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EXECUTIVE SUMMARY

The technology for enhanced geothermal systems (EGS), in which fractures connecting deep underground wells are deliberately formed through high pressure stimulation for energy generation, is projected to enormously expand the available reserves of geothermal energy in the U.S. EGS could provide up to 100,000 MWe within the U.S. within 50 years. In order to develop and maintain EGS, it is essential to be able to continually monitor various parameters in the geothermal wells such as temperature, pressure, strain, and acoustics. Ideally, these parameters should be available along the entire length of the well in order to identify the sections of the well which are producing heated water and the liquid and/or gas composition of the water, to determine flow rate, to monitor thermal drawdown of the well and local seismic events, and to determine the efficiency of well stimulation. These data are also essential for development of geothermal models of the local geologic formation.

Commercial instruments are now being used in the oil and gas industry for making distributed measurements of temperature, strain, and acoustics along the length of a fiber cable in a well with a depth resolution of 1 to 10 m. One aspect of this project was to actually test and evaluate the performance of a commercial Raman distributed temperature sensing instrument, a Brillouin distributed temperature and strain sensing instrument, and a Rayleigh coherent optical time domain reflectometer for acoustic measurements in a geothermal well. Fiber Bragg gratings (FBGs) are another fiber technology developed for temperature and strain measurements. In this project, the viability of these gratings for geothermal temperature measurements and as pressure sensors in geothermal wells was evaluated. Long term drift of the FBG sensors was found to be a significant problem. Pressure measurements are also very important for determining the state of the fluid, i.e., liquid or steam, the fluid flow, and the effectiveness of the well stimulation. However, it has been especially difficult to accurately measure pressure at temperatures above ~200°C and for distances of up to 10 km below ground. MEMS technology has been employed for many years for extremely accurate pressure measurements in other applications through electrical readout. In this project MEMS sensors have been specifically developed for the harsh environment and high pressures of geothermal wells. Also, an interrogation system for these sensors based on fiber optics for high temperatures has been designed and developed. Both a MEMS sensor and an interrogation system have been demonstrated in a geothermal well. Downhole pressure measurements were found to be accurate to within the $\pm 0.1\%$. One additional problem addressed in this project is hydrogen darkening of the fiber. When optical fiber is in the presence of hydrogen in the geothermal well, either from the water or from residual organics in the fiber cable, the optical transmissivity of the fiber can significantly degrade over time. Several companies have developed “pure silica core” fiber that is supposed to be highly resistant to this hydrogen darkening effect. In this project the hydrogen darkening resistance of commercially available fibers and their mechanical integrity at high temperatures was assessed.

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ABSTRACT

An optical fiber cable which supports multiple sensing modalities for measurements of pressure, temperature and acoustics in the harsh environment of enhanced geothermal systems was developed. To accomplish this task, optical fiber was tested at both high temperatures and strains for mechanical integrity, and in the presence of hydrogen for resistance to darkening. Both single mode (SM) and multimode (MM) commercially available optical fiber were identified and selected for the cable based on the results of these tests. The cable was designed and fabricated using a tube-within-tube construction containing two MM fibers and one SM fiber, and without supporting gel that is not suitable for high temperature environments. Commercial fiber optic sensing instruments using Raman DTS (distributed temperature sensing), Brillouin DTSS (distributed temperature and strain sensing), and Rayleigh COTDR (coherent optical time domain reflectometry) were selected for field testing. A microelectromechanical systems (MEMS) pressure sensor was designed, fabricated, packaged, and calibrated for high pressure measurements at high temperatures and spliced to the cable. A fiber Bragg grating (FBG) temperature sensor was also spliced to the cable. A geothermal well was selected and its temperature and pressure were logged. The cable was then deployed in the well in two separate field tests and measurements were made on these different sensing modalities. Raman DTS measurements were found to be accurate to $\pm 5^{\circ}\text{C}$, even with some residual hydrogen darkening. Brillouin DTSS measurements were in good agreement with the Raman results. The Rayleigh COTDR instrument was able to detect some acoustic signatures, but was generally disappointing. The FBG sensor was used to determine the effects of hydrogen darkening, but drift over time made it unreliable as a temperature or pressure sensor. The MEMS sensor was found to be highly stable and accurate to better than its 0.1% calibration.

