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UNITED STATES DEPARTMENT OF ENERGY (DOE)
Announcement of Scientific and Technical Information (STI)
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OMB CONTROL NO. 1910-1400

PART I: STI PRODUCT DESCRIPTION
(To be completed by Recipient/Contractor)

A. STI Product Identifiers

1. REPORT/PRODUCT NUMBER(s) DOE/ER/83035-1
2. DOE AWARD/CONTRACT NUMBER(s) DE-FG02-00ER83035
3. OTHER IDENTIFYING NUMBER(s)

B. Recipient/Contractor LEL CORPORATION

C. STI Product Title ADVANCED GEOTHERMAL TRANSDUCER

D. Author(s) LEL CORP.

E-mail Address(es): LEL.CORP@WORLDNET.ATT.NET

E. STI Product Issue Date/Date of Publication 9/14/2003

F. STI Product Type *(Select only one)*

☒ 1. TECHNICAL REPORT
☒ *Final* ☐ *Other (specify)*

☐ 2. CONFERENCE PAPER/PROCEEDINGS

Conference Information (title, location, dates)

☐ 3. JOURNAL ARTICLE
a. *TYPE:* ☐ *Announcement Citation Only* ☐ *Preprint* ☐ *Postprint*
b. *JOURNAL NAME*
c. *VOLUME* d. *ISSUE*
e. *SERIAL IDENTIFIER (e.g. ISSN or CODEN)*

☐ 4. OTHER, SPECIFY

G. STI Product Reporting Period 09/02/2000 Thru 06/03/2004

H. Sponsoring DOE Program Office CHICAGO OPERATION

I. Subject Categories *(list primary one first)*

Keywords

J. Description/Abstract

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L. Recipient/Contractor Point of Contact *Contact for additional information (contact or organization name to be included in published citations and who would receive any external questions about the content of the STI Product or the research contained therein)*

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Announcement of Scientific and Technical Information (STI)

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☐ 2. THIS DELIVERABLE FULFILLS A TECHNICAL INFORMATION REPORTING REQUIREMENT, BUT SHOULD NOT BE DISSEMINATED BEYOND DOE.

B. Awarding Office is the Source of STI Product Availability

☐ THE STI PRODUCT IS NOT AVAILABLE IN AN ELECTRONIC MEDIUM. THE AWARDING OFFICE WILL SERVE AS THE INTERIM SOURCE OF AVAILABILITY.

C. DOE Releasing Official

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DOE/ER/83035-1

LEL Corporation

Final Report

Advanced Geothermal Optical Transducer (AGOT)

SBIR Phase II Grant No. DE-FG02-00ER83035

Prepared for:

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September 2004

This report is a highly condensed amalgam of Semi Annual Reports submitted by LEL Corporation and its subcontractor, Sandia Laboratories, during the course of the project; it is offered in the interest of conciseness as an extended summary of these reports.

Executive Summary

Sensors capable of making accurate pressure and temperature measurements (so-called "PT Tools") in the hot, corrosive environment of a geothermal well can be purchased (at a price!), but none of those presently available, regardless of price, remains serviceable for more than a few down-hole hours without a dewar or heatshield. An affordable, essentially indestructible device whose mean time to failure in continuous duty exceeds six months is sorely needed. LEL proposed to meet this need by specializing its patented "Twin Column Transducer" technology to the demands of geothermal pressure/temperature measurements. TCT transducers have very few parts (they can be monolithic), none of which are moving parts, and all of which are fabricated from high-temperature superalloys or from ceramics; the result is an extremely rugged device, essentially impervious to chemical attack and readily designed to operate at high pressure and temperature.

The starting point for development of LEL's PT Tool was the company's model DPT feedback-stabilized 5,000 psi sensor. Employing a pair of identical, low-expansion, pressurized tubes the instrument is insensitive to temperature- and temperature-gradient-induced errors and, by virtue of its inherent ruggedness, withstands 50G shocks and 100G acceleration. To extrapolate it to a PT Tool, however, a temperature-measuring capability was incorporated and tested; the immediate objective of the program was demonstration of a 10,000 psi, 250 degree Tool in a working geothermal environment.

