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OVERCORING AND CALIBRATION OF
IRAD GAGE STRESSMETERS AT THE SPENT FUEL TEST
IN CLIMAX GRANITE*

Nai-hsien Mao

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Table of Contents

	Page
ABSTRACT	1
I INTRODUCTION	1
II PREVIOUS WORK	2
1. Laboratory Calibration	2
2. Stressmeter Installation	6
3. Stressmeter Failure	7
4. Field Data	8
5. In-Situ Stresses	9
III OVERCORE OF STRESSMETERS	10
1. Rationale	10
2. Overcore	11
IV FINAL LABORATORY CALIBRATION	12
V DISCUSSION AND CONCLUSION	13
ACKNOWLEDGMENTS	17
REFERENCES	18

ABSTRACT

IRAD GAGE vibrating-wire stressmeters were installed in the Spent Fuel Facility at the Nevada Test Site to measure the change in in-situ stress during the Spent Fuel Test-Climax (SFT-C). Although extensive pre-installation laboratory tests were conducted, they were generic in nature. Unfortunately the degree of gage-rock contact has a strong influence on gage sensitivity and cannot be predicted before installation. This report discusses the results of removing a cylindrical section of rock and gages as a unit through overcoring and the subsequent post test calibrations of the stressmeters in the laboratory. With the assumption that the gage-rock contact was not disturbed by the overcoring, the results from these calibrations compensate for varying gage-rock contact. The estimated in-situ stresses based on post test calibration data are quite consistent with those directly measured in nearby holes. The magnitude of stress change calculated from pre-installation test data is generally much smaller than that estimated from post test calibration data.

I INTRODUCTION

The Spent Fuel Test - Climax (SFT-C) is part of the Department of Energy's (DOE) Nevada Nuclear Waste Storage Investigations. It is managed by the Nevada Operations Office of the DOE and conducted under the technical direction of the Lawrence Livermore National Laboratory. The overall objective of 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).

In this generic test, located 420 m below the surface in the Climax granite stock at the Nevada Test Site (NTS), 11 canisters containing spent fuel assemblies, approximately 2.5 years out of the reactor core, have been emplaced in the floor of a storage drift along with six electrical simulator canisters. Over 900 data channels were installed to monitor the response of the rock to the heat and radiation produced by the fuel assemblies and to distinguish in that response the effect due to heat alone. A number of laboratory and field studies for site characterization and instrument calibration were carried out and reported (Carlson et al. 1980, Patrick, Carlson, and Rector 1981, Patrick et al. 1982, 1983, and Brough and Patrick 1982). Among these studies, IRAD GAGE vibrating-wire stressmeters were installed in the facility to measure the change in in-situ stress during the SFT-C. This report discusses the results of post test stressmeter calibrations which were conducted in the laboratory following removal of a section of the rock and gages as a unit through overcoring.

II PREVIOUS WORK

1. Laboratory Calibration:

IRAD GAGE, Inc. was contracted to perform laboratory calibration studies of the vibrating-wire stressmeter in Climax granite (Dutta, Hatfield, and Runstadler, 1981). A comprehensive test program was developed to study nine

important factors which influence stressmeter response: test sample size, stressmeter stiffness, gage reproducibility and hysteresis, gage preload, initial stress field, platen geometry, platen orientation, elevated temperature, and rock anisotropy. A summary of the calibration studies was also reported by Patrick et al. (1982). Following are excerpts from the two reports.

The IRAD GAGE vibrating-wire stressmeter uses a tensioned wire across a hollow steel cylinder which is preloaded diametrically across the sides of a 1.5 in. (3.8 cm) borehole by means of a sliding wedge platen assembly. Figure 1 shows the cross-section of a stressmeter set in a borehole. The operation of the vibrating-wire stressmeter is based on the fact that the fundamental frequency of a stressed wire is proportional to the applied stress in the wire. Any deformation of the borehole will change the compression in the gage body and, through deformation of the body, change the stress in the wire. The output of the stressmeter is the vibration frequency of the wire as:

$$f = \frac{1}{2l_w} \sqrt{\frac{\sigma_w g}{\rho}} \quad (1)$$

where:

f is the natural frequency of wire, (sec^{-1})

l_w is the length of vibrating-wire, (in.)

σ_w is the stress in the wire, (psi)

ρ is the density of the wire, (lb/in.^3)

g is the acceleration due to gravity, (in./sec^2)

For the IRAD GAGE stressmeter, $L_w = 0.780$ in. and $\rho = 0.283$ lb/in.³, therefore,

$$f = 23.674 \sqrt{\sigma_w} \quad (\text{sec}^{-1})$$

Defining T as the 4 digit display of the IRAD GAGE vibrating-wire readout unit, T is given by

$$T = \frac{10^7}{f}$$

then

$$\sigma_w = 1.78422 \times 10^{11} \times \frac{1}{T^2} \text{ (psi)} \quad (2)$$

The ratio of the wire stress change ($\Delta \sigma_w$) to the change in rock stress ($\Delta \sigma_r$) is defined as the "stress sensitivity factor" (α) which provides a simple factor to characterize the stressmeter response in various rocks.

The major conclusions from the calibration test results can be summarized under three categories: (1) Host material characteristics, (2) Gage reproducibility, and (3) Temperature effects.

The heterogeneity in composition and cracks in rocks can result in large variations in gage sensitivity. The stressmeter sensitivity factor is non-linear with Young's modulus and is also a complex function of the platen contact area and, hence, the preload. Therefore, the change in sensitivity α with modulus and load should be precisely determined through laboratory calibration for the host materials of interest.

