UCRL 88933
PREPRINT

CONF-8406101--3

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THERMALLY INDUCED DISPLACEMENTS IN LARGE BOREHOLES IN ROCK

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UCRL--88933
DE84 010688

This paper was prepared for submittal to
V International Congress on Experimental Mechanics
Montreal, Canada
June 10-15, 1984

March 1984

Lawrence
Livermore
National
Laboratory

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THE APPLICATION OF PROVING-RING TECHNOLOGY TO MEASURE THERMALLY INDUCED DISPLACEMENTS IN LARGE BOREHOLES IN ROCK*

Wesley C. Patrick, Norman L. Rector, Theodore R. Butkovich

ABSTRACT

A strain-gauged proving-ring transducer was designed and deployed to measure small diametral displacements in 0.61-m diameter boreholes in rock. The rock surrounding the boreholes was previously heated by storage of spent nuclear fuel assemblies and measurements during post-retrieval cooling of the rock were made. To accomplish this, a transducer was designed to measure displacements in the range of 10 to 100 μm , to function in a time-varying temperature regime of 30° to 60°C at a relative humidity of 100%, to be of low stiffness, and to be easily and quickly installed.

INTRODUCTION AND BACKGROUND

The feasibility of deep geologic storage of spent nuclear fuel assemblies is being evaluated at the Spent Fuel Test-Climax (SFT-C) [Rampott et al., 1979]. The SFT-C is being conducted at the U.S. Department of Energy's Nevada Test Site under the technical direction of Lawrence Livermore National Laboratory. The test is located 420 m below surface in the Climax granitic stock. The stock is unsaturated but not dry at the test level.

During April-May 1980, 11 spent-fuel assemblies and 6 electrical simulators were emplaced in 0.61-m diameter by 4.9-m deep vertical storage boreholes located in the floor of a central drift (Fig. 1). Parallel drifts on each side of the central drift housed a total of 20 adjustable-power electrical heaters to simulate a large panel of a full-scale repository. The response of the surrounding region, involving a 10,000 m³ volume of rock, was monitored with nearly 1000 instruments during the three-year spent-fuel storage period and the six-month cooling phase which followed retrieval of the spent fuel and deenergizing of the electrical heaters.

Calculations indicated that while displacements within the underground facility would range from about 0.1 to 3 mm during the spent-fuel storage phase of the experiment, they would be less than 0.1 mm during the cooling phase [Ballou et al., 1982]. Since commercially available field instrumentation was incapable of resolving the small displacements which were expected during cooling, a new transducer was developed and fielded to augment the existing instrumentation.

ESTIMATED BOREHOLE DISPLACEMENTS

Initial estimates of borehole closure were obtained using the analytic solution for displacement of a hollow cylinder which is constrained in the axial direction and

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which has a temperature (T) given as a function of radius (r), only [Zudans et al., 1965]. The solution for radial displacement (u) is

$$u = \frac{1+\nu}{1-\nu} \frac{\alpha}{r} \left[\frac{(1-2\nu)}{b^2-a^2} r^2 + a^2 \int_a^b T r dr + \int_a^r T r dr \right]$$

where

ν is Poisson's ratio,
 α is the linear coefficient of thermal expansion of the rock,
 a is the inner radius, and
 b is the outer radius.

Temperature distributions were obtained from heat-flow calculations of the SFT-C which were performed with the TRUMP finite difference code [Montan and Patrick, 1981, and Ballou et al., 1982]. By expressing T as a function of r, we were able to solve for u in the above equation. The estimated decrease in diameter was found to be 84 μ m.

Although this estimate was adequate for transducer design, we utilized the finite element code ADINA to perform calculations which included such considerations as an anisotropic stress field [Patrick et al., 1984]. This analysis indicated the complex time- and azimuthally-varying nature of the anticipated borehole displacements (Fig. 2). Note that the maximum diametral displacement predicted by this analysis is 65 μ m.

TRANSDUCER DESIGN AND FABRICATION

Four fundamental design criteria were applied which led to selection and deployment of the strain-gauged proving-ring transducer. First, it must be capable of accurately measuring displacements of less than 0.1 mm over a gauge length of 0.61 m. Second, it must function reliably in an environment where temperatures would exponentially decrease during a 6-month period from 60°C to 300°C at 100% relative humidity. Third, its interactions with the borehole must be sufficiently small so as not to influence the response of the borehole; that is, it should be a low stiffness system. Fourth, it must be simple in design and amenable to rapid installation since a major percentage of the near-field displacements resulting from cooling would occur very soon after removal of the thermal sources.

While LVDTs and electromagnetic proximeters perform quite well at stable elevated or lowered temperatures, their calibration characteristics change significantly when they are deployed where temperatures are time-varying. The design criteria thus eliminated LVDTs and electromagnetic proximeters from further consideration. Previous experiences in the humid test environment also led us to eliminate linear potentiometers [Patrick, Carlson, and Rector, 1982].

Analytical solutions were obtained for various combinations of diameter, width, and thickness of proving rings. Based on the calculated outer-fiber strains and stiffnesses, a subjective decision was made with regard to the first and third design criteria. The design calculations resulted in selection of a 203.2 mm (8-in.) outside diameter by 190.5 mm (7.5-in.) inside diameter by 25.4 μ m (1.0-in.) wide steel proving ring (Fig. 3). This configuration, properly strain-gauged, meets the first design criteria by offering a calculated full-bridge output of 1.48 mV at a full-scale borehole displacement of 65 μ m. It meets the third criteria in that the system stiffness is only about 63.5 Kg/mm.