To carry out the design, test, and demonstration tasks, LEL assembled a team consisting of itself, the Sandia Corporation (operating under a "Working for Others" (WFO) Agreement with LEL), and Rutgers University. Program responsibilities were:

- LEL — Mechanical design, prototype fabrication, electronics, bench testing, program management
- Sandia — Optics, fiber optics, electronics, software, geothermal simulation testing, downhole test planning and support
- Rutgers University — Optics, fiber optics, and materials consulting

Additionally, Pruett Industries, a Bakersfield, CA firm specializing in geothermal well technology, was contacted to advise on practical aspects of insertion and retrieval of monitoring instruments and to assist in fielding a working unit, should the project proceed to that stage.

Testing of LEL designed and fabricated twin-column fiber optic pressure transducers both in the Company's laboratory and at Sandia confirmed the sensor's ability to readily and reproducibly record pressures up to 6,000 psi (limit of the apparatus) without hysterisis or short-term offsets. To verify the concept of a twin-column temperature-measuring sensor, Sandia built and tested a variant of the LEL transducer and confirmed its ability to perform reliably up to 250 °C. In view of these results, LEL assembled a three-column pressure-temperature tool and tested it in the Company's laboratories to 5,000 psi and 70 °C (limit of the apparatus), finding no fundamental impediments to fielding working pressure-temperature tools based on the proposed technology. It remains, however, to confront the realities of practical well monitoring with a pressure-temperature package configured for immersion in a representative geothermal well environment. Because the Principal Investigators at LEL and Sandia remain convinced of the potential benefits multi-column fiber optic transducers bring to geothermal monitoring, it is recommended that, should an opportunity to field LEL's transducer arise, DOE and the geothermal community take immediate advantage of it.

1 – Introduction

Today's geothermal pressure-temperature measuring tools are short endurance, high value instruments, used sparingly because their loss is a major expense. In this project LEL offered to build and test a rugged, affordable, downhole sensor capable of returning an uninterrupted data stream at pressures and of 10,000 psi and temperatures up to 250 °C, thus permitting continuous deep-well logging.

It was proposed to meet the need by specializing LEL's patented "Twin Column Transducer" technology to satisfy the demands of geothermal pressure/temperature measurements. TCT transducers have very few parts, none of which are moving parts, and all of which can be fabricated from high-temperature super alloys or from ceramics; the result is an extremely rugged device, essentially impervious to chemical attack and readily modified to operate at high pressure and temperature. To measure pressure and temperature they capitalize on the relative expansion of optical elements subjected to thermal or mechanical stresses; if one element is maintained at a reference pressure while the other is opened to ambient, the differential displacement then serves as a measure of pressure. A transducer responding to temperature rather than pressure is neatly created by "inverting" the pressure-measuring design so that both deflecting structures see identical temperatures and temperature gradients, but whose thermal expansion coefficients are deliberately mismatched to give differential expansion.

The starting point for development of a PT Tool was the company's model DPT feedback-stabilized 5,000 psi sensor (U.S. Patent 5,311,014, "Optical Transducer for Measuring Downhole Pressure", claiming a pressure transducer capable of measuring static, dynamic, and true bi-directional differential pressure at high temperatures), shown in the upper portion of Figure 1.

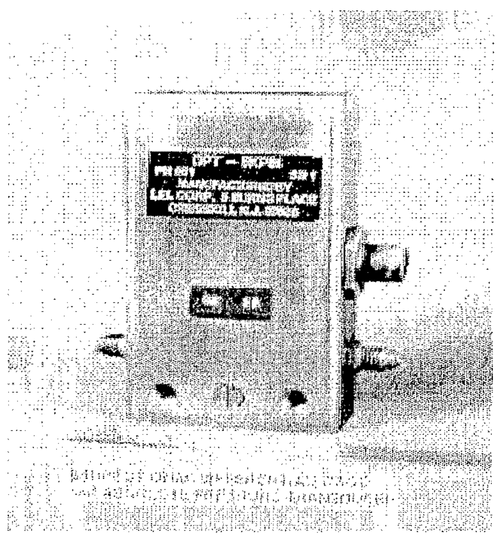

Figure 1. *DPT fiber-optic transducer patented by LEL Corporation. The transducer occupies eight cubic-inches, reads pressures up to 5,000 psi, and can operate at temperatures as high as 60 °C. Phase 2's objective was a transducer with a similar pressure range but an added temperature-measuring capability and a working temperature of 250 °C.*

