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A NEW APPROACH FOR CALIBRATION AND INTERPRETATION of IRAD GAGE VIBRATING-WIRE STRESSMETERS

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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). This paper 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. 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-test calibration data is generally much smaller than that estimated from post test calibration data.

RESUME

Des jauges de contreinte à corde vibrante, IRAD, ont été installées au Spent-Fuel Test, Nevada Test Site, pour mesurer les changements de contraintes in-situ, pendant le test. On décrit les mesures obtenues par hypercarottage des jauges, suivies de calibration des carottes contenant les jauges, au laboratoire. Les valeurs des contraintes in-situ estimées sur la base de calibration apres-test sont proches de celles mesurées directement en place, dans des forages avoisinants. Par contre, le changement de contraintes calculé à partir de calibration avant-test est, en general, beaucoup plus faible que celui estime à partir de calibration apres-test.

ZUSAMMENFASSUNG

IRAD-GAGE-Meßgeräte mit schwingendem Draht zur Messung der Spannungsbeanspruchung wurden in der Anlage für abgebrannten Brennstoff auf dem Testgelände von Nevada eingelagert, um die Veränderungen der in-situ-Spannungen während der Spent Fuel Test-Climax (SFT-C) zu messen. Die vorliegende Arbeit referiert über die Ergebnisse nach Entfernung eines zylindrischen Felsabschnittes samt Meßinstrumenten mittels Overcoring und über die anschließenden, nach dem Testablauf durchgeführten Eichungen der Spannungsmesser im Labor. Die Schätzwerte der auf nach dem Test erhaltenen Eichwerten basierenden in-situ-Spannungen stimmen mit in benachbarten Löchern direkt gemessenen Daten durchaus überein. Die Größenordnung der auf der Grundlage von vor der Einlagerung der Spannungsmesser erhaltenen Veränderungen der Spannungswerte liegt allgemein bedeutend unter der auf Grund der Eichdaten nach dem Test geschätzten Größenordnung.

1. INTRODUCTION

The Spent Fuel Test - Climax (SFT-C) is part of the Department of Energy's (DOE) Nevada Nuclear Waste Storage Investigations Project. 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).

In this generic test, located 420 m below the surface in the Climax granite stock at the Nevada Test Site, 11 canisters containing spent fuel assemblies were 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. A number of laboratory and field studies for site characterization and instrument calibration were carried out and reported (Carlson et al. 1980; Heuze et al. 1982; Patrick et al. 1981, 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 paper 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.

2. PREVIOUS WORK

2.1 Laboratory Calibration:

IRAD GAGE, Inc. was contracted to perform laboratory calibration studies of the vibrating-wire stressmeter in Climax granite (Dutta et al. 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.

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. 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:

$$f = \frac{1}{2\ell_w}\sqrt{\frac{\sigma_w g}{\rho}} \qquad (1)$$

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

For the IRAD GAGE stressmeter, $\ell_w = 0.780$ in. and $\rho = 0.283\ \text{lb/in.}^3$. Defining T as the 4 digit display of the IRAD GAGE vibrating-wire readout unit, where T is given by $10^7/f$, then

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

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 stressmeter sensitivity factor is nonlinear 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.

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 was 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.

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

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

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)

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

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 (°C), and 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%.

2.2 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 1 shows the location of the vibrating-wire stressmeters and other instruments. 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. Each horizontal hole has two rosettes: one installed from the Canister Drift and one from the North Heater Drift.

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). 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.