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

Gage reproducibility was investigated under two conditions, single setting with multiple-load cycles and multiple settings with a single-load cycle. In all tests, a zero shift has been observed between the initial and the second load cycles. The shift, as a percentage of the maximum applied wire stress, was 18% in Climax granite. This is probably a result of the stressmeter "bedding in" on the first cycle since, for later cycles, the effect is almost non-existent.

The LLNL gage was heat treated and electroless-nickel-plated. It had a stiffness of 7.5×10^6 lb/in (1.29×10^7 N/cm), while the standard VBS-IHT had a stiffness of 7.1×10^6 lb/in (1.24×10^7 N/cm). The stiffer gage has a slightly higher sensitivity factor possibly due to the use of a higher preload value in the stiffer gage test.

Test results indicate that above a minimum preload value, sensitivity α is essentially constant with load. For Climax granite, the threshold is + 175 units in T.

The influence of temperature on a stressmeter was a primary concern in pre-installation temperature calibration studies because of the temperature changes expected on the SFT-C. As it turned out, changes in stressmeter sensitivity with increasing temperature were negligible. Changes in temperature merely cause an offset in the initial gage reading (T_1) by an amount

$$T_1' - T_1 = 1.55 \Delta t \quad (3)$$

Based on Eqs. 2 and 3, it was postulated that rock stress changes ($\Delta \sigma_r$) can be estimated according to following relation (Patrick et al. 1982)

$$\Delta \sigma_r = (1.7842 \times 10^{14}) A \left[\frac{1}{T_1'^2} - \frac{1}{T_2^2} \right], \quad (4)$$

where:

$\Delta \sigma_r$ is the stress change in pascals.

T_2 is the gage reading.

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

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

2. Stressmeter Installation:

Eighteen IRAD GAGE vibrating-wire stressmeters were installed in the SFT-C facility during the week of March 17, 1980 (Abey and Washington, 1980). Six stressmeters "rosettes" were used, each rosette consisting of three stressmeters. One was aligned at 0° (0° is vertical for the horizontal holes and perpendicular to the drift axis for the vertical holes), one was rotated 60° ccw, and the third was rotated 60° cw, as viewed from the end of the hole through which the gage was inserted. Figure 2 shows the location of the vibrating-wire stressmeters and other instruments. Figure 3 shows the relative orientation of each gage. CSG01 and CSG02 are vertical holes in the canister drift floor. NSG03 and NSG04 are horizontal boreholes, and are located approximately 2 m above the floor in the pillar between the canister and north heater drifts (Figures 2 and 3). All boreholes were cored using diamond drilling techniques to a nominal 38 mm diameter but have distinct rifling with a wavelength of a few cm and an amplitude of a few tenths of a mm.

Prior to placing the stressmeters at the facility, laboratory tests in a setup designed to simulate field conditions were carried out (Abey and Washington 1980). A smooth 38-mm hole was drilled in a granite cube

approximately 120 mm on a side. A 1-m long metal tube with a 38-mm inside diameter was aligned with the hole in the cube and firmly attached. Stress calibrations were obtained by loading the cube in a hydraulic press. Two distinct calibration curves were found: a "normal" curve associated with little or no drop in preload when the installation tool was removed and a "subnormal" curve associated with a substantial drop ($> 10\%$) in stressmeter preload. The "subnormal" curve is approximately 30% less sensitive than the "normal" curve. Table 1 contains a list of stressmeter placements and their zero load and preload readings. Two of the gages, NSG044 and CSG012, should be categorized as "subnormal". Two others, NSG031 and NSG035 will require an intermediate calibration curve.

3. Stressmeter Failure:

Four of the six gages in vertical holes near the canister emplacement holes failed within 4 months after installation. By June, 1981, 13 of the 18 gages failed. The cause was identified as internal rusting, especially of the wire itself, due to moisture. IRAD GAGE, Inc. redesigned the gage, providing a welded hermetic seal in place of the O-ring seal previously used. All gages were sealed under vacuum. Nine gages of the new design were installed in place of failed units June 16-17, 1981 (Brough and Patrick 1982, Patrick, Carlson, and Rector 1981). Locations and initial readings of the gages are given in Table 2. The change in reading during the first 24 hours is due to the thermal adjustment of the gage with the rock.

By October, 1982, the remaining 5 originally installed gages also failed. Nine additional stressmeters of the modified version were installed October

25-27, 1982. Table 3 represents the locations and orientations of the replacement stressmeters (Patrick et al., 1983).

4. Field Data:

Field data of 9 replaced gages are available from June 17, 1981 to September 30, 1983 and of others from October 27, 1982 to September 30, 1983. The spent fuel was retrieved and the power of heaters was turned off between March 3 and April 6, 1983. Figures 4 to 14 are raw data of selected gages during the last year of operation. These gages are those we had stress relief data during overcoring (see Table 5). The y-axis is labeled count which is the gage readout (T), and the x-axis is the spent fuel age expressed as the number of years out of core. As a reference, the date October 25, 1982, when the last batch of gages was replaced corresponds to 4.93 years out of core. The sharp drop of count between 5.3 and 5.4 years out of core for most of the gages is due to the retrieval of spent fuel and the turning off the power to the heaters.

Figures 15 to 18 are the temperature changes at the gages for the same period. The last three digits of thermocouple license plate correspond to the gage number. For instance, SGT221 is associated with gage CSG221. Both Table 1 and Figure 3 show the initial installation data. The final gage and thermocouple license plate retained the same format except the leading 0 was changed to 2, i.e. CSG021 to CSG221. Temperature has two effects on the readout. First, the readout should be corrected for temperature effect according to Eq. 3. Secondly, temperature changes will generate thermal stress in rock and be seen by the gage.