The DPT occupies a 1 x 2 x 4-inch volume, weighs 14 ounces, and is accurate to 1 percent of full scale. Employing a pair of identical, low-expansion, pressurized tubes machined from a single piece of Ni-span-C 902 alloy, the instrument is insensitive to temperature- and temperature-gradient-induced errors and, by virtue of its inherent ruggedness, withstands 50G shocks and 100G acceleration. In operation the DPT sensor employs a micro-measurement technology employing the variation of signal amplitude as opposed illuminating and detector fibers deviate from their initial alignment under the influence of pressure forces. Phase I demonstrated that a temperature-sensing column can readily be appended to this device, transforming it into a 250 °C-plus pressure-temperature Tool.

Phase I testing of an unsophisticated laboratory transducer proved the concept's viability; the test instrument was linear to 5,000 psi (its design limit), exhibited 10 psi sensitivity (0.2 % of full scale), and demonstrated excellent repeatability when cycled from 0 to 5,000 psi and back. The impediments to extrapolating from this device to a working transducer were, therefore, practical engineering problems rather than fundamental limitations imposed by physics. One of these was packaging the sensing unit in a housing sufficiently robust and small enough in diameter for insertion through several kilometers of typical geothermal pipe; another was designing it to carry auxiliary weight great enough to drop the instrument against a large pressure gradient, while at the same time making provision for easy recovery via standard "fishing" tools should the transducer separate from its cable and fall into the well. An optimal arrangement of optical delivery and signal extraction elements and their configuration was to be selected and suitable signal and data processing hardware and software provided.

2 – Technical Discussion

2.1 *Sensor specifications*

The project opened with opened with a meeting of program principals at LEL Corporation to exchange information on practical aspects of geothermal logging and monitoring, establish a mutually agreed upon set of design requirements, and consider various technical approaches to delivering a transducer which satisfies these requirements. Specifications arising from these deliberations are summarized in Table 1.

Table 1. *Pressure-temperature Tool design specifications*

- Pressure .... 10,000 ± 1% psi at full scale
- Temperature .... 250 ± 2 °C
- External housing diameter .... 3 inches
- Housing material .... 316 stainless steel
- Fishing .... Design for standard recovery tools
- Installation .... Quick connect to cable in a packoff
- Vibration .... "Roughneck" test
- Breakaway cable .... Design for controlled cable breakaway
- Housing collapse pressure .... 20,000 psi

Note: The 10,000 psi design pressure is double the DOE's stated requirement

A number of potential solutions to practical design problems arising from the need for compatibility with standard procedures and equipment for insertion of instrumentation into geothermal wells were proposed and discussed, including the attachment of weights and cables, means of passing sensors through seals and glands, provision for sensor recovery (and for breakaway if necessary), and fiber optic cable management. A design issue identified as impacting most of these elements was the need to orient optical signals vertically rather than horizontally, as in LEL's patented DPT and Phase I instruments; vertical alignment eliminates potential problems associated with imposing a sharp bend radius on glass fibers to turn them up hole. LEL suggested a solution using retro reflectors to turn the signal while Sandia proposed an alternative sensor geometry employing columns carrying horizontal, rather than vertical as in LEL's design (see Figure 2), reflecting surfaces.

