interpretation. The maximum secondary stress values generally tend to be nearly horizontal in these two boreholes; occasionally dipping to the left (SW) and then to the right (NE). Exceptions are tests mostly grouped in the 44 to 52 ft range of ISS-9 where "P" is the most vertical stress.

Figure 3-11 is an upper hemisphere polar stereo net plot of the average principal stress orientations from CSIRO gauge tests in ISS-8 through ISS-10, and the principal stress orientations calculated from USBM gauge tests in these three boreholes. The maximum principal stress (σ_1) values tend to cluster at about 570° W with a plunge of 20 to 30 degrees to the NE. The intermediate and least principal stress (σ_2 and σ_3) values are more widely distributed.

Figure 3-9. Secondary principal stress values of P and Q versus borehole depth for both USBM gauge and CSIRO gauge measurements in boreholes ISS-9 and ISS-10 (after Creveling et al., 1983).

Figure 3-10. Secondary principal stress orientations of P and Q versus borehole depth for both USBM gauge and CSIRO gauge measurements in boreholes ISS-9 and ISS-10 (after Creveling et al., 1983).

Figure 3-11. Polar stereo net plot showing principal stress orientations obtained from CSIRO gauge measurements, and principal stresses calculated from USBM gauge measurements in boreholes ISS-8, ISS-9, and ISS-10 (after Creveling et al., 1983).

and 3) values alternate from nearly horizontal and trending to the NW, to nearly vertical. This is because they tend to be more nearly equal in magnitude. It is interesting to note that the lower hemisphere trend of the nearly horizontal maximum stress value (N70° E) is reasonably consistent with Carr's (1974) estimate of N40° E based on many lines of evidence. Also, Wilder and Yow (1982), and Zoback and Zoback (1980) estimate that the least principal horizontal stress is oriented about N45° W which compares favorably to the N30° W calculated from these data.

3.1.4. Proposed Measurements

As mentioned above, the maximum principal stress "P" is generally higher in ISS-10 than ISS-9. Both boreholes are located at the end of the tail drift extension and are drilled on a bearing of N62° W. ISS-9 and ISS-10 are inclined upward 4 degrees and 46 degrees, respectively. Creveling et al. (1983) suggested that the apparent stress disparity may be caused by the existence of a shear zone that separates the blocks of rock in which the two test series were conducted. Four planar discontinuities along which some shearing displacements have occurred are located at about 34 ft in the core from borehole ISS-9. Three are essentially vertical and parallel while the fourth dips about 34 degrees to the SE. These features are not developed in the core to an extent that suggests the ability to strongly affect *in situ* stress magnitudes within a large volume of rock. Another possibility is that a strange type of "positional" (shadow) effect caused by the complex interrelationships of the canister, heater, and tail drifts might somehow cause the observed stress difference. A third, although unlikely, reason might be some form of gauge orientational bias that somehow affects both the USBM and CSIRO gauges.

To test these possibilities, we have decided to drill an eighth borehole that will be called ISS-11. It will be located in the tail drift extension at the same position and vertical plane as ISS-9 and ISS-10, and will be angled 45 degrees downward. In general, it will be a mirror image of ISS-10 in that it will first be drilled to a 60-ft depth using the 6-in. core barrel, and then will be tested using both USBM and CSIRO gauges to a total depth of 95 ft. Technical difficulties mainly with bonding the CSIRO cell to the wet borehole wall and equipment manipulation, are expected because of the downward inclination of the borehole.

3.1.5. Conclusions

The following tentative conclusions are offered with regard to this study.

1. In general, this study was successful. Acceptable results have been obtained from both the USBM and CSIRO gauges, and the experimental objectives have been achieved.

2. Boreholes ISS-4 through ISS-7 measured stresses in both the north and south heater drift pillars. The maximum principal stress (sigma 1) is essentially vertical, the intermediate principal stress (sigma 2) is horizontal and aligned parallel to the long axes of the pillars, and the least principal stress (sigma 3) is parallel to the pillar width. These results are consistent with the long, thin geometry of the pillars.

3. The "free field" state of stress has been measured using the CSIRO gauge, and the three non-coplanar boreholes ISS-8, ISS-9, and ISS-10 which allows a principal state of stress to be calculated from USBM gauge measurements. The results indicate that the maximum principal stress plunges gently toward the ENE, the intermediate principal stress is nearly vertical, and the nearly horizontal least principal stress is oriented NNW. These results are consistent with the conclusions of previous investigators and the motions of active faults at the NTS.

4. There appears to be a systematic difference in the maximum secondary principal stress levels measured in boreholes ISS-9 and ISS-10 which does not appear to result from a geologic structural anomaly. An additional stress measurement borehole ISS-11 will be drilled in the near future to attempt to determine the reason for this result.

5. The CSIRO cell stress values appear to average about 30% lower than the USBM gauge values. Creep of the epoxy adhesive used to bond the CSIRO cell to the borehole wall is suspected.

3.2. Summary of Mineralogical and Petrological Studies of Climax Pre-Test Cores

This section presents mineralogical and petrological data from the characterization of samples from the 17 canister core holes (CCH 1-17) (Ryerson and Qualheim, 1983). These cores were obtained from just inside the perimeter of emplacement holes which were subsequently hammer-drilled to 0.61 m diameter and loaded

with either spent-fuel assemblies (hole numbers 1, 3, 5, 7-12, 14, 16) or electrical simulators (hole numbers 2, 4, 6, 13, 15, 17) (Ramspott et al., 1981). The purpose of this investigation is to provide a data base of mineralogical compositions, assemblages and modal proportions from pre-test samples to serve as a comparison to a similar data base that will be obtained from post-test samples. The post-test core samples will be obtained from just outside the perimeter of the canister emplacement holes directly adjacent (along a radius) to the pre-test core. This should allow determination of whether or not any mineralogical changes have occurred during the course of the test. The close proximity of the pre- and post-test cores should also enable us to assess the possible migration of materials produced as a result of the stored spent-fuel assemblies, electrical simulators, and/or the presence of alteration-generated materials along the various types of fractures in the quartz monzonite. The effects of spent-fuel assemblies versus electrical simulators will also be investigated.

3.2.1. Sample Selection

A reference line was drawn longitudinally along the recovered core. This reference line was then used to measure distances along the core and to determine the relative orientations of fractures for logging and sample selection.

The location and orientation of all fractures and alteration zones in the 17 core samples were recorded at NTS. Using these core logs, 1- to 2-ft sections of core were selected using the following criteria:

1. top of core,
2. bottom of core,
3. sample representing (as closely as possible) "fresh" unaltered rock free of fractures, i.e., "bulk sample,"
4. samples encompassing all the different types of alteration that could be described in hand specimen (it turns out that much of the sampling was redundant).

Criteria 1-3 were fulfilled for each hole. Criterion 4 was only applied to holes of specific interest. The 1- to 2-ft core sections were then shipped to LLNL for further selection.

After selecting the desired sample areas, a disk of the section cut perpendicular to the reference line was removed from the core. This disk was then cut in half (parallel to the reference line) and one piece was retained at LLNL while the other was used for the preparation of polished thin sections.

3.2.2. Petrography

3.2.2.1. Petrography and Modal Analysis. All thin sections were observed in plane and cross-polarized transmitted light in order to determine mineral assemblages and textures. A number of samples were then point-counted (2000 point modes) in transmitted light in order to determine modal abundances. The samples selected for modal analyses are:

1. all samples from CCH-1,
2. the "bulk sample" from each hole.

Samples from group (1) are used to demonstrate the variation in modal abundances in a specific hole. These variations are due to alteration and vein injection. The group (2) samples were chosen as "fresh" rock. Modal variations among these samples should, therefore, demonstrate the range of modal abundances in unaltered rock as a function of position along the canister drift.

3.2.2.2. Unaltered Rock. The quartz monzonite is a porphyritic rock composed of a groundmass which is predominately equant, subhedral grains of plagioclase, K-feldspar, quartz, and biotite ranging in size from 0.5-2.0 mm in diameter. Igneous accessory phases (titanite, allanite, zircon, and apatite) are below 3 volume percent.

3.2.2.3. Vein Mineralogy. Two distinctly different types of mineral assemblages are found in the veins within the canister drift region. The first vein, henceforth referred to as "barren," is composed of quartz with or without pyrite. Alteration zones adjacent to the barren veins are typically thin (~5 mm) and lack intense secondary mineralization. In particular, calcite is never found in these alteration zones.

The second vein assemblage is composed of quartz, calcite, pyrite, and apatite. It may also contain grains of muscovite, K-feldspar and intensely altered plagioclase. The alteration zones adjacent to these "fertile" veins can be as large as 2 cm in width and often show intense alteration.

3.2.2.4. Alteration of Plagioclase. Plagioclase from the Climax stock is almost always altered to some combination of muscovite, epidote and calcite (Table 3-1). The most common assemblages are plagioclase and muscovite (B) and plagioclase, muscovite and calcite (C) which are found in 43% and 35% of the sample areas studied, respectively. The alteration phases generally have irregular outlines, although muscovite is often present as fan-shaped aggregates. The percentage of plagioclase converted in a single grain can range from 0-75 volume percent, and the distribution of

Table 3-1. Mineral assemblages formed during the alteration of plagioclase.

	Assemblage	Number ^a
A.	Pc	(10)
B.	Pc, Mu	(55)
C.	Pc, Mu, Cc	(45)
D.	Pc, Mu, Ep	(8)
E.	Pc, Mu, Ep, Cc	(11)

^a Number in parentheses indicates the number of regions found with a particular assemblage.

converted and unconverted is sporadic although greater conversion is noted near veins.

It should also be noted that the plagioclase alteration assemblages can be correlated with the vein mineral assemblage about which they are localized. Assemblages B and D (from Table 3-1) are usually found adjacent to "barren" veins, while assemblages C and E are found adjacent to "fertile" veins.

3.2.2.5. Alteration of Biotite. The alteration of biotite in these samples is extremely complex and makes any classification scheme quite difficult. The secondary phases found on biotite include chlorite, muscovite, epidote, titanite, rutile, calcite, and pyrite. In any particular sample, the number of phases found on biotite may vary. For instance, one biotite grain may include only chlorite while an adjacent grain contains chlorite and epidote. Our classification scheme is based on the maximum number of phases found on biotite rather than on the most frequent assemblage. The variability and, in some cases, large number of phases may be related to variability in the pore fluid composition during alteration and/or the variability in cation transport paths within the rocks.

A large variety of alteration assemblages are found on biotite (Table 3-2). The most common assemblages are (a) biotite and chlorite, and (b) biotite, chlorite and epidote and (c) chlorite, muscovite, epidote, and titanite which are found in 23%, 20% and 13%, respectively, of the samples classified.

The alteration assemblages in Table 3-2 record a progressive loss of iron and magnesium from the biotite sites. This is first seen by the replacement of biotite by chlorite. Further depletion of iron and magnesium results in the complete disappearance of biotite. This often results in symplectic intergrowths of muscovite and chlorite which include scattered anhedral grains of epidote or titanite and/or rutile needles. Eventually, even

Table 3-2. Mineral assemblages formed during the alteration of biotite.

	Assemblage	Number ^a
1	Bt	(0)
2	Bt, Chl	(30)
3	Bt, Chl, Mu	(1)
4	Bt, Chl, Ep	(26)
5	Bt, Chl, Tn	(2)
6	Bt, Chl, Mu, Ep	(1)
7	Bt, Chl, Ep, Tn	(5)
8	Bt, Chl, Mu, Tn, Ru	(1)
9	Bt, Chl, Mu, Ep, Tn	(2)
10	Bt, Chl, Ep, Tn, Ru	(1)
11	Bt, Chl, Mu, Ep, Tn, Ru	(2)
12	Chl, Mu, Tn	(6)
13	Chl, Ep, Tn	(4)
14	Chl, Mu, Ep, Tn	(17)
15	Chl, Mu, Tn, Cc	(2)
16	Chl, Mu, Tn, Ru	(3)
17	Chl, Mu, Ru, Cc	(4)
18	Chl, Ep, Tn, Ru	(1)
19	Chl, Mu, Ep, Tn, Cc	(3)
20	Chl, Mu, Ep, Tn, Ru	(4)
21	Chl, Mu, Ep, Ru, Cc	(3)
22	Chl, Mu, Tn, Ru, Cc	(4)
23	Chl, Mu, Ep, Tn, Ru, Cc	(1)
24	Mu, Tn	(4)
25	Mu, Ep, Tn, Cc	(2)

^a Number in parentheses indicates the number of regions found with a particular assemblage.

chlorite may disappear leaving assemblages that are predominantly muscovite. An additional feature of the biotite-free samples is the presence of calcite after biotite. The calcite commonly appears along cleavage traces in chlorite or muscovite but may also be found as anhedral grains with these phases.