The temperature change due to the retrieval of spent fuel at the horizontal holes was about 6°C which implies a readout temperature correction of about 9 counts according to Eq. 3. Since the vertical hole was much closer to the spent fuel canister, the temperature change was much larger. At CSG02 it was about 20°C implying a readout correction of 31 counts.

Gage NSG243 appears to be malfunctioning. However we brought the signal back during overcoring by fine tuning the control box. The data for NSG246 show a relatively smooth change throughout the spent fuel retrieval period. Table 4 summarizes the data after the retrieval of the spent fuel. The last column is the readout change after temperature correction. This represents the thermal stress effect. The data indicate that little change in thermal stress was seen by NSG244 and NSG246 between installation of the gage and the end of the monitoring period.

5. In-situ Stresses:

In-situ stress measurements in the vicinity of the SFT-C were reported by Creveling et al. (1984). The stress-measuring instruments used for this study included both the U.S. Bureau of Mines Borehole Deformation Gage (USBM gage) and the Australian CSIRO Hollow Inclusion Stress Cell (CSIRO cell). A total of 8 holes were drilled and tested. Among these holes ISS5 and ISS4, located in the north heater drift pillar, are 12 ft and 19 ft away from boreholes NSG03 and NSG04 which contained IRAD GAGE vibrating-wire stressmeters. Boreholes ISS6 and ISS7 are in matching positions in the south pillar.

The stress measurements at these holes began in June 1983 and were completed in September 1983 corresponding to the last leg of the vibrating-wire stressmeter data.

Stress measurements in the four pillar boreholes present a relatively consistent profile of secondary principal stresses. The major secondary principal stresses are predominantly vertical and have a maximum value of about 2000 psi (13.8 MPa) near the heater drift wall, which decreases progressively toward the canister drift wall to values in the range of 700 to 1000 psi (4.83 to 6.90 MPa). Minimum secondary principal stresses are nearly horizontal and are generally less than 700 psi (4.83 MPa).

The results of three CSIRO cell tests indicate that major principal stresses in the pillars are in the order of 2300 to 3000 psi (15.86 to 20.69 MPa), and are oriented at an angle of 20 to 50° from vertical. The minor principal stresses are low, averaging about 500 psi (3.45 MPa), and are oriented across the short dimension of the pillar. The intermediate principal stresses are nearly horizontal, oriented along the long axis of the pillars, and less than about 900 psi (6.21 MPa).

III OVERCORE OF STRESSMETERS

1. Rationale:

The IRAD GAGE vibrating-wire stressmeter is a very sensitive instrument which can be affected by many local irregularities. Therefore, careful calibration of the gage is the key to meaningful interpretation of the data. The calibration studies discussed previously are generic in nature. They provide many useful guidelines on the installation and operation of the gage. However, calibration of individual gages in the rock in which they were set during data taking is probably the best way to take the effect of the

gage-rock interface into account. In order to keep the gage-rock interface intact, we decided to overcore the gage and to calibrate the overcored gage in the laboratory. Since it is generally very difficult to core a concentric sample with high precision in the field, we decided to have a two stage overcoring. First, we cored a 9 1/2" (24.1 cm) diameter rock with gages in place. Then we shipped the large core sample back to the laboratory and made a 5 1/2" (14 cm) core which was precisely concentric with the small 1 1/2" (3.8 cm) gage hole in the middle of the core. The 5 1/2" core with gages in place was then calibrated under uniform biaxial loading. Furthermore, the stress relief data during overcoring should also provide important information about the state of stress in-situ.

2. Overcore:

The overcoring task started on January 12, 1984 and was completed on March 19, 1984. The stressmeter overcoring was of limited success. Among the 18 gages, the stress relief data of 11 were successfully recorded during overcoring but only 8 gages and associated cabling remained intact through the field operation. Two additional gages malfunctioned after the second overcoring in the laboratory. The main problems during the field overcoring were: 1) lead wires cut by broken core rock and 2) natural fracture going through the gage area, causing it to dissociate from the core. Another problem encountered during overcoring was temperature control. Two thermocouples were used to control the temperature during overcoring. One thermocouple monitored the temperature near the gage in the hole and another monitored the water temperature in the water tank which supplied water for circulation through the coring barrel which was heated up by friction during

overcoring. By heating up water in the tank or adding cold mine water, we attempted to keep the temperature in the rock near the gage "constant". In certain cases the thermocouple in the rock was broken. Thus, we could only monitor the tank water temperature which could be quite different from that in the rock. Table 5 summarizes the status of all gages during overcoring. The stress relief data are listed in Tables 6 to 9 and plotted in Figures 19 to 24. For gages NSG241, NSG242, NSG243, NSG244, NSG245, and NSG246, the temperature corrected readout data were also listed in Tables 8 and 9 and plotted in Figures 23 and 24. In general, the corrections were small and did little change to the plots.

The maximum length of a core, limited by the length of the core barrel used, is about 34". The plan was to have the last core between 30" to 32" long and with all three gages in a rosette sitting in the middle of the core. This required a distance about 11" from the starting face to the nearest gage. The label '11" from NSG233' states that the location of gage NSG233 is 11" away from the starting face where the penetration is zero.

IV FINAL LABORATORY CALIBRATION

Only six gages survived the two operations of overcoring. These six gages are contained in two long cores as shown in Figures 25 and 26. One core contains NSG231, NSG232, and NSG233. The gage NSG231 is only about 5/8" from the end which was broken from the rock in a 45° angle. The other core contains NSG244, NSG245, and NSG246. The gage NSG246 is right at the edge of the chipped end as shown in Figure 26.