PROJECT TASKS AND TIMETABLE

This 2½ year project was divided into five tasks as shown in Fig. 1. Tasks 1 and 2 were originally planned to take place in the first year of the project and Tasks 3 and 4 in the second year of the project. In Task 1, a general overall design for the fiber cable and process for field installation were to be completed. The first generation of a MEMS resonator point pressure sensor was to be designed and fabricated, and a fiber Bragg grating (FBG) distributed pressure/temperature sensor was to be designed. In Task 2, pure silica core fiber was to be tested from several vendors and the best fiber selected for the cable manufacture. Commercial instruments for Raman, Brillouin and Rayleigh fiber measurements were to be tested in the lab, and suitable devices selected for a downhole test.

In the second year of the project, in Task 3 the MEMS resonator pressure sensor was to be validated, and the FBG sensor was to be optimized. In Task 4, the fiber cable was to be manufactured, and the complete system assembled and tested in the lab. A plan for field deployment was also to be completed. (In actuality, two field tests were completed during the course of the project.)

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Task 5 covers program management throughout the time of the project.

This report is the final report for the project describing the work that was accomplished over the course of the project from the start of work in April, 2010 to its completion in September, 2012. Although the project was originally planned to last for two years, various delays in fabrication of the sensors and geothermal well availability led to a six month no-cost extension of the project.

Fig. 1: Project Gantt chart.

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Task 1: System Architecture and Component Development

Task 1.1—System Level Specification & Hardware Design

Associated Milestone: Defined system requirements

In order to better define the system level specifications and hardware design for this project, several phone discussions were conducted between GE Global Research (GEGR) and a major geothermal developer to understand the requirements for a sensor cable system. This communication gave the team a better understanding of the sensor environment and desired sensor characteristics. GEGR discussed the preliminary specifications and the geothermal developer was satisfied with the suitability of the potential performance. Below is a summary of the things GEGR learned about the environment and application of sensors in this application.

- Sensors are used on the production side (“out”) rather than the injection side (“in”) of the well
- The well on the injection side is cool and less harsh. The water coming off the production side is hot and has contaminants from the rock.
- The highest temperature well they have seen is 315°C, 3-5 km deep. Some sites in Iceland are supercritical and hotter, but 374°C and 220 bar would cover the entire range. There shouldn’t be excursions beyond that range. In their opinion, 10 km is really deep compared to the state-of-the-art.
- They expressed concerns about the weight of a 10 km cable being too heavy to support itself. They suggested using a light, strong material for the cable tube.
- They are interested in long term trends rather than using the sensors as part of a short-term control loop or failsafe. The data rates they need are more on the order of one sample/hour than one sample/second.
- They call the cable (tube that takes the fiber optic down the hole) the “central line”. This is typically a 1/4” diameter metal capillary.
- The top of the hole is approximately 13 3/8” in diameter and the open hole down further is 8 1/2” diameter.
- A potential location for the interrogator would be on the pad which typically is a metal house with power but no heat or AC. GEGR should be cognizant of temperature swings typical of a location such as Nevada (110°F in summer vs. 10°F in winter for example).
- Sensors typically last <6 months. Five year operation life would be a significant advance.
- They indicated that an accuracy of 1% is fine, but over the life of the sensor its accuracy should not be less than 5%.
- They are most concerned with pressure and temperature at the bottom ~1km of the well.
- When asked for the distribution of the measurements, they stated that each well is unique and custom. They suggested a measurement every hundred feet would be a good starting point.
- Each well could have multiple flow zones and these could be 1000 feet apart. They need only 1 measurement in each flow zone.

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- Inconel 625 should be an adequate material to survive down well.
- They provided specific data on chemical components down well which can be used to guide our design.

Table 1 is a list of target specifications for the point pressure sensor. Table 2 is a list of target specifications for the distributed temperature sensor system and cable.

Table 1: Specifications for the point pressure sensor.

	Point Pressure	
Min Temperature	20	C
Max Operating Temperature Range	374	C
Min Operating Pressure Range	0	bar
Max Operating Pressure Range	210	bar
Calibrated Temp Range	250-375	C
Accuracy @ 250C	0.01%	
Stability @ 250C	0.01%	per year
Accuracy @ 375C	0.10%	
Stability @ 375C	0.01%	per year
Sensor Bandwidth	10	sec
Design Life	5-10	yrs
Size	30	mm diameter
Probe Length	1	m
Chemical Compatibility	Acid Resistant	
Package Material	Inconel 625	
Power	2	kW
Communication	CAN BUS	

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Table 2: Specifications for distributed temperature sensing system and cable.