3.2.2.6. Modal Analyses. Results of modal analyses for CCH-1 samples and "bulk samples" from each of the 17 CCH's are presented in volume percent and were obtained from 2000 point modes. Percentages of key phases have been plotted against sample position in Figs. 3-12 and 3-13.

Modal analyses for the CCH-1 were obtained from the entire thin section regardless of any sample heterogeneity. Material from veins, alteration zones and unaltered regions were all counted equally in order that sample variability on this scale could be documented. Modal percentages for the primary phases, quartz, plagioclase, and

Figure 3-12. Modal abundances of major minerals from CCH-1 samples plotted versus depth in the sample core

Figure 3-13. Modal abundances of major minerals from "bulk" samples plotted versus canister core hole number.

K-feldspar, are fairly constant with average modal volumes of $17.3 \pm 2.1\%$, $32.8 \pm 5.6\%$ and $31.2 \pm 5.3\%$, respectively. The one standard deviation variation for plagioclase and K-feldspar are similar in spite of the much more pronounced alteration of plagioclase. Biotite is also a primary phase but displays a much larger percent variation than do the felsic phases. The average biotite volume is $4.9 \pm 2.7\%$. The higher variability in biotite abundance is consistent with textural variability demonstrated earlier for biotite alteration.

Muscovite, clinochlore, epidote, clinozoisite, titanite, and pyrite are present as secondary minerals. Their secondary origin is reflected in much larger variations in their modal abundance (Fig. 3-12) and results from both variability in alteration down CCH-1 and to the presence or absence of veins which carried the hydrothermal solutions.

The modal abundances for the "bulk samples" are shown in Fig. 3-13. Of the primary phases, only plagioclase appears to be significantly higher in the fresh "bulk samples" than in the variably altered samples from CCH-1, 42.8% vs 32.8%, respectively. This is consistent with the observation that plagioclase is the only felsic phase which undergoes significant alteration.

The modal volumes of the secondary phases are as variable in the "bulk samples" as in those from CCH-1 (Fig. 3-13). However, the variation in average volumes of secondary phases in the bulk samples is less.

3.2.3. Mineral Chemistry

3.2.3.1. Microprobe Analysis. Microprobe analyses were obtained in both automated and interactive modes employing a $2 \times 2 \mu\text{m}$ rastered beam at 15 na sample current (measured in a Faraday cup) with an accelerating voltage of 15 kV. The totally automated analyses were undertaken in order to objectively determine the frequency of K-feldspar and plagioclase compositions within selected samples. In this mode, 300 analyses were obtained along a grid covering the sample surface. The interactive analysis required operator selection of specific analysis points. This was done in order to determine the compositions of alteration phases which are normally low in the mode.

3.2.3.2. Primary Phases. The major primary igneous phases are quartz, plagioclase, K-feldspar, and biotite. Analyses obtained in the interactive mode are presented in Ryerson and Qualheim (1983). In addition to interactive analyses, feldspar analyses were also obtained by automated step-

scan traverses in order to objectively determine the extent of zoning and average feldspar compositions.

Histograms of feldspar analyses obtained from step-scan traverses indicate that the K-feldspar analyses vary between Or_{80} and Or_{98} with only occasional analyses falling at lower Or concentrations (Fig. 3-14). The average analysis is Or_{90} , and shows very little variation from sample to sample. These values agree quite well with those obtained during the interactive analyses. The K-feldspars show very little alteration, so that the variation must be due to a combination of primary igneous zoning coupled with subsolidus reequilibration.

The majority of the plagioclase compositions fall between An_{20} - An_{30} with the average at An_{33} (Fig. 3-14). In contrast to the K-feldspar analyses, comparison of the plagioclase analyses collected in automated and interactive analyses show an important difference. The interactive analyses focused upon plagioclase grains which contained significant amounts of secondary phases. This group of analyses contains significantly more analyses in the range An_{20} - An_0 than do those obtained in the automated step-scan traverses. This feature is indicative of incongruent plagioclase alteration. The albite end member is conserved during hydrothermal alteration, while the anorthite component is preferentially dissolved and transported from the plagioclase site.

The biotite analyses can be represented by the formula,

The $\text{Mg}/(\text{Mg} + \text{Fe})$ ratio in these biotites lies between 0.50 and 0.68.

3.2.3.3. Secondary Phases. All data for secondary minerals was collected in an interactive mode. The muscovite compositions fall in the range approximated by the formula,

with a range in $\text{Mg}/(\text{Mg} + \text{Fe})$ (atom) between 0 and 1.0. The muscovites which are found as pseudomorphs of biotites are generally enriched in MgO and FeO relative to those found on plagioclase. This is most likely indicative of increased activities of the components on the biotite sites and indicates that cation exchange equilibrium

Figure 3-14. Number of feldspar analyses from "bulk" samples plotted versus feldspar composition. Analyses were obtained in step-scan mode.

between plagioclase and biotite sites was not attained on even a thin section scale during hydrothermal alteration.

Chlorite is found exclusively on biotite sites, and its composition is given by the formula $(\text{Fe,Mg})_{4.4}\text{Mn}_{.1}\text{Al}_{2.6}\text{Si}_{2.7}\text{O}_{10}(\text{OH})_2$. The range in $\text{Mg}/(\text{Mg} + \text{Fe})$ is between 0.42 and 0.74 and is slightly larger than the range for the primary biotite.

Mineral compositions and zoning patterns in the clinozoisite-epidote series are complex. The compositions are generally expressed by the formula $\text{Ca}_2(\text{Al,Fe}^{3+})_3\text{Si}_3\text{O}_{12}(\text{OH})$. Generally, the "epidotes" found on biotite are more iron-rich than the "clinozoisites" found on plagioclase. The $\text{Al}/(\text{Al} + \text{Fe})$ in the epidotes ranges from 0.86-0.68 while that in the clinozoisites varies between 0.99 and 0.79.

For all practical purposes, the composition of pyrite can be assumed as FeS_2 and titanite as CaTiSiO_5 . The calcite composition is given by the formula $\text{Ca}_{0.98}\text{Mg}_{0.01}\text{Fe}_{0.01}\text{CO}_3$.

3.2.4. Summary

The data presented here summarize documentation of the chemical, petrographic and modal variations in core samples from the canister drift of the SFT-C and will serve as a data base for comparison with post-test samples (Ryerson and Qualheim, 1983). On a thin-section scale ($3 \times 5 \text{ mm}$), significant variations in all of these properties are found. The variations result from both igneous processes and hydrothermal alteration localized along fractures.

Variations due to primary igneous processes include zonation in plagioclase and K-feldspar within a particular section. The range and frequency of feldspar compositions have been documented through the use of an automated step-scanning procedure on an electron microprobe. Modal variations exist primarily due to the presence or absence of quartz and K-feldspar phenocrysts.

Features due to hydrothermal alteration are highly variable both within a particular section as

well as between samples. Alteration zones (up to 2 cm wide) are localized along veins. The actual assemblages of secondary phases can be quite variable from sample to sample and from grain to grain of primary mineral phases. The compositions of some secondary phases (muscovite and epidote) can be shown to vary between different primary phase reaction sites, documenting gradients in chemical potentials of these components during hydrothermal alteration. The alteration assemblages also demonstrate that CO_2 , S, and H_2O were added to the rock during hydrothermal alteration. The source of CO_2 is presumably the decarbonation of the carbonate country rock during the emplacement of the stock.

3.3. Microfracture Analysis of Laboratory Irradiated Climax Core

We have undertaken an observational study to determine the cause of a possible weakening effect observed in Climax stock quartz monzonite following heavy dosages of gamma irradiation. The weakening effect was detected by Durham (1982) but has not yet been verified by additional testing nor, to our knowledge, has a similar phenomenon been observed in other silicate rocks. The observational study is based on scanning electron microscope (SEM) examination of polished sections of Climax core. For the study, ten identical test cores 63 mm long by 25 mm diameter were prepared for unconfined compressive loading. Prior to testing, five of the cores were given a gamma ray dosage of about 10 MGy from a ^{60}Co source over a nine-day period, approximately the same irradiation treatment given in the study by Durham (1982). All ten samples were then compressively loaded to 150 MPa (approximately 90% of the expected strength of irradiated samples) and held at that stress level for 60 seconds, then unloaded and prepared for SEM examination.

Microfractures in rocks stand out rather clearly in an SEM image and what we were hoping to observe was a difference in the crack structure between the two groups of test specimens. In order to be as quantitative and unbiased as reasonably possible, we used a crack measurement technique developed recently for measuring borehole wall damage induced by hammer drilling at the SFT-C (Weed and Durham, 1983). The results are shown broken down by sample in Table 3-3 and by irradiation treatment in Table 3-4.

The most notable characteristic of the crack data in Tables 3-3 and 3-4 is the scatter. There is no detectable correlation between the measured crack parameters (areal density and average length) and irradiation treatment in stressed rock. In fact, based on a series of measurements on a single section of unirradiated, unstressed rock (Table 3-4), we have only weakly detected an effect on crack structure induced by the loading treatment itself.

The results of the study are presented and discussed in greater detail in a forthcoming report (Beiriger and Durham, 1984). Our principal conclusions are as follows: (1) The crack structure of Climax granite is highly heterogeneous on the scale of laboratory sections (0.1 to 10 mm). The underlying cause may be that grain sizes in the rock are heterogeneous, ranging in scale from 0.1 to 100 mm. (2) Our microstructural measurements reveal no evidence that gamma irradiation lowers the compressive strength of the rock, although the resolution of the measurements is poor. (3) Improvements in the signal-to-noise ratio of the crack measurements in future experiments is not practical. Signal (i.e. damage) does not seem to be very sensitive to unconfined stress except within a few percent of the failure stress, making a target stress difficult to attain in a rock with such a large variance in its fracture strength. Noise can be decreased only by increasing the quantity of measured values.

Table 3-3 Crack statistics by sample.

Sample	Number of cracks counted	Areal number density (mm^{-2})	Average length (μm)	Areal length density (mm/mm^2)
2 (no γ)	18	85	52	4.41
	31 ^a	177	14	2.47
	38	120	30	3.59
	45	157	30	4.70
3 (γ)	66	206	14	2.79
	20	81	32	2.64
	23	109	36	3.98
4 (no γ)	48	171	15	2.54
	51	182	26	4.57
	22	90	41	3.66
5 (γ)	49	124	14	1.74
	22	75	33	2.46
	12	57	35	1.99
6 (no γ)	64	214	12	2.47
	15	71	44	3.12
	25	119	36	4.27
7 (γ)	62	158	13	2.07
	30	107	38	4.01
	49	175	28	4.89
8 (no γ)	45	117	15	1.78
	14	67	29	1.95
	24	114	34	3.88
9 (γ)	46	131	16	2.15
	47	167	23	3.78
	18	86	30	2.53
10 (no γ)	71	285	16	4.44
	35	125	33	4.06

^a Results are given for three independent traces across each sample, a middle scan and two outer scans. The second number of each group gives the statistics for the middle scan. A subtle difference in SEM operating conditions existed for the middle scan.

Table 3-4. Crack statistics by irradiation treatment.

Middle trace ^a					Outer traces ^b			
	Number counted	Areal density (mm^{-2})	Average length, $\bar{L}$ (μm)	$\bar{L}/\text{Area}$ (mm/mm^2)	Number counted	Areal density (mm^{-2})	$\bar{L}$ (μm)	$\bar{L}/\text{Area}$ (mm/mm^2)
no γ	223	149 ± 153^c	14 ± 12	2.11 ± 2.31	235	115 ± 105	32 ± 30	3.64 ± 3.42
γ	259	190 ± 178	14 ± 13	2.71 ± 2.64	273	113 ± 100	32 ± 33	3.61 ± 3.15
untreated, unstressed					54	91 ± 91	36 ± 47	3.24 ± 3.16

^a Corresponds to middle trace in Table 3-3.