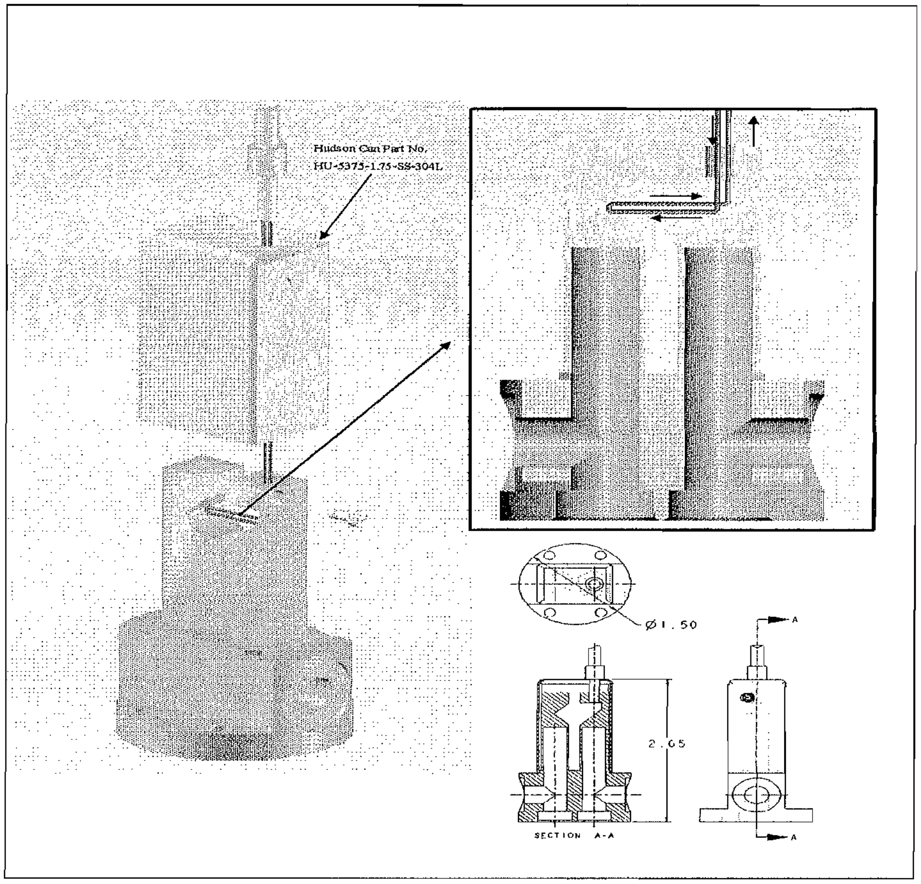

Figure 2. *Twin square-column pressure transducer packaged in a commercially available housing and designed for vertical fiber deployment (the housing shown is Hudson Can part number HU-5375-1.75-SS-304L).*

2.2 *Preliminary testing*

To study sensor stability and sensitivity at constant temperature, LEL fabricated a set of pressure sensors of the type shown in Figures 3 and 4. These employed a buttress threaded base with a Kalrez "O" ring (Kalrez is a proprietary high-temperature fluorocarbon polymer) as the primary high pressure seal, backed up by a secondary Viton "O" ring. Anticipating transducer deployment from a tube reel, fibers were brought out through a dual "O" ring seal-sealed cylindrical cover via gyrolok tube fittings on both the fiber ferrule (attached at the through-hole in the housing cap) and pressure inlet tube (inserted in the base) to provide for "quick disconnect" gland nut attachment.

Forced deflection testing of both round and square tube twin-column transducers constructed in this fashion was performed using Sandia-designed and built electronics at hydraulic pressures up to 5,000 psi. Columns of both types yielded linear pressure-voltage curves over the range of pressures spanned by the test (0 to 5,000 psi). Slopes of the voltage-pressure plots were 50 micro volts/psi for 2-inch long, 0.015-inch wall-thickness, round columns and 70 micro volts/psi for 1-inch long, 0.030-inch wall square tubes. This suggests, because sensor output is relatively large and therefore easily measured, these sensors are capable of delivering extremely accurate data.