Adjustable standoffs were developed to allow for variations in borehole diameters and to permit preloading of the transducers in the borehole. A baseplate and support bracket designed to accommodate a rosette of three transducers minimizes the likelihood of the transducers slipping vertically in the borehole. The support bracket is screw actuated against a spring load, so changes in borehole diameter resulting from the rock cooling will not adversely influence the support. Incorporation of the proving ring into this relatively simply designed fixture produced a transducer which can be easily and quickly installed 3.0 to 4.6 m (10 to 15 ft.) deep in a 0.61 m diameter borehole, thus meeting the fourth criteria (Fig. 4).

Work by Freynik and Dittbenner (1976) indicated that Micro-Measurement's Karma foil gauge would perform well at the elevated temperatures expected in this application. Based on their results and manufacturer's data, we selected Micro-Measurement's SK-06-125AD-350 for our application. The gauges were purchased with a single lot number in order to take advantage of uniformity of materials and construction. Conventional surface preparations were made and the gauges were bonded with M-Bond 610, oven cured for two hours at 176°C. The strain gauges were wired in a full bridge configuration to minimize thermally induced errors in the gauge readings. A four-layer environmental protection was applied in accordance with manufacturer's suggestions: M-Coat D (toulene-thinned acrylic), M-Coat W1 (microcrystalline wax), M-Coat FB (butyl rubber sealant), and M-Coat FM (Neoprene rubber sheet). While the first three coatings protect against invasion of moisture, the latter coating has the dual purpose of protecting from moisture and mechanical damage to the strain gauges.

A single Type K thermocouple was mounted on each set of proving rings to provide data for compensation of the effects of thermal expansion of transducer components. The rings were calibrated on a Ormond Beam Balance Calibrator. A Bourns Model 141 rectilinear potentiometer was installed diametrically across the ring as demonstrated in Fig. 5. The ring was exercised ten times through the 0.51 mm (0.02 in.) range to insure that all mechanical interfaces were stable, that test frame hardware alignments were correct, and that related hysteresis would be minimized. This calibration was performed at the laboratory ambient temperature of 23°C. An elevated-temperature calibration was also performed. To accomplish this, a styrofoam box was constructed around the ring and the temperature of the proving-ring was raised to 49°C by means of a heat lamp and a small stirring fan. Following the elevated temperature calibration, a third calibration was performed at the ambient temperature to determine if operation at elevated temperature produced any changes in ambient temperature calibration characteristics. No significant changes were detected.

RESULTS

Two sets of three proving-ring assemblies were installed in each of two boreholes at the SFI-C site; a total of 12 transducers. Each set of three transducers was arranged on the support brackets in a 60° rosette. Additional transducers were installed in a third borehole in an unloaded and in a dead-weight loaded configuration to help evaluate transducer drift and zero offset.

Six of the original 14 transducers failed during the six-month period of service. All failures are a direct result of inadequacy of the environmental protection measures: moisture entered the strain gauges producing electrical shorts and erratic readings. However, even the transducers which failed provided data during the most significant phase of cooling. Transducer life ranged from 60 to 100 days with a mean time to failure of 85 days.

Performance of the remaining eight transducers was good. Post-test calibrations were used to evaluate these transducers. Table 1 summarizes changes in the pre- and post-calibration characteristics of the eight transducers which remained functional throughout the measurement period. Changes in sensitivity ranged from +0.023% to -1.498% with an average of -0.951%. Shifts in zero offset ranged from 0.001 mV to 3.21 mV with an average of 0.867 mV with one exception where the offset was 20.449 mV.

Fig. 6 shows a typical borehole displacement history recorded with a proving-ring transducer. Raw data corrected for the effects of thermal expansion of transducer components are shown.

CONCLUSION AND RECOMMENDATION

Strain-gauged proving-ring technology provides a viable means of recording displacements in large (0.61 m) diameter boreholes in rock which are subjected to a time-varying thermal field. Design of a relatively simple transducer to measure borehole displacements was moderately successful. Inadequate environmental protection of the strain gauges resulted in 6 of 14 transducers failing with a mean life of 85 days. The surviving transducers performed adequately, based on comparisons of pretest and post-test calibration results.

Table 1 - Changes in Calibration Characteristics of Strain-Gauged Proving-Ring Transducers.*

Transducer Serial Number	Calibration Characteristic				
	Sensitivity, % change	Span, % change	Zero Offset, mV change	Pre-Test Error Band, %	Post-Test Error Band, %
04	+0.023	+0.056	20.449	+0.50,-0.71	+0.15,-0.17
07	-0.598	-0.511	3.210	+0.30,-0.18	+0.16,-0.15
08	-1.498	-1.411	0.309	+0.24,-0.29	+0.07,-0.13
09	-1.497	-1.401	0.817	+0.34,-0.19	+0.11,-0.13
10	-1.009	-0.919	0.083	+0.34,-0.25	+0.13,-0.16
12	-1.442	-1.357	0.001	+0.30,-0.40	+0.12,-0.14
13	-0.835	-2.092	1.007	+0.21,-0.29	+0.05,-0.13
14	-0.751	-0.827	0.628	+0.22,-0.26	+0.37,-0.33

* Calibration performed over a range of 0.51 mm.

Nominal 10 V excitation.

Average transducer sensitivity is 0.567627 mV/V per mm.

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Fig. 1. Plan view of the SFT-C.

Fig. 2. Calculated decrease in emplacement hole diameter.

Fig. 3. Strain-gauged proving-ring transducer.

Fig. 4. Transducer support brackets.

Fig. 5. Laboratory calibration fixture.

Fig. 6. Typical borehole displacement history.