Parameter	Value
System Operating Performance	
Operating Temperature Range	50°C to 300°C
Maximum Non-Operating Temperature	300°C
Temperature Accuracy	+/-0.8°C
Temperature Resolution	+/-0.1°C
Update Rate	10 Minute
Typical Operating Lifetime	>5 Years
Maximum Sensor Cable Length	>6 km
Down-hole Sensing Cable	
Max Operating Temperature	300°C
Storage Temperature	-50°C to 85°C
Outer Diameter	1/4"
Surface Cable and Connectors	
Storage Temperature	-50°C to 85°C
Operating Temperature	-50°C to 85°C
Operating Humidity	0 to 100%
Surface Instrument	
Storage Temperature	-40 to 80°C
Operating Temperature	-10 to 60°C
Operating Humidity	0 to 95% Non-condensing
Surface Power Requirements	40W
Data Transfer Protocol	MODBUS over TCP/IP
Cabinet Housing Type	IP66 Enclosure

Task 1.2—Field Installation Design

The purpose of this task is to ensure that system and component design is consistent with field deployment. This included a study of the logistics of field installation and the corresponding implications for cable design, system architecture and sensor design. In addition, a supply chain process verification for all major surface and downhole components was performed.

Conventional well installation equipment and methods such as wireline, coiled-tubing, and tubing-conveyed (clamped) used routinely for installing downhole fiber optic sensors in the oil and gas industry to deploy such systems in geothermal wells were selected for this project. A key consideration was to develop a fiber optic sensing cable and associated hardware amenable to these installation techniques that endure handling and well conditions, depths, and chemistry particular to geothermal wells. In *Task 1.5—Cable Design*, a downhole cable design with form factor and mechanical properties consistent with these installation methods is described with an

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overall design objective of maintaining the sensing fiber in a low strain condition out of direct contact with well fluids during installation and operation in the geothermal well environment.

A review of conventional installation methods was made by first gathering existing and planned geothermal well completion information and diagrams along with associated well operating conditions and fluid environment. Upon initial review, beside the different well chemistry of geothermal applications, some of the well completions contrast with oil and gas thermal recovery wells in having longer vertical depths and uncased borehole sections. This information was taken into consideration for cable design and the applicability of various installation methods and equipment for the geothermal application. The investigation expanded into understanding major EGS operating phases, and desired subsurface monitoring to support these operations. Sensor placement in terms of depth/time and potential installation methods over these operating phases were considered, as well as equipment compatibility with EGS surface facilities.

Meetings with AFL Telecom and Sandia in Q1, 2011 provided additional information to finalize a fiber cable design for downhole testing at the Sandia well site. The project team selected a multi-fiber steel alloy armored downhole sensor cable design. This cable form factor is compatible with the aforementioned well installation techniques, and the mechanical handling characteristics of the steel armor is suitable to resist typical strain and tension applied to the cable during installation to maintain the sensing fiber in a low strain condition. This technique has also been proven in Oil & Gas wells in which such cables have been used in successful commercial deployment for over 10-years using these installation methods. Furthermore, over this time, pump-in or fluid drag methods have been refined for installing these cables, even over long horizontal wells, with dedicated instrumentation conduits, typically installed in the well annulus, available for installing these cables on an on-call demand basis. Such techniques could provide an opportunity for intervention during different operating phases of EGS.

The baseline EGS well operating conditions and downhole sensor placement for the field test were also established. The baseline installation approach was chosen to be spool-in using a wireline spooling rig unit. A vertical observation well was selected for the field test which presents low risk in terms of landing the sensor at a target depth with minimum cable abrasion. While installing sensors in deviated wells is not a significant challenge, it is assumed that EGS wells will be open-bore without a well casing, creating potential for cable abrasion against the formation during spool-in cable installation. This has been identified as a risk item for installing sensor cables in this program.

A trial well was identified, operated by Ormat at its Brady operations in Nevada. The well is cased with 2 7/8" tubing, its depth is >4800 ft, the bottom hole temperature is slightly >200°C, and it is roughly vertical with no deviation. These conditions are favorable for validating operation and hydrogen tolerance of an initial trial system, and amenable for conventional spool-in cable deployment using a wireline spooling rig unit.