^b Corresponds to outer traces in Table 3-3.

^c One standard deviation.

Chapter 4

Thermal Sources

Spent-fuel retrieval was accomplished during March-April 1983. Electrical simulators were de-energized during this time frame and the guard heaters were de-energized near the end of the retrieval period on March 30, 1983. Facility lighting became the only significant thermal source during post-retrieval cool-down of the SFT-C. Table 4-1 summarizes the schedule of spent-fuel retrieval and electrical simulator removal operations.

Total thermal energy input to the test array was 1041 MW·h through retrieval with an additional 19 MW·h added during the cool-down period. This total is the aggregate of four sources: the decay heat of 11 spent-fuel assemblies from a pressurized water reactor (PWR), 6 electrically heated simulators, 20 electrical guard heaters, and the facility lights. The partition of these thermal loads is summarized in Table 4-2 and is shown graphically as a function of time in Fig. 4-1.

4.1. Pressurized Water Reactor Fuel Assemblies

The thermal characteristics of the spent-fuel assemblies are essentially unchanged from last year. During the approximately four-month period between presenting data in the previous interim report (Patrick et al., 1983) and retrieval, the calculated average thermal output decreased from 680W to about 640W. Thermal output resulting from radioactive decay ranged from 1564W/assembly at the first emplacement at 2.412 YOC to 638W/assembly at the last retrieval at 5.372 YOC.

Boiling water calorimetry of spent-fuel assembly S/N D15 was performed July 28, 1983 (fuel age 5.687 YOC) at Westinghouse E-MAD facility. Data obtained from four consecutive condensate collection periods which agreed within $\pm 3\%$ indicated a decay heat generation rate of 625W. This

Table 4-1. Schedule of retrieval of spent-fuel and de-energizing of electrical simulators.

Date 1983	Spent-fuel retrieval		Electrical simulator de-energized emplacement hole
	Emplacement hole	Serial number	
3 March	CEH01	D-34	CEH17
7 March	CEH16	D-22	CEH02
9 March	—	—	CEH15 & CEH13
10 March	CEH03	D-40	—
11 March	—	—	CEH04 & CEH06
14 March	CEH05	D-46	—
16 March	CEH14	D-35	—
22 March	CEH12	D-15	—
24 March	CEH09	D-47	—
29 March	CEH07	D-09	—
31 March	CEH11	D-18	—
4 April	CEH08	D-16	—
6 April	CEH10	D-01	—

Table 4-2. Cumulative energy input to the SFT-C by source.

Source	Cumulative energy through retrieval		Cumulative energy through cool-down	
	MW·h	% of total	MW·h	% of total
PWR fuel assemblies (11)	263.4	25.3	263.4	24.8
Electrical simulators (6)	148.0	14.2	148.0	14.0
Guard heaters (20)	600.6	57.7	600.6	56.7
Facility lights	29.0	2.8	48.0	4.5
Totals	1041.0	100.0	1060.0	100.0

Figure 4-1. Cumulative thermal energy input by source.

rate agrees within 3% of the 609W decay heat generation rate which was calculated with the ORIGEN II code (Schmittroth et al., 1980) and was utilized as input to all SFT-C thermal and thermo-mechanical calculations. The calculated average spent-fuel decay curve, adjusted for all calorimeter results except this most recent minor difference, is shown in Fig. 4-2.

4.2. Electrical Simulators

The electrical simulators, located in alternate boreholes on each end of the spent-fuel array, operated reliably throughout the final months of the test. Figures 4-2 and 4-3 show the simulator power levels in relation to the calculated average spent-fuel decay power curve. The former figure depicts the stair-step function to which the electrical simulator controllers were set. The latter figure shows actual ten-day-average power levels for each of the six simulators. With minor exceptions, the simulators have closely tracked the spent-fuel de-

cay curve. The marked improvement in agreement between simulator and spent-fuel power levels after 3.1 YOC reflects adjustment of the original calculated curve for calorimeter results and a commensurate adjustment in simulator power levels.

A set of loop controllers with power-sensing feedback was installed to provide better control of simulator power. We indicated last year (Patrick et al., 1983), with data from only a week of operation, that these controllers were substantially reducing variations in simulator power. The data beyond 5.0 YOC in Fig. 4-3 confirms the marked reduction in variability achieved with the new controllers.

4.3. Guard Heaters

The 20 guard heaters functioned reliably through the end of the heated phase of experimentation. No heaters failed or exhibited erratic

Figure 4-2. PWR fuel assembly and electrical simulator power history.

performance. Inspection of the heaters following their extraction at the end of the test revealed no corrosion of the resistive heating elements. One unit, which was in a hole intersected by a water-bearing fracture, was lightly coated with carbonate minerals but there was no evidence of degradation of heater performance.

To produce the desired simulation of a large panel of a full-scale repository, the guard heater power levels were periodically adjusted upward while the spent-fuel decayed with time. The result was that well over half the total energy input to the facility was provided by the guard heaters.

4.4. Facility Lights

Facility lights represent a major component of the facility power requirement but since they are utilized relatively little (during routine test operations and tours), their cumulative energy contribution was only 29 MW·h or 2.8% of the total during the approximately three-year spent-fuel storage phase of the test. In the six months following retrieval, post-test sampling and characterization activities required nearly continuous access to the subsurface; increasing the cumulative energy input from the lights by 19 MW·h. This is a 65% increase over the previous three years.

Figure 4-3. Electrical simulator power history showing effect of loop controller addition at 5.0 YOC.

Chapter 5

Data Acquisition System

The Spent Fuel Test—Climax Data Acquisition System (SFT-C DAS) has been specified and documented in Nyholm, Brough, and Rector (1982) and Nyholm (1983). In addition, the DAS has been reported on in the ongoing series of project interim reports (Carlson et al., 1980, Patrick et al., 1982, and Patrick et al., 1983). The purpose of this section is to further report on the operation of the DAS, and to note modifications to its configuration through September 30, 1983

5.1. System Configuration and Operation

The SFT-C DAS hardware configuration, as illustrated in Fig. 5-1, has remained unchanged during the past year of operation. Leased line telecommunications service (provided by Bell Telephone Co.) to the CP-40 Remote Terminal Station was discontinued in May, 1983. This alarm reporting station was only required to operate while spent-fuel was stored at the experiment site.

Routine data acquisition on all but the system status monitors and system standard references was terminated on September 30, 1983 (5.862 YOC). The remaining data channels will continue to be scanned until all post-test instrumentation calibrations are performed, at which time the DAS is scheduled to be decommissioned.

5.2. Performance

5.2.1. Measurement Accuracy

In past reports we have stated that although the DAS is capable of making measurements over a broad range of scales, its scientific data most heavily depends on dc voltage readings in the millivolt range and on four-wire resistance readings in the 125- Ω range. To assure long-term measurement accuracy, the digital voltmeters (DVMs) are recalibrated every 90 days and are operated at $\sim 23^{\circ}\text{C}$. In addition, several system standard references are measured periodically. These include a precision millivolt source (channels SSR002 and SSR005), two nominally 120- Ω precision resistances (channels SSR003 and SSR006), and several temperature references (channels SSR007, SSR008, RTD200, TRT011, TRT012, and TRT013). The millivolt source is accurate to 1 μV ; the resistance standards are stable to 0.00018 Ω .

Figure 5-2 illustrates the results obtained from the dc voltage and four-wire resistance references. The readings provided by the DVMs are guaranteed to 1 μV and 0.0042 Ω with 90-day drifts not to exceed 4 μV and 0.005 Ω , respectively. Resolutions are specified at 1 μV and 0.001 Ω . Examination of those $\sim 30,000$ data points/channel collected from 2.7 to 5.862 YOC show that the voltage source is always measured in the envelope 0.996 to 1.004 mV. Minor perturbations are observed, as expected, when DVMs are exchanged for calibration, as indicated by the upward arrows. The four-wire resistance measurements should be stable to $\pm 0.0092 \Omega$. However, several periods of out-of-limits readings are evident and have been previously reported (Patrick et al., 1983). Variations in four-wire resistance references continue to be an early indicator of potential hardware malfunction and are therefore carefully scrutinized on a daily basis.

5.2.2. System Reliability

The SFT-C DAS has now been operational for more than four years and has proven to perform above the operational specification set forth by Hewlett-Packard. That specification called for a single-point mean-time-between-failure (MTBF) of 30 days, and downtime of 2 to 4 days. The relatively long downtime estimate is a function of both the remote siting of the experiment and the availability of qualified service personnel. These figures translate to an average "functionally disabled index" (FDI) of approximately 7%, where the FDI (Nyholm, Brough, and Rector, 1982) is a measure of the likelihood that data cannot be properly recorded and archived on schedule by the DAS as designed. Thus, one node or the other should be capable of acquiring data 93% of the time. In the past we have suggested the reader bear in mind that miscellaneous factors that inflate the FDI must also be considered if a true estimate of the FDI is to be made. These include:

- Installation and development of software updates.
- Fuel handling operations—data channels of significant interest are scanned rapidly; others may be turned off.
- Hardware maintenance and/or calibration.
- Instrumentation maintenance and/or calibration.
- Cartridge disc unit backup to digital magnetic tape.

Figure 5-1. SFT-DAS hardware configuration.

Figure 5-2. SFT-DAS system standard references. Note: up arrows indicate DVM exchanges.

- Software failure.
- Computer overburden.

Taken collectively, these factors should account for approximately two additional FDI points, bringing the total FDI to about 9% per computer system.

Figure 5-3 illustrates observed monthly FDIs for the interval May 1, 1980 through September 30, 1983. The upper plot specifies the likelihood that a scheduled data point was not recorded and archived via the front-end data acquisition hardware normally connected to computer node 100 (Fig. 5-1). Similarly, the middle plot reports identical information for data points collected via the acquisition hardware normally connected to computer node 200. The bottom plot presents the likelihood that neither computer node was able to

collect a scheduled data point; i.e., both computer nodes were disabled concurrently.

To date, the average observed FDI (41 consecutive months) for node 100, node 200, and the DAS is 14.98%, 8.79%, and 4.06%, respectively. Recording outages through November 1982 have been previously reported and have been basically attributed to software difficulties and a variety of hardware failures. The vast majority of software cures were in place by May 1981. The last was resolved on March 26, 1982. Since November 1982, principal system failures have been attributed to faulty disc drives, notably on node 200. Telecommunications links continue to be a source of irritation but are not responsible for loss of data.

Figure 5-3. SFT-DAS front-end data acquisition hardware monthly FDI.

Chapter 6

Heat Transfer Measurements

6.1. Measurement System Reliability and Post-Test Calibrations

The thermocouple instruments along with their reference resistance temperature devices (RTD) have maintained the highest integrity of all instruments deployed on the SFT-C. As Figs. 6-1 through 6-4 demonstrate, total system accuracy was within the design criteria and the ISA standards of error of $\pm 1.1^{\circ}\text{C}$, in pre-test and post-test calibrations. As previously reported (Patrick et al., 1983), interim calibrations conducted during spent-fuel exchange periods provided confidence in the system integrity. Periodic resistance checks on six-month intervals further increased our confidence. A total of 303 thermocouples have been post-test calibrated. These represent 18 thermocouples located in each of the 17 emplacement holes, excluding three thermocouples which were destroyed during handling procedures. Preliminary resistance measurements had not indicated an integrity problem with these three thermocouples prior to calibration. Subsequent metallurgy tests revealed that one thermocouple was Inconel 600, the other two were 304-series stainless steel. Inspection of thermocouples during calibration procedures has not indicated further corrosion problems.

6.2. Comparison of Data with Calculational Results

Comparisons between measured and TRUMP-calculated temperatures have been very good throughout the spent-fuel storage phase of the SFT-C. Pretest calculational results agreed with measurements within a few degrees Celsius (Patrick et al., 1982) and revisions to these calculations produced even better agreement in the near-

field environment (Patrick et al., 1983). As indicated in Fig. 6-5, the near-field temperature histories closely followed the calculational values near the axial midplane of the spent-fuel assemblies. Somewhat larger discrepancies were reported at the top and bottom of these thermal sources. Good agreement was not confined to the near-field environment as can be seen in the cross section of the temperature field depicted in Fig. 6-6.