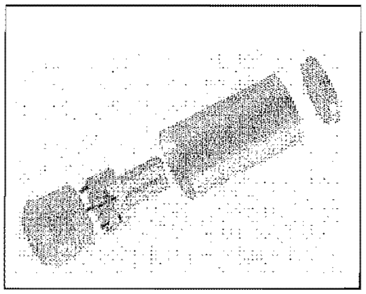

Figure 3. *Exploded view*

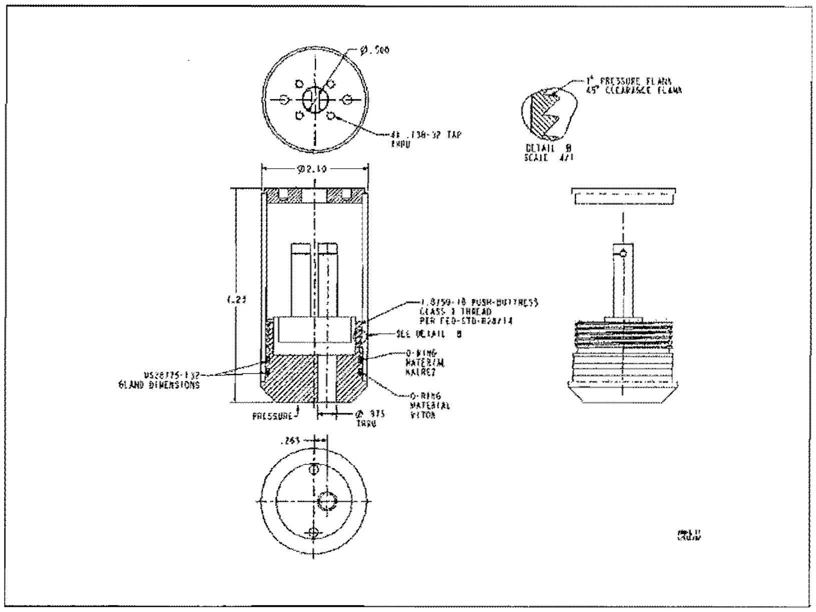

Figure 4. *Cylindrical twin-column transducer designed for mechanical attachment of housing to base.*

To check stability and reproducibility of electronics and mechanical elements, a round-column unit was tested and then retested twice more after delays of 24 and 48 hours. As Table 2 shows, data reproduced almost exactly from one test to another, verifying the stability, linearity, and reproducibility of both electronics and transducer when pressurized at room temperature.

Table 2. *Results of testing a Twin-column Transducer with 2-inch long, round columns*

Pressure (kpsi)	Signal measured on 18-June-02 (volts)	Signal measured on 19-June-02 (volts)	Signal measured on 21-June-02 (volts)
0.0	0.001	0.001	0.001
1.0	0.045	0.045	0.045
2.0	0.094	0.095	0.094
2.5	0.120	0.120	0.120
3.0	0.150	0.150	0.148
4.0	0.200	0.200	0.200
5.0	0.250	0.250	0.255

Given these results LEL was encouraged to make several adjustments to the test sensor optics in advance of forwarding units to Sandia for independent evaluation in their Laboratory. Eight fiber-optic cable types were tested for in-and-out light transmission to the transducer optical interface and for quality of alignment provided by a clamping screw/alignment key design. Of the eight, two, Fiber Guide CE11479 and Sandia's 200/220/240 glass-on-glass, gave satisfactory results. To improve the speed and quality of fiber alignment, ferrules were redesigned to incorporate a tapered shoulder and keyway groove. Working with Fiber-optic Systems, Inc., a trifurcated fiber-optic cable for mirror prism displacement sensing was incorporated into the sensor.