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The main installation “drive” was chosen to be gravity-assisted by a sinker bar attached to the end of the trial sensing cable, with an attachment feature welded to the end of the cable. A set of documents and specifications were developed to specify the necessary installation equipment including sheaves, straighteners, and tensioning equipment:

- Specification for downhole cable handling
- Split Spool Cable Drawing
- Downhole Cable Termination Package Drawing

Because the cable spool was planned for two field tests, the spool integrity under raw outdoor storage conditions was important. To ensure optimum cable wind on the source spool - critical for reducing the susceptibility of the cable to cross-over points and mechanical binding during payout, it was decided to use the QOREX 3-flange wooden spool, and coat the spool with a protective waterproofing treatment. After installation of the cable, the spool was further covered with a plastic tarp to protect it from the elements during the first downhole field test in December, 2011 to January, 2012.

A draft cable field test plan that included major tasks and objectives for the general activity leading up to and through the trial installation was also prepared, covering:

- Injury and damage incident-free deployment and operation of the sensor system.
- Successful deployment of the system into a geothermal well using conventional installation methods and equipment.
- Evaluation of sensor performance relative to baseline specifications and laboratory tests.
- Validation of the cable design for operating the suite of sensors in the geothermal application.
- Creation of better understanding of downhole geothermal well conditions and characterization of any cable or fiber aging due to the downhole environment.
- Generation of an initial reliability model for the downhole sensor cable in geothermal well environments to project lifetime and performance under a range of conditions.

Joe Henfling at Sandia National Laboratories reviewed and contributed to the draft document (see Appendix 1). Using this document, bids were solicited by Dr. Henfling from four different companies to insert and remove the cable and monitor the instrumentation during the test.

The field installation design was completed in October, 2011, prior to the first downhole field test. The field test was begun on December 13th, with cable deployment completed on the 14th. Collection of field data was begun immediately and continued into January, 2012, as described in subsequent sections of this report.

The first cable deployment was supervised by Dr. Joseph Henfling, and the second field test was supervised by Dr. Scott Lindblom, both of Sandia National Laboratories. Sandia subcontracted Pacific Process Systems to provide some of the installation equipment and required manpower. Sandia was instrumental in locating the geothermal observation well owned by Ormat in Nevada that was available and suitable for the downhole tests of the cable.

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Prior to installation of the cable, all people at the site participated in a one hour safety course taught on-site by Ormat on December 13th, 2011.

Task 1.3—Point Optical Pressure Gauge Development

Associated Milestone: First iteration of point pressure gauge which performs at 374°C with clear path to 220 bar full scale on second iteration

There are two primary thrusts of this task: GE Sensing's development of the MEMS sensor structure and packaging and GE Global Research's development of the system design, optical interrogator, test apparatus, and readout electronics.

An overall optical system model was developed to estimate the input optical power required from the light source for the high temperature pressure monitor. This model focused on maximizing the signal-to-noise ratio (SNR) of the read portion of the system which drives the accuracy of the overall sensor and is most affected by any optical attenuation in the cable due to the round trip path of the light in the cable. Because there are several different options for the optical design of this device, including the resonator method, light source and wavelength, type of fiber (single-mode, multi-mode, or combination) and number of fibers to drive and read the sensor, it was not clear a priori which approach was most likely to provide an acceptable SNR. This model in combination with the inputs from the resonator and package design teams was used to drive the first iteration of the sensor and interrogator design.

The optical model was based on the layout shown in Fig. 2. Light from a laser diode, LED, or SLED is coupled into an optical fiber. An optical isolator spliced into the fiber if necessary prevents light feedback into the light source for noise reduction. A beamsplitter or circulator in the fiber enables a fraction of the return light to be split off to the detector.

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Fig. 2: Optical layout for model.

The starting point for the model is the desired SNR and bandwidth of the detected signal. The initial assumption for the model was that a SNR of at least 30 dB was required with a bandwidth of 100 kHz to enable active feedback control of the frequency of the optical power that excites the resonance. In the final feedback circuit, a lock-in amplifier was employed to greatly reduce the effective bandwidth to ~1 kHz enabling feedback control even when the SNR was only 10 dB or less. In the case of this model, however, once the bandwidth and SNR are specified, it is possible to work backwards from the detector to determine the necessary source input power.