The level of agreement during the post-retrieval cool-down phase of the test was not as good. Examining the temperature regime at the axial midplane of the center spent-fuel assembly, we observe discrepancies of 4 to 5°C at the end of the six-month post-retrieval cool-down period (Fig. 6-7). Data obtained throughout the test array reveal the same trend: calculated temperatures are consistently 1 to 5°C higher than measured except at locations far from the underground openings (Figs. 6-8 and 6-9). This trend implies that the calculation is not removing sufficient energy through the various heat transfer processes; in particular through the ventilation airstream.

Since the acquisition of cool-down data has just been completed, revisions of calculations are premature. Revised calculational models, together with temperature measurements, will be the subject of a future topical report. We have already identified several aspects of the calculational model which need to be re-examined. These include:

- Heat removal in the ventilation airstream.
- Convective processes in the canister-scale environment.
- Differences in end effects resulting from a calculation which models the finite-length SFT-C as an infinitely long array.
- Variations in initial thermal conditions, power levels, etc., measured during the SFT-C which were not available for pretest calculations.

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

Figure 6-1. Thermocouple calibration results at 0°C.

Figure 6-2. Thermocouple calibration results at 50°C.

Figure 6-3. Thermocouple calibration results at 100°C.

Figure 6-4. Thermocouple calibration results at 150°C.

Figure 6-5. Calculated and measured temperature histories at various radial locations at axial midplane of CEH09 (revised calculation).

Figure 6-7. Calculated and measured temperature histories throughout the heating and cooling phases of the SFT-C. Temperatures at various radial locations at the axial midplane of CEH09.

Figure 6-8. Comparison of measured temperatures with TRUMP-calculated temperature contours at a fuel age of 5.51 YOC (approximately 2 months into the cooling phase) at Station 2+83 (first solid contour at 30°C, contour interval 2°C).

Chapter 7

Ventilation System Measurements

7.1. Instrumentation

The ventilation system has continued to operate reliably with only periodic preventative maintenance. The flow straightener immediately upstream from the insertion turbine flowmeter was checked periodically during fuel exchange and retrieval times. Pieces of the graphite shim used as gasketing material on the spent-fuel canister shield block would at times be sucked into the ventilation takeoff box during operations, necessitating the cleaning of the flow straightener. Figure 7-1 displays the ventilation rates for the test duration. Activities which introduced significant changes in the flowrate are noted.

The dewpoint sensors have operated continuously throughout the test. Visual inspections as well as data checks confirmed their integrity. Figures 7-2a and 7-2b present dewpoint temperature data as collected for the test duration. Specific activities affecting dewpoint temperatures have been highlighted.

After the fuel was retrieved in March-April 1983, the ventilation rates were increased to promote rapid cooling of the experimental area. Ventilation ducts were extended to the far end of each heater drift and a Sutorbilt blower system on the surface was energized to increase the nominal flowrate by 80%. Additional instrumentation was required to monitor these additional flow paths. The long straight ventilation ducts in the heater drifts provided ideal conditions for insertion flowmeters. Dewpoint sensors and thermocouples at each exhaust point completed the instrumentation package.

7.2. Ventilation Measurements

The energy inputs to the test array are discussed in detail in Chapter 4. The principal mechanism for removal of energy is heat transfer in the ventilation airstream.

Figure 7-3 displays ten-day average input and output power levels for the duration of the storage and cool-down phases of the SFT-C. Significant changes in input and output power are annotated on the figure. Following spent-fuel retrieval, the input power resulted solely from facility lighting and therefore decreased to where power output typically exceeded power input. This condition is clearly evident in Figure 7-4 which shows the ratio of output to input power.

Energy removed in the ventilation airstream is of two types: sensible heat and latent heat of vaporization. The former is the energy associated with increasing the temperature of air at a constant water content while the latter is the energy associated with vaporizing water and adding it to the airstream. Figure 7-5 displays the history of energy removal by type. About 76.7% of the energy is associated with sensible heat while 23.3% is associated with heat of vaporization, through completion of retrieval operations. The sensible heat fraction increased to an average of about 78.2% during the post-retrieval period. Figure 7-6 shows the difference between the sensible heat and total heat curves shown in the previous figure. The change in character of the curves (Figs. 7-5 and 7-6) beyond 5.4 YOC is a direct result of increased sensible heat contribution through increased utilization of areal lighting. Increased drilling activities, which conceptually would increase the availability of water for vaporization into the airstream, did not appear to increase the latent heat contribution.

Figure 7-1. Ventilation flowrates.

Figure 7-2a. Inlet air dewpoint temperature.

Figure 7-2b. Outlet air dewpoint temperature.

Figure 7-3. Power input and removal history annotated for significant events.

Figure 7-4. Comparison of calculated and actual percentage of input energy removed by ventilation.

Figure 7-5. Cumulative thermal energy removed by ventilation.

Figure 7-6. History of cumulative thermal energy removed by vaporization of water.

Chapter 8

Radiation Measurements

8.1. Radiation Dose to Granite

Several problems have resulted in the need to reassess the techniques used in calibration and correction for thermal effects on the SFT-C dosimeters (Quam and Devore, 1982 and Quam et al., 1982). Specific problems being addressed are the effects of heat on the dosimeters, the influence of the dosimeter holder (whether stainless steel or aluminum) on calibration data, and the role of a defective electronic barometer utilized at the calibration facility on variability in the data set.

To address these problems the subcontractor, EG&G-Santa Barbara Operations, repeated the dosimeter calibrations this year at the Sandia gamma irradiation facility. Corrections to all previously acquired and reported data are in progress and will be presented in a forthcoming topical report.

The final sets of dosimetry data were obtained during spent-fuel retrieval in March-April 1983. The seven sets of LiF dosimeters were extracted and returned for reading at that time. In addition, a second set of short-term dosimetry data was obtained to further our understanding of temperature effects on the standard long-term dosimeters. These data will also be presented in the report mentioned above.

8.2. Reliability and Availability of RAM/CAM System

Monthly system checks, using the instrument internal calibration feature, have demonstrated a trouble-free system.

The RAM/CAM (remote area monitor/continuous air monitor) system was recalibrated in the time period from 7 February 1983 to 16 February 1983. The low level RAMS were calibrated with a ^{60}Co source positioned to provide intensities ranging from 1 to 1000 mr/hr. All high level units were calibrated with a 200 Ci ^{137}Cs source. The CAM systems were calibrated with a ^{90}Sr source. Table 8-1 reflects the changes in the "K" transfer function used by the data acquisition system in conversions to engineering units.

8.3. Summary of Personnel Radiation Exposures

Radiological monitoring and personnel dosimetry have been an ongoing part of the SFT-C. The radiological safety program utilized personnel and area dosimeters, bioassays, continuous monitoring with RAMs and CAMs, routine surveys with portable instruments, swipes, and sampling of air, soil, rock, water, and appropriate test hardware.

Maximum occupational exposure data obtained during spent-fuel emplacement, storage, and retrieval operations are shown in Table 8-2 (Raschke et al., 1983). These data are normalized to an "operation" involving the emplacement or retrieval of a single spent-fuel assembly. The reduction in exposure during retrieval is due partially to a factor of two decay in the source term and an apparent reduction in exposure time by an additional factor of two or more.

Figure 8-1 expands on the tabulated maximum exposure data by providing the distribution of gamma and neutron exposures during the retrieval operation. The two relatively high exposures were received by the health and safety officer and the operations coordinator whose roles in the retrieval resulted in their being nearer the shielded spent-fuel for longer periods of time than most of the crew.

Radiation exposures for the duration of SFT-C were less than 0.4 person-Rem or, on average, less than 0.016 person-Rem/operation (Raschke et al., 1983).

8.4. Radon-Thoron Measurements

Radon-thoron concentrations in the subsurface areas of the SFT-C were monitored to insure that no health hazards resulted from this natural source of radiation. The measurements indicate a gradual increase from 1×10^{-10} Ci/m³ to about 6×10^{-10} Ci/m³ as the rock mass was heated.

These data, obtained at a nominal ventilation flowrate of 1.3 m³/s through the canister drift, were augmented by measurements during a ventilation effects test in which flowrates were varied

Table 8-1. Calibration factors for RAM and CAM units.

Instr.	"K" value	Old "K" value	Instr.	"K" value	Old "K" value
^a RAM 001	2.04	2.19	CAM 101	2.45	2.48
RAM 002	2.36	2.29	CAM 201	2.51	2.53
RAM 003	2.49	2.38	CAM 102	2.56	2.55
^a RAM 004	2.03	2.30	CAM 202	2.43	2.49
^a RAM 005	2.12	2.18	CAM 103	2.51	2.53
RAM 006	2.23	2.29	CAM 203	2.49	2.46
RAM 007	2.26	2.25	CAM 104	2.48	2.48
RAM 008	2.03	2.00	CAM 204	2.49	2.49
^b RAM 009	2.00	2.00	CAM 105	2.46	2.46
RAM 010	2.22	2.21	CAM 205	2.45	2.46
RAM 011	2.13	2.17	CAM 106	2.52	2.52
^c RAM 012	2.00	2.00	CAM 206	2.42	2.42
^d RAM 013	2.00	2.00	CAM 007	2.23	2.23
RAM-SPARE	2.00	—	CAM 008	1.96	2.03

^a RAM units adjusted to give correct response.

^b High level RAM, voltage not measured. Switched to headframe on 2-15-83.

^c High level RAM, voltage not measured. Switched to access hole on 2-15-83.

^d High level RAM, voltage not measured.

from 0 to 3.2 m³/s (Raschke et al., 1983). There was a definite trend to decreasing radon-thoron concentration with increasing ventilation flowrate up to 1.3 m³/s (Fig. 8-2). An additional measurement at 3.2 m³/s indicated a radon-thoron concentration of 6×10^{-10} Ci/m³ whereas the expected value from this linear relationship would be about 10^{-11} Ci/m³. This suggests that a threshold concentration exists at flowrates in excess of about 1.0 to 1.5 m³/s. Hypothetically, such a threshold could result when the flow was such that the increased emanation of radon, which is enhanced by the negative-pressure ventilation, is balanced by the increased volumetric dilution of the radon. It is important to note that the peak radon-thoron concentrations, which occurred during a 12-day period of no ventilation, were 75% of one maximum permissible concentration (1×10^{-8} Ci/m³ for nonradiation workers).

Table 8-2. Maximum personnel doses associated with spent-fuel handling operations.^a

Handling operation	Dose, mRem/Operation	
	Gamma ^b	Neutron ^b
Fuel emplacement	2	8
Fuel storage	0	— ^c
Fuel retrieval	0.1	2

^a Natural background levels have been subtracted from these values. An "operation" is the emplacement or retrieval of a single spent-fuel assembly.

^b Neutron exposures were measured with albedo dosimeters, personnel gamma exposures were estimated from measured neutron/gamma ratios since no gamma exposure exceeded the 30 mR threshold of the film badges.

^c Not measured.

Figure 8-1. SFT-C personnel dose distribution during spent fuel retrieval.

Figure 8-2. Radon-thoron concentration versus ventilation flowrate.

Chapter 9

Displacement Measurements

This chapter presents the status and interpretation of rock displacement measurements at the Spent Fuel Test-Climax (SFT-C). The chapter is divided into four sections dealing with, in the following order:

- Tunnel closures as measured by tape extensometers.
- Relative displacement measurements made with the rod extensometers.
- Calculations of canister emplacement-hole deformation following removal of the spent-fuel.
- The Whittemore gauge crack aperture measurements.

The measurements and calculational results reported here include results from the three-year heating phase as well as a six-month cooling phase which followed the retrieval of spent fuel and the de-energizing of electrical heat sources.

The types of instruments and locations are given by Brough and Patrick (1982) and Carlson et al. (1980). The relationship of instrument location to the geology of the Climax site were presented in Patrick et al. (1982).

9.1. Drift Deformations

Vertical and horizontal drift deformation was monitored at numerous locations in the spent-fuel drift and both the north and south heater drifts. Although measurements were made with different types of instrumentation, only those obtained manually with tape extensometers are available for comparison with calculations at this time. Similar comparisons for earlier time periods were made in the interim report for FY 1982 (Patrick et al., 1983) and are also reported by Yow and Butkovich (1982). Additional data were obtained during the remaining months of the heating phase and during the cooling phase. The latter results are compared with the cooldown calculational results (Ballou et al., 1982). As before, data from various locations along the drifts were averaged to use for comparison with the calculations.