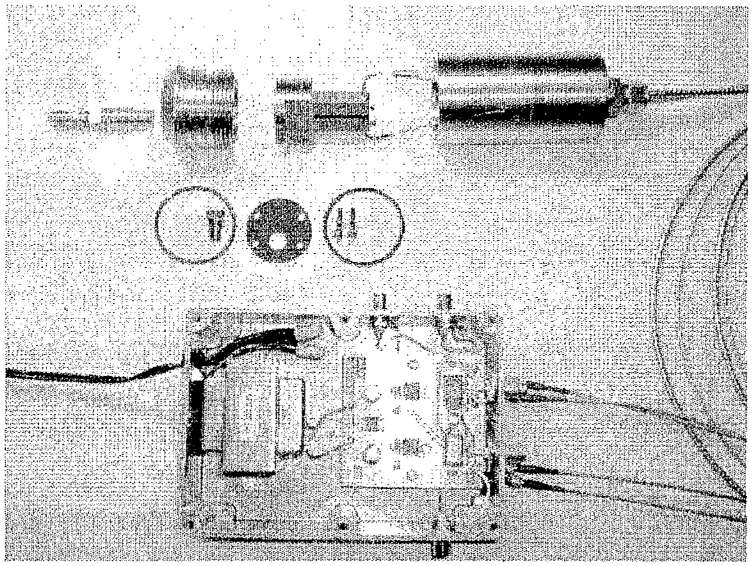

Figure 5. *Pressure test unit and electronics as-shipped to Sandia*

2.3 *Testing of LEL's transducer at Sandia*

2.3.1 *Transducer Specifications*

The transducer tested at Sandia employed square columns constructed of Ni Span C, 25.4 mm (1") long, 9.5 mm (3/8") on a side, containing a round hole 8.0 mm (0.315") in diameter. All optical fibers were glass-on-glass, pure-silica core, with a numerical aperture, nominally = 0.2. The core, cladding, and buffer diameters of the transmitting fiber were 100/120/140 microns and those of the receiving fibers 400/440/480 microns. Face-to-face separation between the two sets of fibers was about 1.2 mm (0.046"), a somewhat larger than optimal gap which, though readily correctable, reduced sensor response somewhat. Receiving fibers were, as a result of fabrication problems acknowledged by the supplier (Romack, Incorporated) deployed 10 to 15 degrees off the vertical; this deviation is also easily corrected but further reduced pressure response by about 2%.

2.3.2 *Experimental Arrangement*

Figure 5 shows the arrangement for the experiment. This is the same arrangement used for an earlier (room-temperature) experiment on another LEL transducer, but with the addition of an oven (equipped with feedthroughs and a temperature controller) and two thermocouples. In order to "span" the transducer, the thermocouples were attached to the base of the transducer near one column and to the top of the opposite column. The two agreed to within less than 1 C when pressure measurements were made. Photodetector circuits Z_1 and Z_2 (see Figure 5) responded linearly to light and were set to the same sensitivity within about 0.1%. Thus, for example, a one-volt output from both circuits was the result of essentially the same optical power falling on both photodiodes.

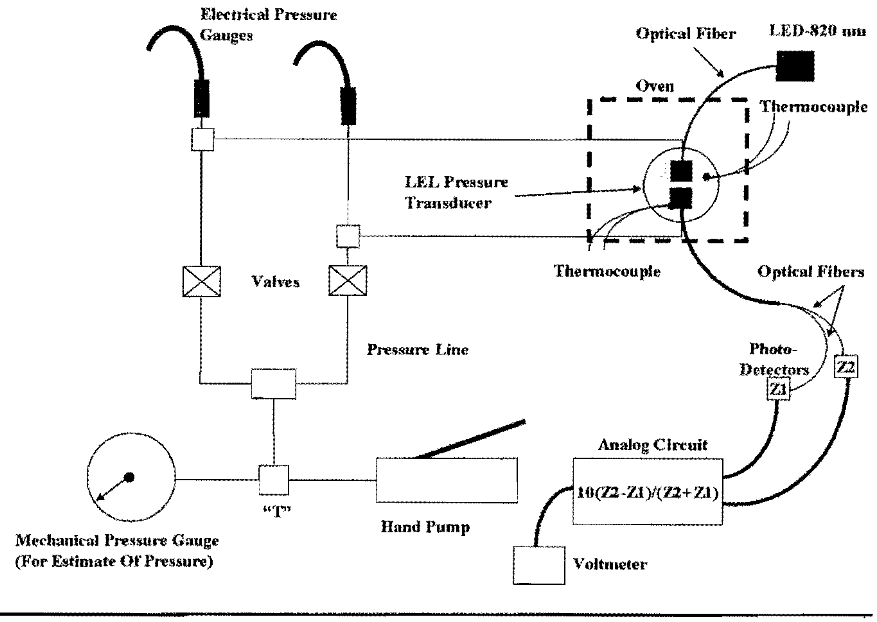

Figure 5. *Setup for testing LEL's pressure transducer.*

Although the experimental arrangement afforded the capability of pressurizing either or both columns to equal or unequal pressures, only the receiver column was pressurized during this experiment.

2.3.3 <u>Room temperature pressure testing</u>

Room-temperature calibration of an LEL pressure transducer consisting of hollow, 1-inch long square columns 0.375-inches on a side with an inner bore 0.315" in diameter was conducted. The gap between transmitting and receiving fibers was 0.62-inches; the fibers employed pure-silica-cores 100 and 400 microns in diameter, respectively. Testing permitted pressurization of either column individually or both simultaneously and, to obtain a complete picture of sensor operation, data were obtained using all three options.