There are two noise sources to consider, the shot noise generated by the incident light, and the background detector noise even in the absence of light (given by the detector NEP). The dimensions for NEP are $\text{Watts}/\sqrt{\text{Hz}}$. Multiplying the NEP by the square root of the post-detection bandwidth gives a value for the noise power. Multiplying this by the SNR gives the required minimum optical signal power incident upon the detector.

Shot noise is determined in the following manner. The standard deviation of the noise current from the photodetector is given by

$$i_{rms} = \sqrt{2 e R B P_0} \quad (1)$$

where e is the electronic charge (1.602×10^{-16} C), R is the responsivity (A/W) of the detector, B is the post-detection bandwidth, and P_0 is the optical power incident upon the detector. The signal current is

$$i_s = R P_0. \quad (2)$$

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The ratio of Eq. (2) to Eq. (1) gives the SNR. If the SNR is specified in dB, then the ratio of signal current to shot noise current is given by

$$\frac{RP_0}{\sqrt{2 e R B P_0}} = 10^{0.1(SNR)} . \quad (3)$$

Solving Eq. (3) for the required minimum optical power on the detector P_0 gives

$$P_0 = \frac{2 e B}{R} 10^{0.2(SNR)} . \quad (4)$$

Because the incident optical signal is varying sinusoidally in time at the resonator frequency, the peak-to-peak amplitude of the optical power variation must be twice as large as P_0 to obtain the required SNR. This assumes that all of the optical power coming out of the fiber is signal power. If there are other sources of optical power that are not being modulated by the resonator, these must be added into the shot noise calculation and will act to increase the required signal power.

The tradeoffs in design and construction of the sensor system were evaluated to maximize the amount of light reaching the detector and minimize the optical losses in the system. Based on this, the following system choices were made:

1. Single mode fiber – Projected attenuation losses for Multimode fiber are an order of magnitude greater than that of single mode fiber. In addition, the optical sources under consideration are typically coupled by single mode fiber. The downside of this decision is that it may increase losses at the connection with the sensor due to a much smaller acceptance angle for the reflected light.
2. Laser Diode – A laser diode source provides the highest power output while being compatible with single mode fiber architecture.
3. Four methods of signal modulation were considered: a Fabry-Perot interferometer, a shutter resonator, a tilting mirror, and a type of focus shift. Tradeoffs exist between the optical performance of these approaches and the resonator design which were explored prior to the construction of a prototype sensor.

Four methods of modulation of the optical signal by the MEMS device were considered and modeled using Finite Element Analysis (FEA).

1. Shutter resonator that modulated the light through holes in the resonator providing 0-100% light modulation back to the receiver based on reflection or transmission off the resonator
2. Tilting mirror resonator which would modulate the light back through the fiber by changing the angle the light reflects and directing the light away from the fiber

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3. Focus shift provided by the resonator changing the focus of the light back through the fiber
4. Fabry-Perot cavity between the resonator and the top of the die causing interference of the light leaving and exiting the cavity.

The Fabry-Perot cavity approach was chosen due to its simplicity and manufacturability. The other three methods were found to have significant disadvantages and challenges. The shutter method required large movement for significant signal which would be hard to achieve. For the tilting mirror approach, it was found that it would be difficult to measure and control the resonator amplitude to get the performance required. The focus shift method was rejected due to the manufacturing complexity of adding a lens to the design.

To realize a Fabry-Perot design, three classes of resonator structure were examined and modeled:

1. Single (double) beam resonating at the 3rd vibration mode.
2. Multi-beam resonator, including 3 beam and 4 beam structures.
3. Butterfly shaped resonator

The performance of the three resonator types was predicted using an ANSYS FEA model. Due to the earlier work by GE on optically driving and reading of silicon MEMS devices, the existing Resonant Pressure Transducer (RPT) design was also modeled as a baseline. The results are shown in Table 3. There were several key assumptions in the model in order to simplify the analysis. First, the diaphragm of the pressure sensor was assumed to be 28 microns, which is typical of a 1 bar range pressure transducer. The resonator was assumed to be 20 microns thick and the mechanical quality factor (Q) of the structure was assumed to be 1000. Figure 3 shows the ANSYS models of these structures.