The laboratory calibration was carried out with the IRAD GAGE model MC-1 biaxial Modulus Chamber which is a hydraulic device which applied pressure over a 6" length of the core with a hand-operated jack. The overcore sample was mounted in the chamber with one gage positioned at the center so that rock/chamber contact was only through the rubber membrane housing. The finished cores were slightly undersized for the biaxial chamber. Thus, we had to shim it with a layer of hard rubber. The hydrostatic load was applied to the overcore exterior via the rubber membrane. The core was load cycled three times with the pressure recorded every 200 psi (1.4 MPa). The biaxial chamber can generate a maximum pressure of 3000 psi (20.7 MPa). We experienced some oil leaking problems at high pressure. Therefore, we operated the biaxial chamber only up to 2600 psi (17.9 MPa). The equivalent uniaxial stress for the core is only 0.72 of the biaxial chamber pressure for our configuration (Dutta, Hatfield, and Runstadler 1981). The gage response was read from a MB6-1 vibrating-wire readout meter. The results of the biaxial calibration are listed in the Tables 10 to 15 and plotted in Figures 27 to 32. The pressure gage on the biaxial chamber was calibrated at LLNL. The calibration data are shown in Table 16. The largest deviation is at the low pressure end and is of an order of 2%. However, the deviation is generally below 0.5% for most of the pressure range.

V DISCUSSION AND CONCLUSION

If we assume that the gage-rock interface has been the same since the gage was installed, then the gage should have the same reading under the same temperature and load condition. The temperature during the laboratory cali-

bration of the overcored gage was about 20°C. We corrected all vibrating-wire stressmeter data to this temperature by Eq. 2 and read the corresponding stress level at 20°C from the biaxial calibration data (Figures 27-32). Table 17 lists the data where t_{f1} , t_{f2} , and T_{f1} , T_{f2} are the temperatures and vibrating-wire readout when the spent fuel was retrieved and at the end of the test as shown in Figures 4 to 18. T'_{f1} and T'_{f2} are the temperature corrected T_{f1} and T_{f2} at 20°C. σ_{f1} and σ_{f2} are corresponding stress levels at 20°C. Similarly, t_{01} , t_{02} etc. are those for the overcoring stress relief data. The numbers in the parentheses are either extrapolated values or not temperature corrected due to lack of temperature data.

The estimated in-situ stresses (σ_{f2}) are quite consistent with those reported (Creveling et al. 1984). The largest stress (σ_{f2}), at the end of the test, was about 2015 psi (13.9 MPa) for NSG231 which is located 2.8 m from the north heater drift wall and oriented 60°CW as viewed from north heater drift wall. Both the vertically oriented gages (NSG232 and NSG245) gave stress levels between 1150 to 1296 psi (7.9 to 8.9 MPa). The other three gages all had stresses between 145 to 292 psi (1 to 2 MPa).

Thermal stress changes after retrieval of spent fuel were mainly seen by those gages oriented vertically in the horizontal holes in the pillar. The magnitude of stress drop ($\sigma_{f1} - \sigma_{f2}$) is about 300 psi (2 MPa).

The stressmeter responses due to stress relief for the gages in the two horizontal holes are somewhat different. For instance, data in Table 17 indicate nearly complete stress relief for NSG244, NSG245, and NSG246 but substantial residual stresses for NSG231, NSG232, and NSG233 right after overcoring. The relative gage response within a rosette for NSG231, NSG232, and NSG233 is also different from that for NSG241, NSG242, and NSG243 as shown in Figures 20 and 21. One possible explanation is that holes NSG03 and NSG04

are separated by a shear zone (Wilder and Yow, 1981). Consequently, they are in different local stress regions.

The installation data shown in Table 3 indicate that all the six gages calibrated in the laboratory belong to "normal" type. In Table 17, we also listed the initial and final readout (T_{L1} and T_{L2}) during the laboratory calibration. The stress sensitivity factor (α) was calculated for each gage by calculating the wire stress according to Eq. 2 and divided by the applied stress (1872 psi). The calculated stress sensitivity factor for NSG231 and NSG232 are 0.99 and 1.30 respectively and are much smaller than those for other four gages (2.34 to 2.85) as shown in Table 17. All these six gages had a preload above + 200 digits when they were installed. At that time, the rock was under in-situ stress loading. After overcoring, the stresses were relieved, the effective preload was much lower (all below + 150 digits). Since the stress sensitivity factor (α) is a function of preload for preload below + 175 digits (Dutta, Hatfield, and Runstadler, 1961), we would see some variation in the stress sensitivity factor.

A close examination of the laboratory calibration data also indicate that: 1) NSG231 has a larger hysteresis than others; 2) hysteresis is smaller at high rock stress than those at low rock stress; 3) there is an initial steep change in readout for NSG244, NSG245, and NSG246. All these could be the results of low preload value. In addition, stress relief due to overcoring may generate microcracks or allow existing ones to open which in turn could change the modulus of the sample. The steep change of readout for NSG244, NSG245, and NSG246 could be due to closing of microcracks at low pressure.

The triaxial chamber used in this study was unable to attain pressures in the range of the highest stress values recorded in situ. Since calibration of

the gage is stress dependent, it is important that the calibration be conducted over the full range of stresses observed in the field. The appropriate segment of the calibration may then be used, in accordance with the range of stresses encountered in the field by a particular gage.

Rock stress changes ($\Delta \sigma_p$) may be calculated according to Eq. 4.

Three sets of stress changes were calculated for each of the six gages calibrated in the laboratory. These changes are shown in Table 18 together with the changes read directly from post test calibration data as shown in Table 17. Negative values in Table 18 imply stress drop. In general stress changes estimated from post test calibration data are much larger than those calculated from Eq. 4 (with $A=1.6$). This implies that calculated stress changes from Eq. 4 could underestimate the magnitude of stress change as much as 75%.