2.3 Stressmeter Failure:

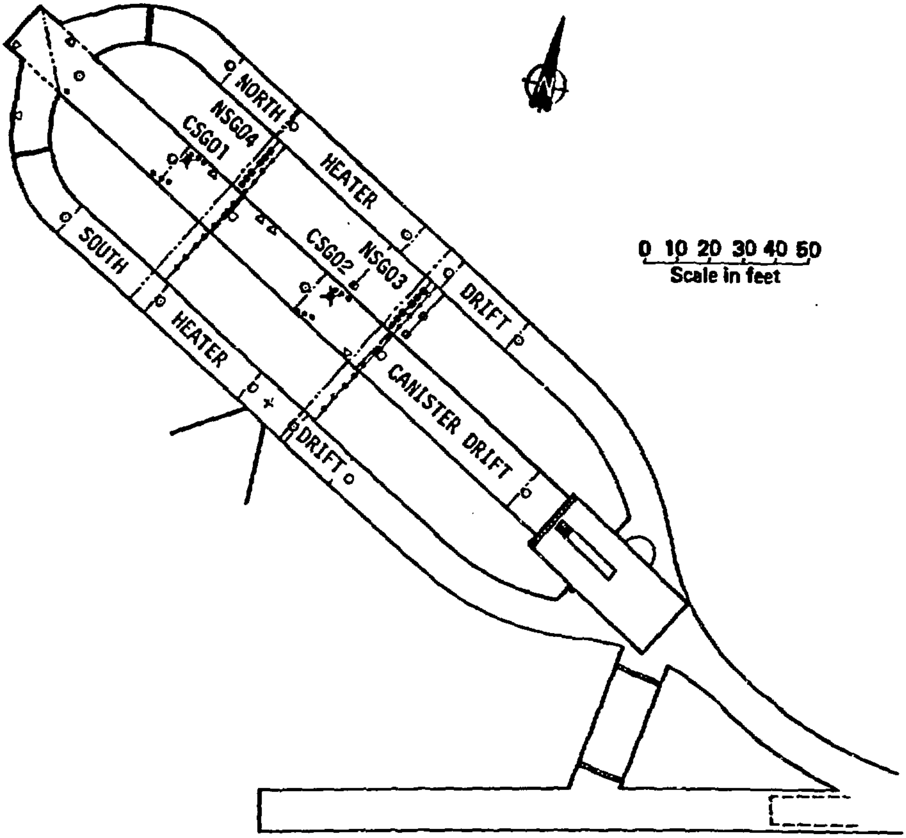
Four of the six gages in vertical holes near the canister emplacement holes failed within 4 months after installation. By June, 1981, 13 of the 18 gages failed. The cause was identified as internal rusting, especially of the wire itself, due to moisture. IRAD GAGE, Inc. redesigned the gage, providing 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 et al. 1981).

By October, 1982, the remaining 5 originally installed gages also failed. Nine additional stressmeters of the modified version were installed on October 25-27, 1982.

2.4 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 electrical heaters were turned off between March 3 and April 6, 1983. Figure 2 shows the raw data of NSG245 during the last year of operation. 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 near 5.3 years out of core is due to the retrieval of spent fuel and the turning off the power to the heaters.

Figure 3 shows the temperature changes at the gage NSG244 next to NSG245 for the same period.



Legend

-•-•-•-	Reconditioned mine-by extensometer array (circles indicate approximate anchor locations for upper extensometer).
•	*Thermal phase extensometer installed vertically.*
o–o–	Vibrating wire stressmeters showing approximate gage location (not reinstalled for thermal phase monitoring).
–■■■–	Thermal phase vibrating wire stressmeters in horizontal bore hole (squares show approximate location for three-gage array).
✖	Thermal phase vibrating wire stressmeters in vertical bore holes.
— - - —	Horizontal convergence (wire) extensometer.
○	Vertical convergence (wire) extensometer.
△	*Three component fracture monitor systems.*
+	Vertical overcore boring.
═	Horizontal overcore boring.

Figure 1. Location of thermal phase instrumentation (after Carlson et al. 1980).

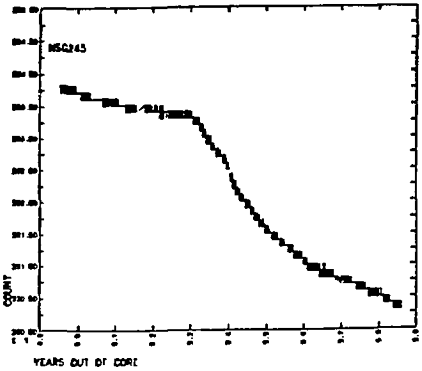


Figure 2. Field data for NSG245.

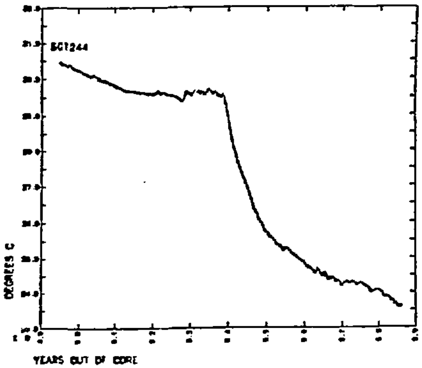


Figure 3. Temperature data for SGT244.

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 that is sensed 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.

2.5 In-situ Stresses:

In-situ stress measurements in the vicinity of the SFT-C were reported by Creveling et al. (1984). The 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).

3. OVERCORE OF STRESSMETERS

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 the SFT-C 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.

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 due to a broken thermocouple in the rock. The stress relief data for gages NSG244, NSG245, and NSG246 are shown in Figure 4. In general, the temperature corrections were small and produced little change in the plots.