For calculational purposes, the first day of the test was considered to be May 7, 1980, the day the centrally located spent-fuel canister was installed. The first tape extensometer measurement was made on June 26, 1980, some 6 weeks after the start of the test. Consequently the data are com-

pared with calculations assuming that measurements and calculations agree on the day of the first measurements. As before, the calculation used for comparison assumed isotropic thermoelastic rock response with a deformation modulus of 27 GPa throughout the entire mesh.

Figures 9-1 and 9-2 show the averaged tape extensometer data compared with calculation for canister drift horizontal and vertical closures respectively. The measurements are shown as solid lines and the calculational results are point by point results for each cycle in the calculation. Note the effect of the removal of the spent-fuel at 3.0 years after the start of the test. Similar effects are not visible from the data since the variability from measurement to measurement far exceeds the small changes which were calculated to occur following removal of the spent-fuel. Figures 9-3 and 9-4 show a similar comparison for the north and south heater drifts respectively. For these locations no data were taken during the cool-down period because the instruments were removed to facilitate drilling activities. Measurements in the heater drifts and the spent-fuel storage drifts display an unexplainable large percentage change in closure around 2.5 years which returns to the original trends at about 2.8 years (Patrick et al., 1983).

In general the agreement between calculation and measurements is quite good. With the exception noted above, the trends of data and calculation are similar. Where data indicate closure continuing for the entire measurement period, calculations agree. Where data indicate closure followed by a reversal as for the vertical closure of the spent-fuel drift, calculations agree in form.

9.2. Deformations Within the Rock Mass

Relative displacements from the thermal loads were measured with multiposition rod extensometers between hole collars and anchor points in holes drilled from the north and south heater drifts. The instruments were emplaced in horizontal holes and in holes inclined at 34° and 50° upward from horizontal (Brough and Patrick, 1982). Temperatures were monitored with thermocouples emplaced near each anchor point and on the extensometer head assembly. Temperature corrections to the measurement for each anchor

Figure 9-1. Measured and calculated horizontal convergence of the canister storage drift.

Figure 9-2. Measured and calculated vertical convergence of the canister storage drift.

Figure 9-3. Measured and calculated horizontal and vertical convergence of the north heater drift.

Figure 9-4. Measured and calculated horizontal and vertical convergence of the south heater drift.

point were necessary to account for the thermal expansion of the rods.

Calculations of the thermomechanical response of the facility to heating and subsequent cooling used in this comparison incorporate a 0.5 m explosively damaged zone around each opening with a reduced deformation modulus of 13 GPa. Nodal-point displacement vectors are calculated along each extensometer line and are presented as relative displacements between the extensometer head assembly and various positions along the rod extensometers. An examination of the calculational results shows that the displacements for each rod extensometer orientation continue to increase with time during the heating phase to 3 years (Fig. 9-5). Most of the deformations occur within the first 0.25 years and, thus, are not included in Figs. 9-6 through 9-8 which are indexed to 0.5 years into the test. For the cooldown period, the trend of increasing displacement reverses, as expected, and displacements which occurred during the previous two years of heating are largely recovered.

As with the measurements of drift closure, measurements of relative displacement were not started until after spent-fuel emplacement. Displacement measurements are therefore compared with calculated values beginning about 0.5 years since start of test (3.0 YOC). Temperature corrections to the data were made with hand calculations. These calculations show the temperature correction to be from two to several times greater than the indicated instrument readings. This is because the thermal expansion coefficients of the rock and the carbon steel rods of these instruments are very similar over the temperature range of interest, i.e., rods = $11.7 \times 10^{-6}/^{\circ}\text{C}$ vs rock = $10.0 \times 10^{-6}/^{\circ}\text{C}$. As a result, temperature changes induce rod expansion and rock displacements of about the same magnitude, resulting in very small net displacements at the extensometer head assemblies.

Comparisons between calculational results and temperature-corrected displacements, measured relative to the hole collars, were reported previously (Patrick et al., 1983). It was recently discovered that the sign of the instrument readings was omitted from the computer printout used in earlier analyses; necessitating reevaluation of these heated-phase results. Results of these corrections and detailed comparisons between calculated and measured displacements will be reported at a later date.

Figure 9-5 shows the calculated changes in relative displacement since 0.5 years since start of

test (2.96 YOC), for each rod extensometer orientation. Figures 9-6, 9-7, and 9-8 show the temperature corrected changes in relative displacements for each of two locations along the drifts where rod extensometer instrumentation was emplaced. These stations are designated as 2+83 and 3+45.

Figures 9-9 and 9-10 show comparisons of calculational results and temperature corrected relative displacement measurements for each anchor during the period 0.5 years since start of test and 0.5 years into cooldown (2.96 and 5.85 YOC, respectively). The calculational values were interpolated from straight line segments between points shown in Fig. 9-5. Although the calculational values have decreased, the measured results have decreased significantly more, resulting in net negative displacements (relative to 0.5 years into the heating phase). As discussed in Chapter 6 and as shown in Figs. 6-8 and 6-9, the actual temperatures are significantly lower than those calculated. This temperature difference qualitatively explains the observed differences between measured and calculated displacements during the cooling phase of the test.

9.3. Canister Emplacement Hole Deformation

Prior to the removal of the spent fuel, consideration was given to measuring thermomechanical response of a spent-fuel canister emplacement hole during the cool-down phase, where the rock immediately adjacent to the heat sources had been subjected to the greatest temperature changes and consequent relatively large displacements. In this way it was suggested that we could learn about motion in a plane perpendicular to the canister axis, whether the motion is due to thermoelastic behavior, or whether the presence of discontinuities, strain relief, and time-dependent properties have a significant role. Thermoelastic calculations were therefore performed and instrument design and fabrication were undertaken.

An analytic calculation using the solution for displacement of a hollow cylinder with a temperature distribution as a function of radius was initially used to estimate the magnitude of the expected motion. This showed that for the expected temperature change between removal of the spent fuel and 0.5 years later, the diameter of the 0.61 m diameter hole would change by 0.084 mm. Strain-gauged proving rings were designed to provide

Figure 9-5. Calculated displacements at selected distances along rod extensometers. Displacements are referenced to the extensometer head assembly with a start time of 0.5 years after spent fuel emplacement (2.96 YOC).

Figure 9-6. Displacements at various rod extensometer anchor points measured relative to the extensometer head assembly. Measurements were obtained at two stations in each of two drifts with horizontally oriented extensometers. Start was 0.5 years after spent fuel emplacement (2.96 YOC).

Figure 9-7. Displacements at various rod extensometer anchor points measured relative to the extensometer head assembly. Measurements were obtained at two stations in each of two drifts with 34° upwardly inclined extensometers. Start was 0.5 years after spent fuel emplacement (2.96 YOC).

Figure 9-8. Displacements at various rod extensometer anchor points measured relative to the extensometer head assembly. Measurements were obtained at two stations in each of two drifts with 50° upwardly inclined extensometers. Start was 0.5 years after spent fuel emplacement (2.96 YOC).

Figure 9-9. Comparison of measured (upper numbers) and calculated (lower numbers) relative displacements at Station 2+83. Time interval is 0.5 years since start of test (2.96 YOC) to 0.5 years into the cooling period. Displacements given in mm.

Figure 9-10. Comparison of measured (upper numbers) and calculated (lower numbers) relative displacements at Station 3+45. Time interval is 0.5 years since start of test (2.96 YOC) to 0.5 years into the cooling period. Displacements given in mm.

the necessary precision. These were installed in two emplacement holes immediately after removal of spent-fuel canisters and associated emplacement-hole liners.

A two dimensional thermoelastic finite element calculation was made using ADINA to refine the results of the analytic solution. Figure 9-11 shows the finite element mesh along with the boundary conditions used. Because of the symmetry about the hole, only 1/4 of the canister hole was modeled. The nodal temperature histories used to drive the calculation were obtained from a three-dimensional TRUMP code calculation. Temperature-time results for a horizontal plane through the center canister emplacement hole were interpolated to obtain the nodal temperatures at the proper space coordinates for use in the ADINA displacement and stress-analysis calculation. Figure 9-12 shows the calculated diameter changes vs time for three different orientations: normal, at 45°, and parallel to the tunnel axis. Note that most of the changes occur immediately following removal of the spent fuel canister. The hole initially closes and then begins to expand again, decreasing the total closure but not changing the net direction of the total. It should be noted that the maximum diameter change is quite similar to the result obtained with the analytic calculation: 0.065 mm vs 0.084 mm, respectively.

Data on hole closures have recently become available and a preliminary analysis has begun. Results will be presented in a future report.

9.4. Whittemore Gauge Crack Aperture Measurements

Movements of selected discrete fractures at different locations in the concrete floor of the can-

ister drift are being monitored with Whittemore gauges. In the time span since these fractures were first observed, extension of the fractures continued until cracks originating at adjacent holes intersected. The cracking continued after the original features coalesced, and the cracking pattern changed from a radial one to a roughly rectangular one in the region of the floor between the emplacement holes.

Figure 9-13 shows the change in aperture of a typical crack in the floor of the canister drift, as measured by a Whittemore gauge. Positive displacements represent crack opening and negative displacements represent closure. The nature of the cracking and the "seesaw" effect seen in the plot have been discussed previously (Patrick et al., 1983). The plot shows crack closure at about 5.3 to 5.4 YOC followed by a slight reopening of the crack. This corresponds to retrieval of the spent-fuel and commencement of the cool-down phase of the test. Crack behavior after 5.3 YOC appears to be a result of cooling of the rock beneath the floor. Crack closure occurred until cooling of the surface of the floor began to dominate the behavior of the concrete, at which time the cracks began to open as the immediate floor surface cooled. At four of six measurement stations the magnitude of crack closure at the initiation of rock cooling is comparable with the closure at 3.6 YOC, when ventilation rate experiments were in progress. During the ventilation experiments, by comparison, reductions in ventilation rates caused an apparent increase in floor surface temperature, and crack closure was reversed when full ventilation was resumed.

Figure 9-11. Stress boundary conditions for calculation of canister emplacement borehole displacements.

Figure 9-12. Calculated changes in diameter as a function of time at three orientations for 0.61-m diameter canister emplacement holes.

Figure 9-13. Typical change in fracture aperture as recorded by a Whittemore gauge at station WAF1415 on the concrete floor of the canister drift.

Chapter 10

Acoustic Emission and Wave Propagation Monitoring

This experiment was conducted as part of the SFT-C to determine if acoustic emission (AE) and wave-propagation monitoring could, in concept, provide a reliable means for assessing changes in conditions, such as rock stability and permeability, in and around a nuclear waste repository. The results and conclusions of over 3-1/2 years of continuous monitoring of acoustic emission and wave propagation characteristics are summarized here. A detailed description of the instrumentation and experimental procedures are provided elsewhere (Majer et al., 1981 and 1982, Patrick et al., 1982).

10.1. Summary Results of Acoustic Emission Monitoring

Continuous monitoring of AE activity began about three months before spent-fuel emplacement, was conducted throughout the three-year storage phase of the SFT-C, and was completed about five months subsequent to spent-fuel retrieval. The locations of seismic events are shown in relation to the thermal sources deployed at the SFT-C in Figs. 10-1 and 10-2. Locations were calculated using raw data acquired by the automatic seismic processor (ASP) in conjunction with calibration data obtained by recording the signals resulting from hammer blows at known locations. This technique resulted in determination of locations to within ± 0.5 m.

Although the clustering of events near the canister emplacement holes was expected, the spatial segregation of AE activity in plan view is striking. Despite a uniform distribution of AE sensors, nearly all events are located in the southeastern region of the test array. Geologic structural data reported by Wilder and Yow (1981) provides a possible reason for this segregation. All events reported here are located to the south of an NE-SW trending fault which passes between canister emplacement holes (CEH) 5 and 6. In addition, nearly all events are east of a NE-SW trending shear zone which passes through CEH9 (the center hole). It appears that although the thermal load is relatively uniform throughout the test array, stresses and/or strength (which govern rock failure and hence AE) are not uniform. Stress differences under uniform loading conditions could

be the direct result of differences in rock mass deformation moduli whereas strength differences may be the result of spatially varying fracture intensities and orientations, both of which may be related to the fault or shear zones, particularly ones oriented N55°E. Insufficient data are available to conclude whether or not variations in moduli and strength may be the cause of the observed anomaly in AE activity.