The approach of calibrating overcored IRAD gages following completion of field measurements is fundamentally sound. It addresses the concerns of the unique gage/rock interactions which profoundly influence the relationship between gage reading and change in rock stress. The practical matter of overcoring the gages was a limited success--only 6 of 18 gages survived both the field and laboratory coring processes. Additional fixtures must be developed and tested to provide reliable overcoring and a higher success rate of gage recovery. Although not a specific objective of this study, we found good agreement between the stress relief data obtained from the IRAD gages and the results of conventional stress-relief overcoring using USBM and CSIRO cells.

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- D = bore hole diameter - $1\frac{1}{2} \pm \frac{1}{16}$ in. (gauge range $\frac{1}{8}$ ")
 d_o = gauge diameter - 1.125 ± 0.003 in.
 D_i = gauge bore - $0.500, +0.002, -0.000$ in.
 h = gauge height to flat - 1.064 ± 0.002 in.
 l_w = wire length - 0.780 ± 0.002 in.
 L_g = gauge length - 1.500 ± 0.050 in.
 L_p = wedge length - $3\frac{1}{2}$ in. ± 0.050 in.

Figure 1. Critical dimensions of vibrating-wire stressmeter (After Dutta, Hatfield, and Runstadler, 1981).

Figure 2. Location of thermal phase instrumentation (After Carlson, et al., 1980).

Figure 3. Stressmeter placement (hole designations are given in parenthesis)
(After Carlson et al. 1980).

Figure 4. Field data for CSG222.

Figure 5. Field data for CSG223.

Figure 6. Field data for NSG231.

Figure 7. Field data for NSG232

Figure 8. Field data for NSG233.

Figure 9. Field data for NSG241.

Figure 10. Field data for NSG242.

Figure 11. Field data for NSG243.

Figure 12. Field data for NSG244.

Figure 13. Field data for NSG245.

Figure 14. Field data for NSG246.

Figure 15. Temperature data for SGT221.

Figure 16. Temperature data for SGT231.

Figure 17. Temperature data for SGT241.

Figure 18. Temperature data for SGT246.

Figure 19. Stress relief raw data

Figure 20. Stress relief raw data

Figure 21. Stress relief raw data

Figure 22. Stress relief raw data

Figure 23. Stress relief T-corrected

Figure 24. Stress relief T-corrected

Figure 25. Stressmeter location of cored sample for NSG231, NSG232, and NSG233.

Figure 26. Stressmeter location of cored sample for NSG244, NSG245, and NSG246.

Figure 27. Biaxial calibration data

Figure 28. Biaxial calibration data

Figure 29. Biaxial calibration data

Figure 30. Biaxial calibration data

Figure 31. Biaxial calibration data

Figure 32. Biaxial calibration data

Table 1. Stressmeter initial installation data.
(After Carlson et al. 1980)

DAS license plate	Position	Gage serial number	Zero load reading	Preload reading				Thermocouple license plate
				Tool in place	Tool removed	Δ	%	
CSG011	Shallow	07	2049	2389	2384	5	1	SGT011
CSG012	Mid	Q15	2018	2233	2205	28	13	
CSG013	Deep	05	2016	2232	2227	5	2	
CSG021	Shallow	Q1	2188	2397	2398	1	0	SGT021
CSG022	Mid	Q27	1839	2053	2035	18	8	
CSG023	Deep	Q4	1924	2129	2124	5	2	
NSG031	Shallow	Q9	2122	2322	2300	22	11	SGT031
NSG032	Mid	Q13	1837	2056	2042	16	7	
NSG033	Deep	Q18	1918	2122	2122	0	0	
NSG034	Shallow	Q17	2186	2416	2401	15	7	SFT034
NSG035	Mid	Q22	2177	2397	2372	25	11	
NSG036	Deep	Q26	2028	2230	2222	8	4	
NSG041	Shallow	011	2181	2429	2421	8	3	SGT041
NSG042	Mid	020	2200	2405	2391	14	7	
NSG043	Deep	03	1878	2090	2089	1	0	
NSG044	Shallow	012	2072	2275	2240	35	17	SGT044
NSG045	Mid	023	2121	2349	2343	6	3	
NSG046	Deep	024	2200	2404	2394	10	5	

Table 2. Stressmeter data for June 1981 installation
(After Patrick, et al., 1982)

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

^a Hole NSG04 (containing gauges NSG241-243) is 5.702 m long.

(N) = depth from north drift

Table 3. Stressmeter data for October 1982 installation
(After Patrick et al., 1983)

License	Serial number	IRAD channel	Depth, cm	Orientation	Emplacement reading				$\Delta(\%)$
					Zero	Tool set	Tool slack	Tool out	
NSG231	6-15	1	325	CW60°	2110	2313	2312	2307	2.96
NSG232	6-3	2	335	Vertical	2121	2334	2334	2325	4.23
NSG233	6-46	3	345	CCW60°	1928	2133	2132	2115	8.78
NSG234	6-47	4	95	CCW60°	1790	1997	1993	N/A	1.93
NSG235	6-2	5	105	Vertical	2120	2332	2329	2313	8.96
NSG236	6-13	6	115	CS60°	1983	2180	2178	2174	3.05
NSG244	6-53	10	75	CCW60°	1776	1979	1984	1975	1.97
NSG245	6-20	11	85	Vertical	2145	2347	2354	2342	2.48
NSG246	6-11	12	95	CW60°	2121	2329	2320	2318	5.29

Note: CW = clockwise looking down drill hole.

CCW = counterclockwise looking down drill hole.

Table 4. Temperature adjusted field data after spent fuel retrieval for selected gages.