Table 3. Frequency characteristics of Fabry-Perot based resonators

<i>Resonator type</i>	3rd mode 2 beam	4 beam	Modified butterfly	<i>RPT</i>
f_0 (kHz)	85770.6	25556.8	58021.8	47972.3
df (kHz)	2929.2	6510.9	-6487.8	4806.2
Amplitude (microns)	126.5	367.4	358.1	425.6
Nonlinearity (ppm)	75123.4	0.0028	12.9	7877.3
Drive efficiency (nm/°C)	25.3	73.5	143.2	85.1

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Fig. 3. Detailed design and FEA was performed for various resonator structures: A- 2 beam resonator at third vibratory mode, B- 4 beam resonator, C-butterfly shaped resonator, and D-GE's existing RPT resonator (butterfly type).

Table 3 lays out several key parameters for evaluating the resonator. The parameter, f_0 , denotes the frequency of resonator. The chosen frequency is important because of spurious effects of mode crossings between the resonator and diaphragm. The df of the resonator denotes the total frequency change over the full scale pressure range. Higher values have better sensitivity. The resonator amplitude determines the amount of modulation of the Fabry-Perot cavity. Table 3 also estimates the non-linearity due to the resonance of the actuator, which affects the output of the resonator. The drive efficiency is based on the effect of temperature at the drive laser point to generate vibration of the actuator. Higher numbers denote more sensitivity to drive laser and lower power requirements on the drive laser.

Based on the analysis, each of the designs could potentially meet the resonator subsystem requirements. In addition, the underlying resonator designs are compatible with the same fabrication process. In order to mitigate the design risk of the resonator, each of the designs were fabricated on the first iteration of silicon fabrication.

With the resonator design complete, the mask set was subsequently laid out. Figure 4 shows the basic fabrication process used to make the resonator. First, the pressure sensitive diaphragms

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and mesas that connect the diaphragms to the resonator are etched into silicon. The resonator is patterned onto the mesas and boron doped to absorb the drive signal. The resonator is capped with a wafer bonding process, creating a vacuum necessary for high Q operation.

Fig. 4: The basic silicon fabrication process used to build the optical driven and read pressure resonator. (a) Diaphragm and cavity etching, (b) resonator etching and boron doping, and (c) cap cavity etching, bonding, and mounting, and pillar etching.

Three new sensor die designs and one similar to the original low pressure sensor were developed, and in Q4/2010 the design of the MEMS mask set was completed. The masks were manufactured and received, and two wafers were fabricated. SEM images of the four resonator designs are shown in Fig. 5.

Fig. 5: SEM images of the four resonator designs that have been fabricated.

The conceptual structure for the mechanical design of the sensor head package was evaluated against the CTQs shown in Fig. 6 and Table 4. Five concepts were originally considered and evaluated against key performance and manufacturability criteria.

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CTQs:

1. Temperature: 20 (cal) ~375°C
2. Pressure range: 0~210 bar
3. Fiber diameter: 125um
4. Fiber to cap distance: ~3mm
5. Fiber to target misalignment tolerance is ~100um
6. Isolated (oil filled)
7. Die size: ~ 5x5mm

Fig. 6: The conceptual operating structure and CTQs.

Table 4. The conceptual operating structure and CTQs.

	Optical Alignment		Oil Volume		Life time reliability / robustness		Optical budget		Oil fill simplicity		Weld simplicity		Parts availability		Stress on chip		Lead time		Existing processes		Design flexibility (Gauge)		Design flexibility (cable length)		
weighting		5		4		5		5		2		2		3		5		3		4		1		1	
1	1	5	1	4	1	5	2	10	1	2	1	2	1	3	5	25	1	3	1	4	1	1	1	1	65
2	1	5	1	4	1	5	5	25	1	2	1	2	1	3	1	5	2	6	2	8	3	3	1	1	69
3a	5	25	3	12	1	5	4	20	1	2	1	2	1	3	1	5	1	3	1	4	3	3	1	1	85
3b	5	25	1	4	1	5	4	20	1	2	1	2	5	15	1	5	4	12	1	4	3	3	1	1	98
4a	1	5	3	12	1	5	2	10	5	10	5	10	1	3	1	5	1	3	1	4	3	3	1	1	71
4b	1	5	3	12	2	10	2	10	1	2	1	2	1	3	1	5	3	9	1	4	3	3	1	1	66
5	1	5	1	4	5	25	1	5	5	10	5	10	5	15	5	25	5	15	1	4	3	3	1	1	122

The principal challenge in the package is to combine the mechanical strength necessary to withstand the 220 bar operating pressure with the need to apply minimal packaging stress to the resonator chip over the operating temperature range to 374°C. The outer package needs to be metallic to survive the environment, while the chip is made of silicon and glass resulting in a large thermal coefficient of expansion mismatch.