The time-varying nature of AE activity is clearly shown in Fig. 10-3. Several peaks of activity superposed on a background of two to three events per week are evident. The major peaks at the beginning and end of the storage phase of the test demonstrate the sensitivity of the monitoring technique to rapid changes in thermal stresses induced in the rock. The three short-duration peaks which occur late in 1980, 1981, and 1982 are the direct result of rapid thermal transients resulting from an increase or decrease in the thermal output of heaters.

Two distinct types of events were recorded during this study (Majer et al., 1982). Type 1 events had characteristics similar to what one would observe in a microearthquake: clear P- and S-wave arrivals, impulsive onsets, and near unity b-values. Type 2 events occurred in "swarms" with quite different characteristics: poorly defined S-wave, emergent onset of the P-wave, and with a restricted range of magnitudes. Although attenuation could be expected to produce similar differences in characteristics, this does not appear to be the case here. Comparing Type 1 and Type 2 events with similar travel path lengths, the latter are generally of greater magnitude and lower frequency content than the former.

It is interesting to note that although laboratory research (Yong and Wang, 1980) indicates that AE activity does not begin until about 70°C, we observed significant activity at lower temperatures. We hypothesize that the incremental thermal stress superposed on tectonic and excavation-induced stresses was sufficient to produce AE at lower temperatures. An additional contributing factor is the existence of macroscopic fractures in the rock mass which were absent in the laboratory specimens. Majer et al. (1982) have previously reported that the AE events appear to cluster on or near such geologic features.

Figure 10-1. Plan view of acoustic-emission instrumentation locations and zones of principal seismic activity.

Figure 10-2. Cross-sectional view of acoustic-emission instrumentation locations and zones of principal seismic activity.

Figure 10-3. AE activity and temperatures from January 1980 through July 1983.

10.2. Summary Results of Wave Propagation Studies

Wave propagation studies were initiated about six months following spent-fuel emplacement. A piezoelectric crystal installed in the bottom of AE13 and pulsed with a 1.6 kV, 3 microsecond rise-time power supply provided the source for monitoring amplitudes and arrival times at AE sensors throughout the test array. Because of concern for possible recording and source-receiver coupling variations, P-wave amplitude data are reported relative to data received at AE19. It is important to note in the following discussion that it was not possible to locate the path between AE13 and AE19 outside the thermally effected zone. Therefore ratios of the data may cancel out thermal effects on P-wave amplitude which might otherwise have been observed.

Examining Figs. 10-4a through 10-4c, we detect no discernable trend in P-wave amplitude relative to the P-wave amplitude at AE19. As observed above, this is very likely the result of experiment bias. The S- to P-wave amplitude ratios shown in the same figures display a definite increasing trend during the early phases of the test, followed by a broad, somewhat erratic plateau, and ending in a slight downturn. This trend in S/P amplitude ratio approximates the temperature trend in the central region of the SFT-C. Only minor variations in S/P amplitude ratio are observed at AE19, probably because the path between AE19 and the source in AE13 is much shorter than the other paths. It is interesting that although the trend of S/P amplitude ratios follows that of temperatures, the S/P ratio at the end of the test is definitely greater than at the beginning of the test. This difference remains although temperatures are only slightly (10 to 15°C) above ambient; indicating a more or less permanent change in the wave-propagation characteristics of the rock mass in the vicinity of the SFT-C.

In addition to these amplitude data, arrival times were also recorded. Based on a digitizing rate of 100,000 samples/second or 10 microseconds and a maximum travel time of 3 milliseconds, we were able to resolve velocity changes to better than 1%. No changes in P- or S-wave velocities were recorded throughout the monitoring period.

10.3. Conclusions and Recommendations

The frequency of AE activity is directly related to changes in energy input to the rock mass.

Changes in AE frequency rapidly follow such changes in the rate of energy input. Spatial variations in AE activity appear to relate to variations in rock mass strength and deformation characteristics although insufficient data exist to conclusively establish this relationship. Previous analyses of the AE data (Patrick et al., 1983) indicate small-scale shear or fracturing on the order of 0.01 to 0.05 mm per event with source dimensions of several centimetres.

Monitoring revealed that no variations in P- and S-wave velocities occurred at the scale and temperature ranges of the SFT-C. Measurable changes in the S/P amplitude ratios were recorded where path lengths exceeded several metres. These changes are hypothesized to be due to closure of fractures and/or drying of the rock mass at elevated temperatures. Changes in P-wave amplitudes could not be unequivocally determined because the reference path could not be located outside the zone of influence of the SFT-C.

It is recommended that if future studies are undertaken that:

1. Monitoring be done before, during, and after any thermal disturbances.
2. The station spacing be on the order of several metres.
3. If velocity variation is monitored, resolution must be on the order of 1 microsecond.
4. Total processing be carried out. Event count or occurrence rate is not adequate at the scales involved; fault plane solution and moment tensor analysis related to available stress and displacement measurements are also required. Such analysis was attempted but too few events occurred at the scales involved (tens of metres) to obtain any conclusive results.
5. Once zones of AE have been determined, a smaller scale array should be emplaced to collect information for comprehensive data analysis.
6. A larger number of sources be used for controlled velocity and amplitude monitoring and that a reference path be established well outside the zone of influence of the experiment.

In general, we conclude that seismic measurements can provide useful information on the overall stability and integrity of a rock mass subjected to stress changes from excavation activities either alone or in combination with thermal loads. It also appears that the techniques employed at the SFT-C have broad utility in monitoring suspected zones of weakness. Application of these techniques for delineating individual small fractures appears neither possible nor particularly useful at this time.

Figure 10-4a. P- and S-wave amplitude changes through day 285, 1981.

Figure 10-4b. P- and S-wave amplitude changes from day 285, 1981 through day 190, 1982.

Figure 10-4c. P- and S-wave amplitude changes from day 190, 1982 through day 215, 1983.

Chapter 11

Metallurgical Studies

Metallurgical studies were conducted this year to address two areas of concern: leakage of water into the interior of a welded canister emplacement hole liner and failure of connecting rods in borehole extensometers.

11.1. Analysis of Emplacement-Hole Liner Weld

Each of the 0.61-m diameter canister emplacement holes (CEH) was lined with a 0.46-m diameter, 6.4-mm thick carbon steel liner constructed of tubular pipe sections with a flat 6.4-mm thick plate welded to the bottom. Although the liners were specified to be watertight, temperature measurements on CEH01 indicated that the liner leaked within the first month following spent-fuel emplacement (Patrick et al., 1983). Further monitoring of temperatures indicated that the water boiled away about seven months later.

We inspected the CEH01 canister and liner during a scheduled spent-fuel exchange in August 1982. Although it appeared undamaged during a remote videotape examination, numerous "high water marks" formed by iron oxide stains were present on the stainless steel canister. The interior of the liner was completely dry despite the existence of about 2 m of water in the liner/emplacement hole annulus. An abundance of iron oxide materials was present which resulted from partial corrosion of the inside of the liner. No radioactive products were present.

Following retrieval of the spent-fuel assemblies during March and April 1983, all 17 CEH liners were extracted. In the process, the bottom weld on the CEH01 liner broke loose and water from outside the liner once again entered. Inspection of the other liners revealed partially broken welds and, more typically, a fine line of iron oxide on the exterior of the liner at the location of the weld.

A carbide-tipped saw was used to obtain samples of the CEH01 liner that were returned to LLNL for analysis of corrosion and weld integrity. The question of corrosion was simple and direct to answer: the corrosion was limited in extent and normal in character. There was no evidence of pitting or crevice attack. The question of weld quality was investigated further to determine the

cause of the weld failure and to determine if recurrence of the failure could be avoided in future applications.

The weld specification called for a non-dimensioned chamfer and a dye penetrant inspection. This type of test is useful in determining surface cracks but not weld penetration. In this particular case, there was no reference on the drawing to a required penetration other than filling the chamfer.

Figure 11-1 shows a cross section of a typical section of the CEH01 liner weld. This cross section indicates the lack of penetration: part of the chamfer is still in evidence (note the dotted line). There is a corrosion crack in the weld that was generated as a result of the crevice and high stresses (Fig. 11-2). This latter figure shows why the welded parts have separated: the crack has almost reached the outer surface of the liner. As a result of the narrow crevice created by the shallow weld, selective corrosion of an intergranular and transgranular nature occurred in the joint.

An ultrasonic technique was developed and evaluated that can provide 100% field inspection of welds of this type. The technique utilizes a combination of shear-wave angle-beam and longitudinal-wave normal incidence search units. Because plate thickness variations may result from corrosion or metal-forming processes, it was necessary to determine actual plate thickness at each point where lack of penetration (LP) was to be measured. This was done with a normal incidence search unit. Knowing the plate thickness, the 45° angle-beam search unit was used to find and measure the extent of LP. Accuracy of the LP measurement is a function of three variables: material thickness, refracted angle of the search unit, and length of the sound path of the LP indication. All must be accurately known. Our test geometry provided LP accuracy of ± 0.010 in.

In conclusion, it appears that the adequacy of the canister-emplacement-hole liner weld could have been ensured by three basic steps, which we recommend for future welding in tests and full-scale nuclear waste storage schemes. First, provide proper welding instructions in the drawings. Second, specify testing appropriate to the function the weld must fulfill. Third, inspect 100% of the parts using the proposed ultrasonic technique when a high level of certainty is required.

Figure 11-1. Lack of weld penetration and remnant chamfer associated with CEH01 liner weld.

11.2. Analysis of Extensometer Connecting-Rod Failures

The 6.35-mm diameter connecting rods associated with the borehole extensometers located in the canister drift of the SFT-C began to experience failures shortly before spent-fuel retrieval operations began. At this writing, 5 of 56 (9% of the total) have failed.

Metallographic sections of the failure surfaces revealed classic stress-corrosion cracking to be the mechanism of failure in this 31.5% Ni, 5% Co, iron alloy (Superinvar). The environment to which the rods were subjected is relatively benign: temperatures fairly uniform in the range of 45° to 55°C, low tensile stresses, sealed (at least at installation) from groundwater, and test duration of about three years. The presence of a small amount of calcium carbonate in the root of the corrosion cracks led us to believe that the sealing had failed at some time during the test, allowing groundwater to contact the rods and possibly causing galvanic coupling with the copper hydraulic anchorage system and zinc-plated hardware present on the outside of the extensometer.

We attempted to reproduce in the laboratory the type of failure observed in the field instrumentation in an effort to determine the conditions which contributed to the failures. Two series of experiments were conducted using virgin Superinvar obtained from the same lot as was used in the field instrumentation. A variety of couplings and specimen surface preparations were evaluated, as described below, but all specimens had in common exposure to Climax groundwater and temperature of 50°C.

In the first series of experiments, single Superinvar specimens turned to a reduced diameter of 0.76 mm were dead-weight loaded to attain stresses of 90% of tensile yield strength. Five cells were set up for this series: Cell 1 contained only Superinvar; cell 2, Superinvar coupled to copper; cell 3, Superinvar coupled to 1020 steel; cell 4, Superinvar coupled to zinc-coated 1020 steel; and cell 5, Superinvar coupled to copper, steel, and zinc.

The specimen in cell 2 (coupling with Cu) failed after 22 days of exposure. Fractography of the failed surface indicated that corrosion did influence the failure, but the fracture was mostly

Figure 11-2. Corrosion crack in the crevice of the CEH01 liner weld. Note remnant of chamfer.

ductile and not like the fractured surfaces from the extensometer rods that failed in the field. This test was repeated with no failure noted.

A second test specimen failed after 2000 hours. This unit had both copper and carbon steel segments attached to the test frame. The surface morphology of this specimen was one of stress-corrosion cracking and ductile failure of the reduced cross-section. Intergranular and transgranular fracture dominate the morphology with evidence of ductile deformation present in the form of "dimples." The surface morphology of the specimens which failed in the field was primarily

transgranular, that is, flat and across the grains. Thus, the failure mechanism was somewhat different in the laboratory test, making extrapolation to the field tenuous. However, if one extrapolates from the observed corrosion rate of 0.30 to 0.56 mm per year, then these data are consistent, in terms of time to failure, with failures observed in the field.