4. FINAL LABORATORY CALIBRATION

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

The laboratory calibration was carried out with the IRAD GAGE model MC-1 biaxial Modulus Chamber, 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. The hydrostatic load was applied to the overcore exterior via a rubber membrane. The load was cycled three times with the pressure recorded at 200 psi (1.4 MPa) increments up to 2600 psi (17.9 MPa). The equivalent uniaxial stress for the core was only 0.72 of the biaxial chamber pressure for our configuration (Dutta et al. 1981). The gage response was read from a MB6-1 vibrating-wire readout meter. The results of the biaxial calibration for NSG245 are shown in Figure 5.

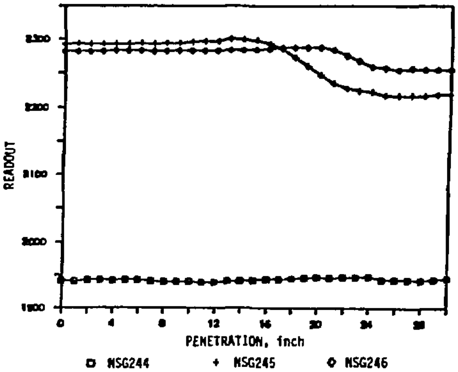


Figure 4. Stress relief data for NSG244-246.

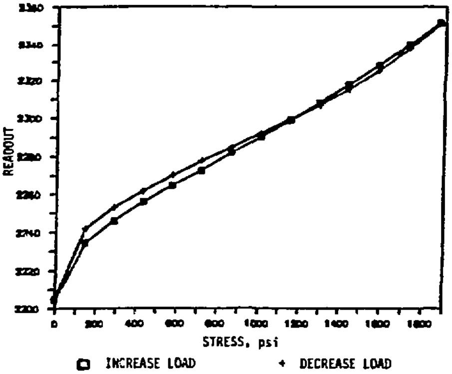


Figure 5. Laboratory calibration data for NSG245, post-test.

5. 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 calibration 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. All data can be grouped according to the three stages of operations, i.e., the field data of the spent fuel retrieval, the data during overcoring, and the biaxial calibration data in the laboratory. These stages are indicated by the first subscript f, o, and ℓ, respectively (see Table 1). The second subscript is either 1 or 2 to indicate the values at the start and end of each stage. Thus, 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 Figure 2. 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. 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 and 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 (σ_{f1}-σ_{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 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. 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 indicate that all the six gages calibrated in the laboratory belong to the "normal" type. In Table 1, we also listed the initial and final readout ($T_{\ell1}$ and $T_{\ell2}$) during the laboratory calibration. The stress sensitivity factor (α) was calculated for each gage by calculating the wire stress according to Eq. 2 and dividing by the applied stress (1872 psi). The calculated stress sensitivity factors for NSG231 and NSG232 are 0.99 and 1.30 respectively and are much smaller than those for the other four gages (2.34 to 2.85), as shown in Table 1. All 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 and 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 et al. 1981), we would expect some variation in the stress sensitivity factor.

A close examination of the laboratory calibration data also indicates that: 1) NSG231 has a larger hysteresis than others; 2) hysteresis is smaller at high rock stress than 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.

Table 1. Calculated stresses at 20°C based on laboratory calibrations (parentheses indicate either extrapolated values or not temperature correlated).

Gage		NSG231	NSG232	NSG233	NSG244	NSG245	NSG246
Orientation		cw60°	vertical	ccw60°	ccw60°	vertical	cw60°
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							
$T_{\ell 1}$		2208	2242	2070	1927	2206	2246
$T_{\ell 2}$		2266	2323	2217	2025	2351	2412
Stress Sensitivity Factor (α)		0.99	1.30	2.85	2.42	2.34	2.51

The biaxial 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 ($\Delta \sigma_r$) 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 2 together with the changes read directly from post test calibration data as shown in Table 1. Negative values in Table 2 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. However, the results from biaxial calibration can only be adjusted to an equivalent uniaxial case which can be somewhat different from in-situ condition of triaxial loading. Nevertheless, we believe that the error introduced by biaxial calibration may be relatively small as compared with that from the effect of gage/rock interactions. 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. 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.

Table 2. Estimated stress changes (psi) at 20°C based on laboratory calculation and Eq. 4 (A=1.6).

Gage Orientation	NSG231 cw60°	NSG232 vertical	NSG233 ccw60°	NSG244 ccw60°	NSG245 vertical	NSG246 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
$\Delta \sigma_r$ $(\sigma_{f1}-\sigma_{f2})$	-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
$\Delta \sigma_r$ $(\sigma_{o1}-\sigma_{o2})$	-992	-472	120	40	-950	-140
Values during Laboratory Calibration						
$T_{\ell 1}$	2208	2242	2070	1927	2206	2246
$T_{\ell 2}$	2266	2323	2217	2025	2351	2412
$\Delta \sigma_r$ Eq. 4	429	564	1239	1053	1017	1091
$\Delta \sigma_r$ (applied)	1872	1872	1872	1872	1872	1872

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