Gage	Readout		Temperature		Readout	Readout
	-----		-----		Change	Change
	Start	End	Start	End	Raw	T corrected
CSG222	2338	2238	51.7	31.5	100	69
CSG223	2015	1945	51.7	31.5	70	39
NSG231	2308	2289	29.6	23.7	19	10
NSG232	2323	2300	29.6	23.7	23	14
NSG233	2114	2095	29.6	23.7	19	10
NSG241	2442	2416	30.7	24.5	26	16
NSG242	2436	2421	30.7	24.5	15	5
NSG243	----	----	30.7	24.5	----	----
NSG244	1957	1946	29.6	23.6	11	2
NSG245	2333	2303	29.6	23.6	30	21
NSG246	2300	2288	29.6	23.6	12	3

Table 5. Stressmeter overcoring and laboratory calibration status

Gage	Date	Stress	Temp	Lab.	Orientation
Overcored		Relief	Control	Calib	
CSG211	3-19-84	No	----	No	CW60
CSG212	3-19-84	No	----	No	<u>1</u> Rail
CSG213	3-19-84	No	----	No	CCW60
CSG221	3-13-84	No	Tank	No	CW60
CSG222	3-13-84	Yes	Tank	No	<u>1</u> Rail
CSG223	3-13-84	Yes	Tank	No	CCW60
NSG231	1-12-84	Yes	Tank	Yes	CW60
NSG232	1-12-84	Yes	Tank	Yes	Vertical
NSG233	1-12-84	Yes	Tank	Yes	CCW60
NSG234	1-05-84	No	----	No	CW60
NSG235	1-05-84	No	----	No	Vertical
NSG236	1-05-84	No	----	No	CCW60
NSG241	1-20-84	Yes	Rock	No	CW60
NSG242	1-20-84	Yes	Rock	No	Vertical
NSG243	1-20-84	Yes	Rock	No	CCW60
NSG244	1-17-84	Yes	Rock	Yes	CW60
NSG245	1-17-84	Yes	Rock	Yes	Vertical
NSG246	1-17-84	Yes	Rock	Yes	CCW60

Table 6. Stress relief data from CSG222 and CSG223 during overcoring.

Date: March 13, 1984

Depth inch	Readout csg222	Readout csg223
0	2222	1933
2	2222	1932
4	2222	1934
6	2223	1933
8	2224	1933
10	2224	1932
12	2226	1933
14	2228	1934
16	2227	1933
18	2199	1933
20	2162	1930
22	2147	1932
24	2144	1925
26	2147	1924
28	2147	1929
30	2147	1939
32	2146	1940

Table 7. Stress relief data for NSG231, NSG232,
and NSG233 during overcoring.

Note: Depth Measurements Start at 11" from NSG233
Date: January 12, 1984

Depth inch	Readout nsg231	Readout nsg232	Readout nsg233
0	2279	2288	2086
1	2277	2287	2089
2	2282	2290	2093
3	2286	2295	2096
4	2289	2298	2098
5	2289	2298	2101
6	2289	2300	2098
7	2282	2292	2097
8	2276	2286	2087
9	2275	2285	2083
10	2276	2285	2083
11	2277	2287	2083
12	2277	2287	2083
13	2278	2288	2084
14	2279	2288	2084
15	2281	2287	2084
16	2283	2285	2085
17	2284	2281	2086
18	2285	2277	2087
19	2286	2273	2089
20	2275	2268	2090
21	2269	2266	2090
22	2254	2266	2092
23	2247	2266	2092
24	2237	2266	2092
25	2236	2266	2091
26	2232	2267	2092
27	2231	2268	2092
28	2232	2270	2094
29	2232	2269	2093
30	2232	2268	2091

Table 8. Stress relief data for NSG241, NSG242, and NSG243 during overcoring

Note: Depth Measurements Start at 11" from NSG243

Date: Jan. 20, 1984

Depth inch	Temp. degree	Raw Data			Temperature Corrected		
		Readout nsq241	Readout nsq242	Readout nsq243	Readout nsq241	Readout nsq242	Readout nsq243
0	22.0	2407	2418	2162	2407	2418	2162
1	21.8	2406	2418	2162	2406	2418	2162
2	23.5	2413	2422	2169	2415	2424	2171
3	24.0	2415	2425	2170	2418	2428	2173
4	22.9	2411	2422	2165	2412	2423	2166
5	22.3	2408	2419	2163	2408	2419	2163
6	22.1	2407	2419	2162	2407	2419	2162
7	21.9	2406	2420	2162	2406	2420	2162
8	21.4	2405	2418	2159	2404	2417	2158
9	20.8	2402	2418	2157	2400	2416	2155
10	20.7	2401	2417	2156	2399	2415	2154
11	20.8	2402	2417	2157	2400	2415	2155
12	20.9	2403	2419	2158	2401	2417	2156
13	21.0	2402	2419	2157	2400	2417	2155
14	20.9	2403	2419	2156	2401	2417	2154
15	21.0	2403	2420	2155	2401	2418	2153
16	20.4	2400	2419	2153	2398	2417	2151
17	20.3	2399	2418	2153	2396	2415	2150
18	22.6	2410	2422	2161	2411	2423	2162
19	24.0	2416	2428	2161	2419	2431	2164
20	24.4	2417	2430	2155	2421	2434	2159
21	24.7	2418	2432	2152	2422	2436	2156
22	24.7	2418	2432	2151	2422	2436	2155
23	24.6	2417	2432	2152	2421	2436	2156
24	24.3	2415	2429	2156	2419	2433	2160
25	24.2	2415	2422	2160	2418	2425	2163
26	23.8	2414	2412	2163	2417	2415	2166
27	23.2	2412	2403	2162	2414	2405	2164
28	22.8	2411	2396	2163	2412	2397	2164
29	22.3	2410	2389	2165	2410	2389	2165
30	21.9	2407	2387	2164	2407	2387	2164

Table 9. Stress relief data for NSG244, NSG245, and NSG246 during overcoring.