Testing confirmed results obtained earlier at LEL, producing linear, reproducible, essentially hysteresis-free signals over the entire test range (0 to about 7,000 psi), independent of which of the two columns was pressurized. Error analysis calculations show signal magnitude is relatively sensitive to size of the gap between source and receiving fibers, and that thermal expansion offset arising from mechanical or property variations of the columns or the base on which they are mounted may introduce substantial measurement error. Both potential sources of error can be overcome by calibrating each transducer in a pressure-temperature facility before sending it downhole.

Figure 6 (obtained with the receiving column pressurized), typical of results obtained in this test sequence, demonstrates the sensor's excellent linearity.

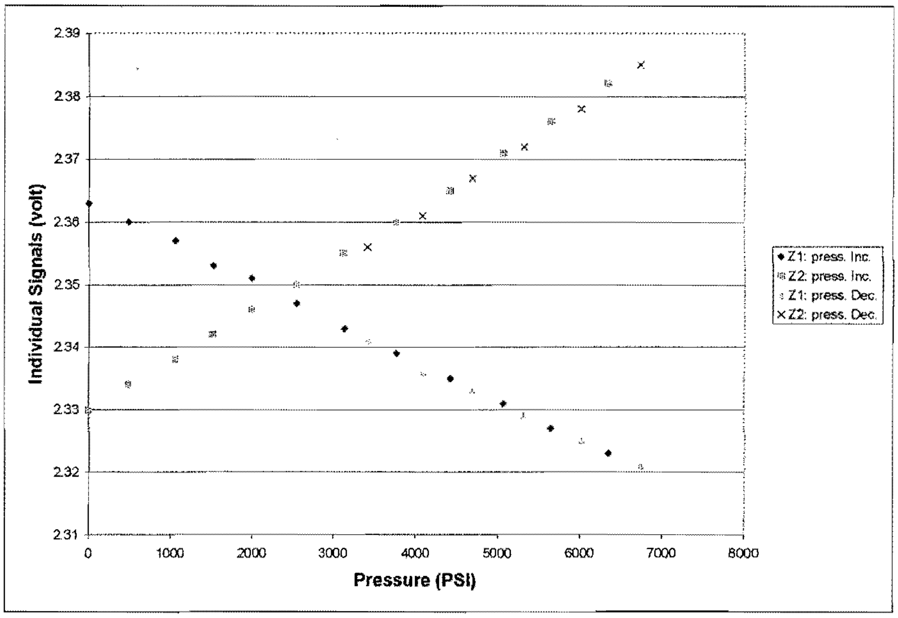

Figure 6. *Typical signals (Z_1 and Z_2) from the LEL transducer*

2.4 *Pressure-Temperature (PT) Tool*

To the twin column pressure measuring sensor of Figure 5 was added a third square column fabricated from Invar, taking advantage of the thermal expansion coefficient mismatch between it and Ni-Span C to provide temperature-correlated differential expansion. By simultaneously recording optical signals from the paired pressurized and reference Ni-Span pressure tubes and paired pressure reference and Invar temperature tubes, measurements of both pressure and temperature were obtained from a single sensor "head". Experiments employed a Ni-Span/Invar PT tool pressurized hydraulically from 0 to 5,000 psi at temperatures ranging from laboratory ambient (20 °C) to the limit of the forced convection heater used, 72 °C. At each temperature point the sensor was heated for approximately an hour to assure the entire unit was at a constant temperature, output of the paired temperature columns was recorded, and the tool was cycled from atmosphere to 5,000 psi and back in 1,000 psi steps. Results of a typical experiment (conducted on 10-Dec-03) are plotted in Figure 7. The Figure shows pressure signal remained linear as the sensor was heated to 72 °C, as anticipated by prior testing at both LEL and Sandia, and that sensitivity was essentially constant at a value of 0.124 volts/kpsi, independent of temperature.

Furthermore, the unit exhibited good temperature sensitivity, about 12 millivolts/degree, while output of the temperature measuring column-pair was pressure independent, as indicated in Table 3. These results confirm that the multi-column concept is, at least within the range of the measurements, capable of simultaneously providing reliable pressure and temperature data.