The thermally induced stress was modelled for a simple low thermal expansion alloy bulkhead mounted within an Inconel housing as shown in Fig. 7. As expected, the induced strain was excessively high at the bond surface with significant bulk yielding prior to the application of any pressure. The introduction of a flexible stress-relieving feature was shown to remove this bulk yielding and reduce the thermal bond surface strain. However, as a result, the bulkhead experienced increased deflection due to applied pressure and increased pressure-induced bond surface strain.

The approach of using a low thermal expansion ‘matched’ pressure bulkhead was, therefore, abandoned due to its inherent conflicting performance requirements and the compromises it

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would demand. The approach of a thermal stress-isolating component separate from the Inconel pressure bulkhead next investigated.

Fig. 7: FEA model of thermally induced stress for a simple low thermal expansion alloy bulkhead mounted within an Inconel housing.

The design for the first iteration of the sensor package is shown in Fig. 8.

Fig. 8: First iteration of package containing MEMS pressure sensor and optical fiber.

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As shown in Fig. 9, the package design concept requires that the pressure in the sensing module be retained by a swaged seal between the sensor body and the ferrule brazed to the optical fiber. The sensor body must be made from Inconel 625 in order to withstand the well environment, while the chip carrier and ferrule have to be made from Kovar to match the thermal expansion of glass and silicon. Leak tests have been performed on several designs of swage joint under thermal cycling to 400°C and a satisfactory solution has been found. Parts for the final design of sensor package were then fabricated.

Fig. 9: Test housing for swage seal

Fig. 10: Leak test parts after temperature cycling to 400°C.

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One of the critical parts for the pressure sensor package is the Kovar ferrule to which the metallized optical fiber is brazed to provide a hermetic seal. After designing a Kovar ferrule that could be swaged into the Inconel sensor body to form a reliable leak-tight seal at up to 400°C, the ferrules were manufactured as shown in Fig. 11, complete with a 250 μm drilling to accommodate the optical fiber.

Fig. 11: Photos of the Kovar ferrule with an optical fiber inserted.

A suitable brazing alloy was identified to bond to both the gold coating on the fiber and the Kovar of the ferrule. The silicon die is attached to a flexible Kovar carrier which is thermally matched to the silicon and able to deform to accommodate the expansion of the Inconel. The die attach is accomplished by means of glass frit paste which is fired on a hotplate. The frit is dispensed and the die placed in an automated pick and place machine which uses an etched silicon carrier wafer to fixture the chip carrier. The photograph in Fig. 12 shows a chip being placed into the carrier. The features in the etched wafer, which fixture the chip carrier, are also visible.

Fig. 12: Photo of sensor chip being placed into carrier.

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A pressure vessel was also designed and constructed as shown in Fig. 13 which was large enough to contain the sensor and optical fiber alignment parts. The pressure vessel is rated to 50 psi for testing the MEMS sensors before they are packaged.

Fig. 13: Pressure vessel designed and constructed for housing the optical apparatus to test the unpackaged MEMS sensors.

The first generation of an optical test setup was constructed as shown in Fig. 14 to support the modeling work with data from potential sensing approaches. Key assumptions were made in the model with regards to the losses especially at the interface between the sensor and fiber. This setup was used to quantify those losses to improve the model's ability to predict the sensor performance. Leveraging existing resonant sensors from GE Sensing, tests were initially run to show that the setup could electrically drive and read back the sensor resonant frequency.

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Fig. 14: Optical and electronic system design for read signal fiber delivery optimization.

The sensor is driven electrically in this system. The drive signal is generated by combining the RF output from the network analyzer with a DC offset voltage. The original circuit for doing this was somewhat modified as shown in Fig. 15 in order to have a DC supply with a single voltage output and yet still have potentiometer controls for the full DC and RF variable input range. Individual component values were selected to give the best SNR. The DC voltage can be varied from 0 to 11.7 V. The RF voltage can be varied from 0 to over 100 mV at the typical 35 kHz resonator frequency. The combined input signal is displayed on the oscilloscope via AC coupling and on a DC voltmeter so that the DC bias and RF amplitude of the input signal can be simultaneously measured.