Note: Depth Measurements Start at 11" from NSG244

Date: Jan. 17-19, 84

Depth inch	Temp. degree	Raw Data			Temperature Corrected		
		Readout nsq244	Readout nsq245	Readout nsq246	Readout nsq244	Readout nsq245	Readout nsq246
0	21.6	1942	2293	2282	1942	2293	2282
1	21.8	1941	2294	2282	1941	2294	2282
2	21.7	1943	2293	2282	1943	2293	2282
3	21.8	1943	2293	2282	1943	2293	2282
4	21.8	1942	2293	2283	1942	2293	2283
5	21.9	1943	2293	2283	1943	2293	2283
6	22.1	1943	2294	2283	1944	2295	2284
7	21.4	1941	2293	2282	1941	2293	2282
8	21.2	1940	2294	2282	1939	2293	2281
9	21.6	1940	2294	2283	1940	2294	2283
10	22.4	1940	2296	2283	1941	2297	2284
11	22.3	1939	2297	2283	1940	2298	2284
12	22.8	1939	2297	2283	1941	2299	2285
13	24.3	1941	2301	2284	1945	2305	2288
14	24.3	1941	2300	2284	1945	2304	2288
15	24.3	1942	2299	2285	1946	2303	2289
16	24.4	1944	2294	2286	1948	2298	2290
17	24.6	1944	2287	2288	1949	2292	2293
18	24.8	1945	2274	2288	1950	2279	2293
19	25.2	1946	2261	2288	1952	2267	2294
20	25.7	1947	2248	2288	1953	2254	2294
21	26.1	1946	2236	2285	1953	2243	2292
22	26.8	1947	2229	2276	1955	2237	2284
23	27.2	1947	2225	2268	1956	2234	2277
24	27.6	1948	2223	2259	1957	2232	2268
25	21.7	1943	2218	2257	1943	2218	2257
26	21.8	1943	2217	2254	1943	2217	2254
27	22.0	1943	2217	2256	1944	2218	2257
28	22.1	1942	2217	2255	1943	2218	2256
29	22.2	1943	2219	2255	1944	2220	2256
30	21.9	1945	2219	2255	1945	2219	2255

Table 10. Laboratory calibration of overcore for NSG231.

June 6, 1984

pressure stress		1up	1dn	2up	2dn	3up	3dn	up-avg	dn-avg	average
psi		psi								
0	0	2208	2208	2208	2208	2209	2208	2208	2208	2208
200	144	2211	2212	2211	2211	2211	2211	2211	2211	2211
400	288	2215	2215	2214	2215	2214	2215	2214	2215	2214
600	432	2221	2218	2219	2218	2217	2218	2219	2218	2218
800	576	2225	2222	2221	2221	2220	2221	2222	2221	2221
1000	720	2230	2225	2224	2224	2224	2224	2226	2224	2225
1200	864	2234	2228	2227	2228	2228	2228	2230	2228	2228
1400	1008	2239	2232	2232	2231	2231	2231	2234	2231	2232
1600	1152	2243	2235	2235	2236	2236	2235	2238	2235	2236
1800	1296	2247	2240	2240	2240	2240	2239	2242	2240	2241
2000	1440	2252	2245	2246	2245	2245	2245	2248	2245	2246
2200	1584	2257	2252	2253	2251	2251	2250	2254	2251	2253
2400	1728	2262	2259	2259	2258	2258	2257	2260	2258	2259
2600	1872	2267	2267	2266	2266	2265	2265	2266	2266	2266

Table 11. Laboratory calibration of overcore for NSG232.

January 7, 1984

pressure	stress	1up	1dn	2up	2dn	3up	3dn	up-avg	dn-avg	average
psi	psi									
0	0	2241	2242	2242	2242	2242	2242	2242	2242	2242
200	144	2246	2248	2247	2248	2247	2248	2247	2248	2247
400	288	2252	2254	2253	2254	2253	2253	2253	2254	2253
600	432	2258	2260	2259	2260	2259	2260	2259	2260	2259
800	576	2264	2266	2264	2266	2265	2266	2264	2266	2264
1000	720	2270	2271	2270	2272	2270	2271	2270	2271	2270
1200	864	2276	2277	2276	2277	2276	2277	2276	2277	2276
1400	1008	2282	2284	2282	2283	2282	2283	2282	2283	2282
1600	1152	2289	2290	2289	2290	2289	2289	2289	2290	2289
1800	1296	2295	2295	2295	2295	2295	2295	2295	2295	2295
2000	1440	2301	2301	2301	2302	2302	2302	2301	2302	2301
2200	1584	2309	2308	2308	2309	2308	2308	2308	2308	2308
2400	1728	2315	2315	2315	2315	2315	2315	2315	2315	2315
2600	1872	2325	2325	2323	2323	2323	2323	2324	2324	2323

Table 12. Laboratory calibration of overcore for NSG233.