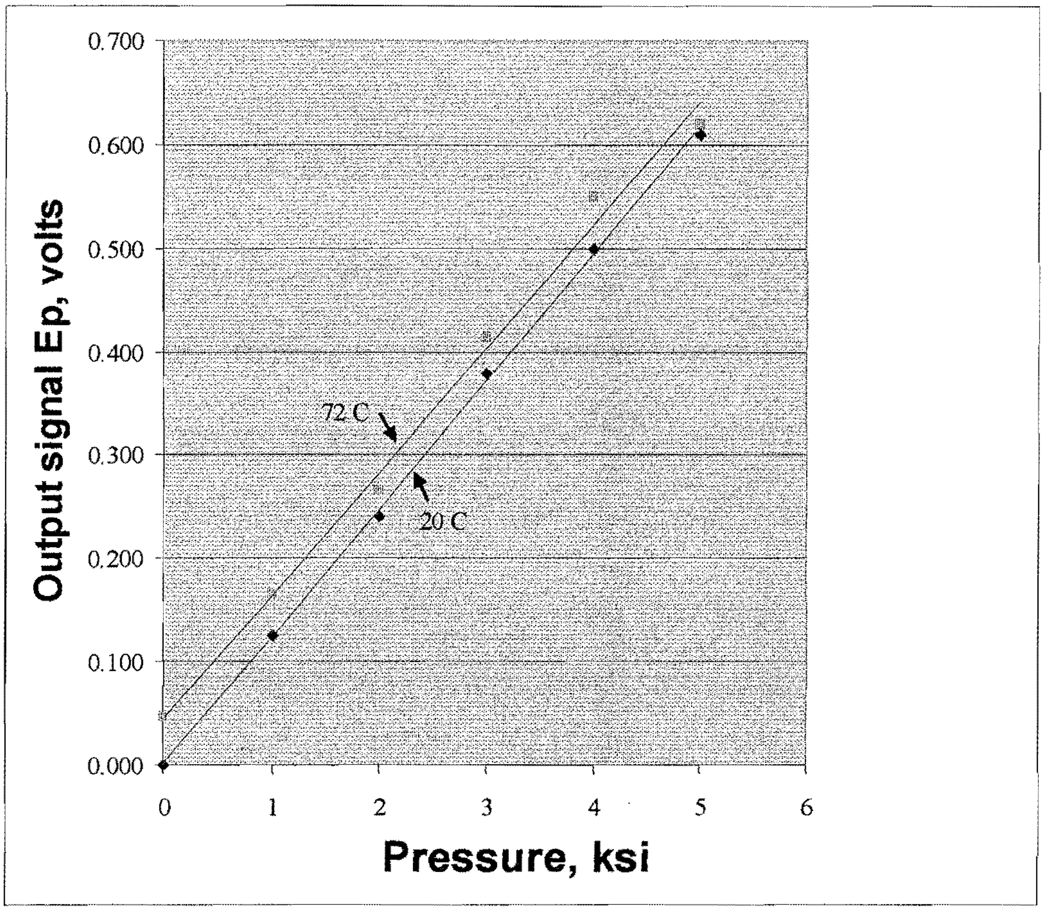

Figure 7. *Pressure signals obtained with prototype LEL PT tool at room temperature and 72 °C.*

3.0 *Conclusions and Recommendations*

Fabrication and testing of sensors employing the "twin column" principal demonstrated that such devices are certainly capable of reproducibly measuring pressure well beyond 5,000 psi (limit of Sandia's testing apparatus was about 6,800 psi) with an accuracy of a few percent. Experiments conducted on a Sandia-designed variant of the LEL transducer targeted at temperature-only measurements similarly proved capable of recording temperatures up to 250 °C with an accuracy estimated to be ± 2 degrees. LEL's prototype pressure-temperature tool, combining both pressure and temperature-measuring structures in a single unit, confirmed the results of pressure-only testing in both laboratories when subjected to temperatures up to 70 °C and simultaneously pressurized to 5,000 psi. It therefore appears that no fundamental impediments to fielding working pressure-temperature tools based on the proposed technology exist. It remains, however, to confront the realities of practical well monitoring with a pressure-temperature package configured for immersion in a representative geothermal well environment. Because the Principal Investigators at LEL and Sandia remain convinced of the potential benefits multi-column fiber optic transducers bring to geothermal monitoring, it is recommended that, should an opportunity to field LEL's transducer arise, DOE and the geothermal community take immediate advantage of it to field a unit.