In the second series of experiments, the Superinvar specimens were loaded in proving ring assemblies to a stress calculated to be 50% of tensile yield strength. The proving ring itself was covered with an impermeable silicone coating and the assemblies were placed in cells containing Climax groundwater at 50°C. Three cells were set up for this experimental series. Cell 1 contained three proving rings with Superinvar having a freshly machined surface and three proving rings of the as-exposed (scaled and oxidized) Superinvar. Three specimens each were used for replication of results. Cell 2 contained three proving rings with Superinvar having as-exposed surfaces galvanically coupled to copper. Cell 3 contained three proving rings with Superinvar having as-exposed surfaces coupled to zinc-coated steel.

When no failures had occurred after several thousand hours of testing these full 6.35-mm diameter specimens, the groundwater in the test cells was made more hostile by adding 94 g/L $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$. Corrosion progressed very rapidly and two failures have occurred at this writing. Corrosion and oxidation of the fracture surfaces was very severe. After cleaning, the fracture surfaces were examined both in the optical and scanning microscopes.

Figures 11-3 and 11-4 are of the first field rod that failed and Figs. 11-5 and 11-6 are of the lab tested specimen in groundwater plus $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$. Although the latter is much more severely attacked, both SEM photos show a similar combination of intergranular and transgranular type fracture. The optical photos also show the combination of both types of stress corrosion cracking. However, the more severely attacked lab specimen shows some pitting along the fracture path related to the presence of chloride ion. The laboratory specimen shows no evidence of a ductile failure, which is thus similar to the surface morphology of the field failure.

Understanding that there are some caveats, it is interesting to compare our failure to the well known curve (Fig. 11-7, Copson, 1959). This suggests that a Fe-Ni-Cr alloy under a very hostile environment would be very sensitive to stress corrosion cracking. Our particular material does not

have the chrome to form a passive layer which certainly would have some effect on the time to failure. Nevertheless, the point to consider is that under a chloride environment plus stress, Superinvar is not a good choice of material for corrosion resistance. In our particular application, selection of Superinvar was based on thermal ex-

pansion rather than corrosion characteristics. Inadvertant leakage through seals apparently allowed the entrance of groundwater with its associated minerals; leading to the eventual failure of the rod. Clearly, exclusion of groundwater from the extensometer could have prevented the observed failures.

Figure 11-3. Fracture developed in a Superinvar extensometer rod which failed in service.

Figure 11-4. Micrograph of stress corrosion cracking in a Superinvar extensometer rod which failed in service.

Figure 11-5. Fracture development in a Superinvar rod which failed during testing.

Figure 11-6. Micrograph of fracture surface of Superinvar rod which failed during testing.

Figure 11-7. Relationship between breaking time and nickel content (after Copson, 1959).

Chapter 12

Data Management System

12.1. Current Processing Technique and Modifications

Although the flow of data and temperature corrections are relatively unchanged from last year, as shown in Fig. 12-1, several important changes have been made in the system's capabilities. The major software change was elimination of the requirement to have many instrument descriptor databases, each valid over a limited and non-overlapping time interval. Associated with this change, we have essentially completed a single database capable of describing all (approximately 1200) instruments over the entire duration of the test (3 years). In addition, the temperature correction algorithms and associated database descriptors have been augmented for two classes of instruments—the rod and wire extensometers—and several software tools have been developed to aid in retrieving and verifying both database information and data from the field.

The arrows between the database and REVERT indicate its varied functions which include the ability to:

1. Read a database dump (HPTP) file from NTS, a corresponding ITEMNAME file, and an

ALTER file, and generate an instrument descriptor database (HPDB) file. The ITEMNAME file tells REVERT the names of the desired parameters to obtain from the HPTP file, and the ALTER file describes changes or additional data to be implemented in the new database.

2. Read an existing HPDB file and add data from another HPTP file or an ALTER file.

3. Read an HPDB file to make a listing and an index of that file.

4. Read an HPDB file and process a binary data file (B-file) to obtain engineering units and temperature conversions from the raw data.

The number of HPTP files transmitted from NTS has grown to 22. From these, Octopus listing files and Octopus data files have been generated as shown in Table 12-1. By merging the first 21 files, HPDB4/83M was generated. Finally, ALTER control file RC5 modified this file to obtain HPDB4/83M5, the current database file being used to process data.

The need for multiple database descriptions for a single instrument arises as follows. Consider the MBI series of rod extensometers as an example. For temperature compensation these instruments require temperature measurements at the

Table 12-1. List of REVERT data base files.

Base no.	HP dump file	Octopus list file	Octopus data file
1	HPTP800731	LIST800730	HPDB800730
2	HPTP800814	LIST800814	HPDB800814
3	HPTP800922	LIST800919	HPDB800919
4	HPTP800117	LIST801016	HPDB801016
5	HPTP810119	LIST780805	HPDB80805
6	HPTP810313	LIST810226	HPDB810226
7	HPTP810402	—	—
8	HPTP810409	LIST810409	HPDB810409
9	HPTP810418	—	—
10	HPT0810625	LIST810625	HPDB810625
11	HPTP811130	LIST811130	HPDB811130
12	HPTP811215	LIST811215	HPDB811215
13	HPTP811223	LIST811222	HPDB811222
14	HPTP820114	LIST820114	HPDB820114
15	HPTP820323	LIST820324	HPDB820324
16	HPTP820413	LIST820413	HPDB820413
17	HPTP820701	LIST820701	HPDB820701
18	HPTP820819	LIST820819	HPDB820819
19	HPTP821118	LIST821119	HPDB821119
20	HPTP830105	LIST830106	HPDB830106

Figure 12-1. Block diagram of Data Management System.

transducer location on the tunnel wall as well as at various points along the rod in the MBI borehole. The first data taken by these instruments was on JD44347 (04/17/80). At this time it was assumed that since air temperature was being measured at many places in the drift, one of those existing measurements would be adequate for each MBI head. Also, since the MBI heads were clustered, one existing measurement would suffice for each group. Thus RTD015 was listed in the instrument descriptor database as the head temperature monitor for MBI08x, MBI09x, and MBI10x, a total of 15 instruments.

Later data indicated the temperature distribution in the drift was fairly complex, and it would be better to install instruments to measure the head temperatures directly. This was accomplished at about JD45005 (02/04/82). For dates later than this, the head temperature references for MBI08x, MBI09x, and MBI10x should be NET080, NET090, and NET100, respectively. If at this time the instrument licenses were changed, e.g. to MBI28x, MBI29x, and MBI30x, the new descriptor information could simply have been added to the existing database. This change, however, would have broken what is essentially a continuous stream of data into two pieces with different names, making subsequent data manipulations more complicated.

We avoided this complication, leaving the instrument names unchanged, by designating an unused position in the instrument descriptor block (IDB) to be used as a one character suffix for the instrument license during the ALTER mode. This change allows for adding or modifying multiple entries for each license.

A further change was needed for the data processing mode. Each IDB contains three dates, DATEIN, DATEOU, and DATEMO, which were originally defined as the date the instrument was installed, the date it was removed, and the date the descriptor coefficients were last modified. These dates were redefined as the date installed, the date beyond which these coefficients are not valid, and the date before which the coefficients are not valid. These dates are Julian days, given to 0.0001 days, or about 8 seconds. In processing a particular instrument, REVERT checks all available descriptor blocks for dates bracketing the data point before considering it invalid. The disk addresses of the descriptor blocks in the database are contained in memory in a table sorted by license. The bracketing dates which have been added to this table are thus contiguous, making the search easy.

As a result of changes made to several algorithms, the instrument descriptor blocks were changed. The new IDB definitions are shown in Table 12-2. The ITEMNAMEs marked by an asterisk are defined in Livermore, are not read from the NTS database dumps (HPTP files), and must be entered using the ALTER mode. The ALTER input file now stands at nearly 1000 lines required to modify a database, merged from the 21 HPTP files, into a HPDB file suitable for processing data.

In processing a particular instrument, e.g., MBI082, the selection of data needed from other instruments, e.g. the excitation voltage, MBI080; the head temperature RTD015; or a rod anchor temperature, NET081 or NET082; is controlled by the "TOOLD" parameters. Any data point must be within TOOLD minutes of the time of the data point being processed in order to be current enough for processing to continue. In general, TOOLD is determined by the time constant of the backup instrument. Since the rod anchors are deep in the rock, their temperatures cannot vary rapidly, and TOOLD can be large, 1440 minutes (one day). For the excitation voltages, which can vary over relatively short time intervals, TOOLD is small, one minute. An exception must be made when the backup instrument is being scanned at a time interval longer than its time constant. In this case the longer interval must be used if any data are to be saved. The TOOLD values were originally written into the algorithm coding. Since the scan rates and the instruments themselves may change with time, this was unacceptable and we redefined IDB positions 10, 11, and 12, as TOOLD1, TOOLD2, and TOOLD3 as shown in Table 12-2.

Originally we intended to consider the coefficients of thermal expansion (CTE's) of the engineering materials used in the SFT-C as constant with temperature. Data presented in the FY 82 Interim Report, however, show that for the Superinvar rods in the GxE series rod extensometers, CTE is better expressed as a linear function of temperature. We therefore rederived the temperature correction equations to take this into account, redefining positions 64 and 65 of the IDB in the process (see Table 12-2). The effective CTE is now defined as:

$$CTE = RXMTC(5) \cdot T + RXMTC(4) \quad ,$$

where T is the temperature of a differential element of the rod, to be integrated over the rod length. For the MBI series extensometers,

Table 12-2. Instrument Descriptor Block coefficient definitions.

Item name	Data type ^a	Descriptor block index	Data description
LCNMBR	I	1	Logical channel number
LCDESC	A	2	License plate
PDTYPE	A	3	Physical device type
LCDSTR	A	4-6	Channel descriptor string
DATEIN	A-R	7	Date device installed
DATEOU	A-R	8	Date device removed
DATEMO	A-R	9	Date coefficients modified
*TOOLD1	-R	10	Time limit 1
*TOOLD2	-R	11	Time limit 2
*TOOLD3	-R	12	Time limit 3
WTSLOP	R	13	Slope coefficient
WTINTR	R	14	Intercept
TCOHMS	R	13	TC resistance
TCCOEF	I	14	TC quartic coefficient set
TCREFC	I-A	15	TC reference channel
TCOC	R	16	TC offset constant
ESWLOC	R	13	Excitation wire loss offset
RXESLC	I-A	13	RX excitation channel
RXRODL	R	14	Rod length, metres
RXKCP1-9	R	15-23	Calibration position 1-9
RXKCC1-9	R	24-32	Calibration reading 1-9
RXTLC0-6	I-A	33-39	Temp. ref. channel 0-6
RXDTT0-6	R	40-46	Distance to temp reading
*RXTOC0-6	R	47-53	RX calibration temperature
RXPCL1-3	R	54-56	Physical component length 1-3
RXPCL4-7	R	57-60	Not used
RXMTCL3	R	61-63	Thermal expansion value 1-3
RXMTCL(4)	R	64	CTE temp adder (B)
*RXMTCL(5)	R	65	CTE temp multiplier (A)
*RXMTCL(6)	R	66	Head temp multiplier (ASS)
*RXMTCL(7)	R	67	Head temp adder (BSS)
RXOC	R	68	RX offset constant
RTR0	R	13	Reference resistance
RTCA	R	14	Coefficient A
RTCB	R	15	Coefficient B
SDOC	R	13	SD offset constant
LDSLOP	R	13	Linear device slope
LDINTR	R	14	Linear device intercept
MDPRON	A	13	Misc. processor name
MDPAR1-5	I	14-18	Misc. processor param. 1-5
VWSF	R	13	IRAD gage sensitivity
VWZLR	R	14	Zero load reading
*VWMM	R	15	Gage-rock thermal modulus
*VWT0	R	16	Initial temperature
*VWR0	R	17	Initial set gage reading
*VWTCLC	I-A	18	Gage temperature channel

Table 12-2. (Continued)

Item name	Data type ^a	Descriptor block index	Data description
WXESLC	I-A	13	WX excitation channel
WXWIRL	R	14	WX wire length
WXSEN	R	15	Sensitivity, volts**2 per metre
*WXTOC1-7	R	16-22	WX offset temperature 1-7
*WXTLC1-7	I-A	23-29	WX temperature ref. channel 1-7
*WXTMU1-7	R	30-36	Temperature multiplier 1-7
*WXTEC1-7	R	37-43	Thermal expansion coefficient 1-7
*WXOC	R	44	WX offset constant
PNC0-4	R	13-17	Polynomial coefficient -4
SYPRON	A	13	System processor name
SYPAR1-5	I	14-18	System processor param. 1-5

^a I is integer; A is BCD (ASCII) characters; R is real floating point; A-R is BCD in the NTS files and real floating point in the HPDB; -R is real entered by ALTER only; I-A is integer channel number in HPTP converted to BCD license plate in HPDB.