January 8, 1984

pressure	stress	clup	cldn	c2up	c2dn	c3up	c3dn	upavg	dnavg	avg
psi	psi									
0	0	2069	2070	2070	2070	2070	2070	2070	2070	2070
200	146	2078	2079	2078	2079	2079	2079	2078	2079	2079
400	292	2089	2089	2088	2089	2088	2089	2088	2089	2089
600	438	2101	2099	2098	2099	2098	2099	2099	2099	2099
800	584	2111	2110	2108	2109	2108	2109	2109	2109	2109
1000	730	2124	2120	2119	2120	2118	2119	2120	2120	2120
1200	876	2135	2129	2129	2129	2129	2129	2131	2129	2130
1400	1022	2146	2140	2140	2140	2139	2140	2142	2140	2141
1600	1168	2158	2151	2151	2150	2150	2150	2153	2150	2152
1800	1314	2169	2162	2162	2162	2162	2161	2164	2162	2163
2000	1460	2181	2173	2175	2174	2174	2173	2177	2173	2175
2200	1606	2193	2187	2188	2187	2187	2186	2189	2187	2188
2400	1752	2205	2202	2203	2201	2201	2200	2203	2201	2202
2600	1898	2218	2218	2217	2217	2215	2215	2217	2217	2217

Table 13. Laboratory calibration of overcore for NSG244.

May 20, 1984

[illegible]

Table 14. Laboratory calibration of overcore for NS6245.

May 30, 1984

pressure	stress	c1up	c1dn	c2up	c2dn	c3up	c3dn	upavg	dnavg	avg
psi	psi									
0	0	2202	2206	2206	2206	2206	2207	2205	2206	2206
200	144	2229	2241	2236	2242	2238	2242	2234	2242	2238
400	288	2241	2252	2248	2253	2249	2254	2246	2253	2250
600	432	2251	2260	2258	2262	2259	2263	2256	2262	2259
800	576	2261	2269	2266	2270	2267	2271	2265	2270	2267
1000	720	2270	2276	2273	2278	2275	2279	2273	2278	2275
1200	864	2281	2283	2282	2285	2283	2286	2282	2285	2283
1400	1008	2291	2291	2290	2292	2290	2293	2290	2292	2291
1600	1152	2302	2298	2297	2300	2298	2300	2299	2299	2299
1800	1296	2311	2306	2306	2307	2307	2307	2308	2307	2307
2000	1440	2321	2315	2316	2315	2316	2315	2318	2315	2316
2200	1584	2331	2325	2327	2325	2326	2325	2328	2325	2327
2400	1728	2342	2338	2339	miss	2338	2337	2340	2338	2339
2600	1872	2353	2353	2350	2350	2351	2351	2351	2351	2351

Table 16. Calibration results for biaxial chamber pressure gage.

True (psi)	Read (psi)	Diff(%)
0	0	0
500	511	2.20
1000	1004	0.40
1500	1502	0.13
2000	1999	-0.05
2500	2504	0.16
3000	3008	0.27

Table 17. Calculated stresses at 20°C based on laboratory calibrations

Gage	NSG231	NSG232	NSG233	NSG244	NSG245	NSG246
Orientation	ccw60°	vertical	ccw60°	ccw60°	vertical	ccw60°
Values at Time of Spent Fuel Retrieval						
t_{f1} °C	29.6	29.6	29.6	29.6	29.6	29.6
T_{f1}	2308	2323	2114	1957	2333	2300
T'_{f1} (20°C)	2293	2308	2099	1942	2318	2285
σ_{f1} (20°C) psi	(2030)	1584	438	150	1470	240
t_{f2} °C	23.7	23.7	23.7	23.6	23.6	23.6
T_{f2}	2289	2300	2095	1946	2303	2288
T'_{f2} (20°C)	2283	2290	2089	1940	2297	2282
σ_{f2} (20°C) psi	(2015)	1296	292	145	1150	230
Values during Overcoring						
t_{o1} °C	----	----	----	21.6	21.6	21.6
T_{o1}	2279	2288	2086	1942	2293	2282
T'_{o1} (20°C)	----	----	----	1939	2290	2279
σ_{o1} (20°C) psi	(2000)	(1152)	(240)	120	1000	170
t_{o2} °C	----	----	----	21.9	21.9	21.9
T_{o2}	2232	2268	2091	1945	2219	2255
T'_{o2} (20°C)	----	----	----	1942	2216	2252
σ_{o2} (20°C) psi	(1008)	(680)	(360)	160	50	30
Values during Laboratory Calibration						
$T_{\&1}$	2208	2242	2070	1927	2206	2246
$T_{\&2}$	2266	2323	2217	2025	2351	2412
Stress Sensitivity						
Factor (α)	0.99	1.30	2.85	2.42	2.34	2.51

Table 18. Estimated stress changes (psi) at 20°C based on laboratory calculation and Eq. 4 ($A=1.6$).

Gage	NSG231	NSG232	NSG233	NSG244	NSG245	NSG246
Orientation	cw60°	vertical	ccw60°	ccw60°	vertical	cw60°
Values at Time of Spent Fuel Retrieval						
T'_{f1}	2293	2308	2099	1942	2318	2285
T'_{f2}	2283	2290	2089	1940	2297	2282
$\Delta \sigma_r$ Eq. 4	-69	-123	-90	-23	-142	-21
$\Delta \sigma_r$ This rpt	-15	-288	-140	-5	-320	-10
Values during Overcoring						
T_{o1}	2279	2288	2086	1939	2290	2279
T_{o2}	2232	2268	2091	1942	2216	2252
$\Delta \sigma_r$ Eq. 4	-339	-140	45	34	-536	-192
$\Delta \sigma_r$ This rpt	-992	-472	120	40	-950	-140
Values during Laboratory Calibration						
T_{L1}	2208	2242	2070	1927	2206	2246
T_{L2}	2266	2323	2217	2025	2351	2412
$\Delta \sigma_r$ Eq. 4	429	564	1239	1053	1017	1091
$\Delta \sigma_r$ This rpt	1872	1872	1872	1872	1872	1872

Note: Negative stress difference implies stress drop.