RXMTC (4) is as previously defined, and RXMTC (5) is set to zero.

Another change to the RX algorithm was to define the head temperature to be a linear function of the temperature actually measured by the head temperature device. This was an attempt to account for the complex air temperature distribution in the drifts. The effective head temperature was thus defined as:

$$\text{HDT} = \text{RXMTC} (6) \cdot T + \text{RXMTC} (7)$$

where RXMTC (6) and RXMTC (7) are in IDB positions 66 and 67, and T is the measured temperature.

A somewhat similar change was made to the WX algorithm, which handles both the wire extensometers (CWE's) and the fracture monitor systems (FMS's). By using the "future expansion" positions 30-36 to store seven temperature multipliers, the algorithm can handle physical components with seven different length-CTE products, each at a temperature defined as a linear function of a different measured temperature. The correction for the *i*th component is:

$$T = TM \cdot \text{WXTMU} (i)$$

$$\text{DTEMP} = T - \text{WXTOC} (i)$$

$$\text{CORR} = \text{DTEMP} \cdot \text{WXTEC} (i)$$

where TM is the measured temperature, WXTMU the temperature multiplier, WXTOC a tempera-

ture offset, DTEMP the change in temperature of this component, WXTEC the length-CTE product for this component, and CORR the correction to add to the uncorrected data. Note that WXTOC is not the initial measured temperature, but that temperature times WXTMU plus a calculated offset. After about JD44989 (01/19/82), when TC's were placed on the FMS's and the temperature of the CWE wires was inferred by directly measuring the wire's electrical resistance, the WXTMU values become 1.0, and the WXTOC values become best estimates of initial temperature.

12.2. Quantity and Quality of Data Received to Date

Table 12-3 shows the data received to date. As before, the "discard" column primarily accounts for data from area radiation monitors and various status devices which are not analyzed and reported. Though archived as raw data, these are discarded from the scientific database to reduce the volume of data processed. The reduction is significant since these data comprise 43% of the data acquired to date. The "NUMBER OF ERRORS" columns show those data lost because they were unreadable or obviously wrong and uncorrectable. These represent about 2% of the acquired data. As shown, 8,691,636 valid data points were accumulated during the 1300-day (3.56 year) period of the test for an average of 6682 data points per day.

Table 12-3. Summary of processed data.

File name	Time, absolute Julian day		Number of data points			Number of errors			
	Start	Stop	Copied	Discard	Total	Range		License	License and channel
						TOR ^a	VOR ^b		
000A/B	44331.437	44569.498	30191	0	30191	—	—	—	—
002A/E	44342.196	44354.011	25393	11407	36800	0	144	39	0
003A/C	344.790	345.250	1692	2245	3937	0	1	0	143
004A/C	345.389	346.967	11181	6548	17729	32	90	32	149
005A/C	346.960	351.929	26491	13114	39605	18	21	0	0
006A/C	351.914	351.917	37567	7027	44594	0	81	0	0
007A/D	357.845	358.507	7145	1636	8781	0	4	0	0
008A/D	358.485	360.566	8883	2427	17310	0	231	0	0
009A/D	359.926	361.134	17281	5971	23252	0	1451	0	0
010A/C	361.143	370.452	119807	45263	175070	0	54	0	0
011A/D	370.452	375.167	50161	18770	68931	0	44	0	0
012A/C	375.161	388.456	150312	57590	207902	0	141	0	0
013A/C	388.196	409.271	159424	58090	217514	0	300	33	0
014A/D	409.266	416.590	91569	28941	120510	0	73	196	0
015A/C	416.590	421.242	45953	14735	60688	0	28	67	0
016A/C	421.246	438.653	182950	68700	251650	0	108	409	0
016B/C	438.648	451.121	138409	52772	191181	0	79	320	0
017A/C	451.107	467.378	178992	68629	247621	0	50	0	0
017B/C	467.161	474.286	72545	23302	95847	3	10	0	0
018A/F	474.278	490.198	154345	56843	211188	6	35	220	205
019A/C	490.193	501.576	118107	40305	158412	0	58	24	0
020A/B	501.563	513.328	97757	48058	145815	0	7	21	0
021A/B	513.321	526.480	156160	69170	225330	0	2	0	0
022A/B	526.478	541.537	172533	64458	236991	0	5	0	1
022B/A	541.532	550.332	115831	73133	188964	0	4	0	0
023A/B	550.252	562.241	113601	50159	163760	0	24	161	0
024A/B	557.404	576.247	72353	31718	102071	0	38	2	0
025A/C	529.800	590.272	104444	71095	135539	0	60	39	0
026A/C	577.327	610.263	84131	117970	202101	0	13	8	0
027A/C	610.564	618.247	40686	203970	244656	12	8	84	229
028A/C	618.247	632.307	84205	165522	249727	2	16	204	0

Table 12-3. (Continued)

File Name	Time, absolute Julian day		Number of data points			Number of errors			
	Start	Stop	Copied	Discard	Total	Range		License	License and channel
029A/C	632.368	651.453	88284	164419	252703	0	11	12	0
029B/C	650.669	661.224	30935	53536	84471	0	266	3	0
030A/C	656.339	686.187	90861	157447	248308	1	7	3	47
030B/B	686.067	695.245	45207	95148	140355	0	4	3	0
031A/C	695.350	705.889	48884	43058	91942	14	186	19	606
032A/C	703.304	722.290	78070	80297	158367	3	8	102	23
033A/C	722.617	781.117	124320	123839	248159	1	37	1	160
034A/B	723.271	772.087	141038	108318	249356	0	79	11	0
034B/B	772.087	781.122	22451	20664	43115	0	2	1	0
035A/C	781.126	801.610	72433	56439	128872	0	22	1	245
036A/C	781.122	802.173	45460	54589	100049	0	286	3	678
037A/B	802.184	826.246	125763	122361	248124	0	6	3	0
037B/B	826.180	842.202	60618	60467	121085	0	5	184	0
038A/C	837.205	852.215	59890	51625	111515	1	2	1	0
039A/B	852.223	873.582	106996	129470	236466	0	12	206	0
039B/B	873.582	890.343	139520	72851	212371	1	28	28	0
040A/A	890.566	905.159	65577	89464	155041	0	10	20	0
041A/A	905.151	932.186	137485	114641	252126	0	31	6	0
041B/B	932.184	939.266	30576	27134	57710	0	2	1	0
042A/B	939.300	965.522	119826	124187	244013	2	102	80	0
042B/A	965.484	984.225	78904	82118	161022	0	5	75	0
043A/E	990.234	5005.301	101456	119178	220634	1	117	1869	12
044A/B	45005.305	5053.225	132236	114582	246818	2	6	109	166
045A/A	45005.260	45030.390	87612	48097	135709	0	44	333	0
045B/A	45030.397	45053.204	81367	47567	128934	0	72	0	0
046A/D	45053.229	45077.681	186845	59844	246689	1	111	59	46
046B/B	45077.681	45080.213	137590	112400	149990	0	14	0	0
047A/D	45053.207	45080.231	116475	79060	195535	1	562	3	46
048A/A	45080.271	45084.987	115728	12690	28418	0	13	319	0
049A/B	45080.683	45106.363	48445	166315	251160	1	154	16	493
049B/A	45106.361	45109.549	21836	16270	38106	0	15	1	0

Table 12-3. (Continued)

File Name	Time, absolute Julian day		Number of data points			Number of errors			
	Start	Stop	Copied	Discard	Total	Range		License	License and channel
050A/B	45085.646	45103.386	44184	34166	78350	1	49	16	217
051A/A	45110.252	45133.155	187505	67807	255311	0	260	66	0
051B/B	45133.153	45152.179	149434	58448	207882	0	82	104	0
052A/A	—	—	0	125108	125108	8738	20	8775	112568
053A/B	45129.603	45148.636	177163	55377	232540	1	51	1	46
054A/A	45152.319	45177.430	28130	23752	51882	0	2	0	0
055A/C	45152.182	45169.359	161569	91101	252670	433	24	576	5035
055B/C	45169.354	45177.468	38772	93132	131904	1731	22	1769	65921
056A/A	45177.431	45201.199	77471	68863	146334	0	65	773	0
057A/A	45177.411	45201.192	70506	61908	132414	0	97	168	0
058A/A	45201.192	45221.369	36943	62424	119367	0	39	162	0
059A/A	45201.199	45218.443	50135	204568	254703	0	5	189	0
060A/A	45226.448	45256.339	76218	88038	164256	0	4	21	0
061A/A	45221.416	45256.336	99734	92536	192270	0	49	0	0
062A/A	45256.339	45288.544	141186	106148	247334	1	12	245	46
062B/A	45288.533	45292.298	19574	199242	39498	0	5	167	0
063A/A	45256.339	45285.208	62320	55826	118146	0	30	109	0
064A/A	45292.298	45331.300	115960	125014	240774	1	1191	29	46
065A/A	45292.219	45339.403	127878	127829	255707	1	83	7	46
065B/A	45339.406	45340.228	1297	481	1784	0	0	0	0
066A/A	45341.326	45359.430	27484	27326	54810	0	0	22	0
067A/A	45340.229	45379.239	141259	109019	250278	0	4299	1	0
067B/A	45379.239	45396.197	52839	41121	93960	0	17	0	0
068A/B	45359.430	45396.235	97187	103609	200796	1	14	319	46
069A/B	45397.554	45436.390	126985	127955	254940	45	7	413	88
069B/B	45436.390	45453.232	42422	20740	63162	0	0	0	0
070A/B	45396.197	45429.555	137282	112707	249989	0	89	140	0
070B/B	45429.558	45453.226	74244	28242	102486	0	40	258	0
071A/B	45453.235	45521.314	167626	86240	253866	0	119	0	0
071B/B	45521.312	45533.418	198636	24606	223242	0	819	0	0

Table 12-3. (Continued)

File Name	Time, absolute Julian day		Number of data points			Number of errors			
	Start	Stop	Copied	Discard	Total	Range		License	License and channel
						TOR ^a	VOR ^b		
072A/D	45453.229	45527.182	178901	75150	254051	349	304	327	14331
072B/B	45527.184	45544.350	33302	10198	43500	0	428	66	0
073A/B	45533.418	45596.208	169408	84416	253824	0	591	112	0
073B/A	45596.208	45632.198	36513	44286	80799	0	524	168	0
074A/B	45544.350	45613.077	165178	55213	220391	1	746	2660	54
075A/A	45613.080	45632.194	7404	14671	22075	0	0	0	0
<u>Totals</u>									
00-45	44331.437	45053.225	4785868	3601064	8386932	99	4599	4933	2663
46-65	45053.229	45340.228	2249098	2009035	4258133	10910	3056	14075	184510
66-75	45341.326	45632.194	1656670	965499	2622169	395	7997	4486	14519
overall	44331.437	45632.194	8691136	6575598	15267234	11404	15652	23494	201692

^a TOR, Time out of range^b VOR, Value out of range

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Primary responsibility for the individual chapters of this multiauthor report is as follows: Chapter 1 – W. C. Patrick; Chapter 2 – W. C. Patrick; Chapter 3 – H. C. Ganow, Section 3.1, F. J. Ryerson, Section 3.2, W. B. Durham, Section 3.3; Chapter 4 – W. C. Patrick and D. N. Montan; Chapter 5 – R. A. Nyholm; Chapter 6 – D. N. Montan, W. C. Patrick and N. L. Rector; Chapter 7 – N. L. Rector and D. N. Montan; Chapter 8 – W. C. Patrick and N. L. Rector; Chapter 9 – T. R. Butkovich and J. L. Yow, Jr.; Chapter 10 – E. L. Majer; Chapter 11 – H. Weiss; and Chapter 12 – R. C. Carlson and G. L. Hage.

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