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Fig. 15: Circuit for combining RF input from network analyzer and DC voltage to drive the resonator, while using a single voltage DC supply.

The electrical and the optical read out signals are both fed back into separate inputs on the network analyzer. The raw optical signal before the high pass filter is also displayed on the oscilloscope. A 50 Ω terminator is inserted between the detector output and the high pass filter for proper signal conditioning from the detector. Both the oscilloscope and the network analyzer are controlled via a simple LabView program on the PC through the GPIB bus and through this it is possible to capture both analyzer and scope traces.

The laser operates at 1550 nm and is mounted on a thermoelectrically cooled stage. The laser current can be varied manually to adjust the output power at the sensor. Most of the experimental measurements have been taken with the laser drive current at 240 mA, which delivers ~17 mW of laser power to the sensor. A plot of laser power at the sensor as a function of drive current is shown in Fig. 16. Higher readout power levels correspond to better SNR values as shown in Fig. 17.

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Fig. 16: Output laser power from a typical MM fiber at the sensor as a function of drive current.

Fig. 17: Dependence of SNR on laser power at the sensor.

The position on the resonator at which the light strikes can have a profound effect on signal amplitude. Therefore, it was found necessary to develop a procedure for alignment of the optical fibers so that with a relatively high degree of confidence each different fiber would interrogate

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the same position on the resonator. With reference to Fig. 18, the alignment procedure is as follows.

1. Set the DC offset to 9 V and the RF drive amplitude to 70 mV. The IF bandwidth of the network analyzer should be set to 100 Hz or lower and the correct frequency range selected to capture the resonance. The electronic resonance should now be observed on the network analyzer trace. If the resonance is not observed, all electrical connections should be rechecked, as well as the frequency range of the network analyzer and other instrumental settings. In particular, the network analyzer input should be set to just “A” or “B” rather than to the ratio “A/R” or “B/R.”
2. The laser current is set to 240 mA and the laser emission from the fiber should be verified to be ~17 mW. If substantially less power is measured, the fiber connector should be checked and cleaned, polished or replaced as necessary.
3. The optical fiber is next aligned by eye to the sensor. From the top down view as shown in Fig. 7(a) the fiber is located ~1 fiber diameter away from the glass tube in the x direction and slightly in front of the tub nub in the -y direction. Using a magnifying optical headset, one can view the gap between the fiber and resonator, which should be reduced until the fiber nearly contacts its reflection in the sensor cover.
4. At this point, a signal is generally present on the analyzer. If it is not, then verify that all electrical and optical connections have been properly made. If everything is connected properly and there is still no signal, then the fiber may be located in a null position. Small adjustments of the fiber in the +x direction should be made to see if a signal is obtained. If not, the fiber should be returned to its original x position and small adjustments of the fiber in the y direction should be made.
5. Once the optical resonance signal is observed on the network analyzer, the fiber position is adjusted in the +x and -y directions to maximize the signal and depth of the notch in the network analyzer trace at the resonance frequency. In particular, the fiber is moved in the -y direction through each resonance position on the resonator until the last (i.e., in the most negative y position) one is found. At this y position, the fiber is then moved in the +x direction again until the last resonance is found. The x and y fiber position should then be tweaked to maximize the signal. The fiber is then further lowered along the -z direction gradually until the signal is maximized. When the fiber actually touches the cover of the sensor, the signal level will begin to drop. Also, one will notice that small x or y adjustments no longer have an effect as friction prevents the fiber from moving.
6. At this point, the signal trace on the scope is highly sensitive to vibrations of the tilt stage. Simply touching either tilt stage knob causes the signal trace on the scope to bounce up and down over a certain range. This range should be noted. In particular, the upper limit of the

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bouncing trace should be noted. The tilt stage knobs are then very gently adjusted until the scope trace rests at the top of this range when the stage is not touched.

7. Final tweaks to the x, y, and z position of the fiber are made to again maximize the signal amplitude.

Fig. 18: Alignment of fiber with respect to the sensor.

A variety of different fibers have been obtained for measurement of SNR. These include SM and MM fibers with cleaved ends, SM and MM fibers with tapered lens ends (~30 – 50 mm focal length), and SM fibers with ball lenses and nearly collimated beams. A few representative measurements are described here. The optical power out each type of fiber was fairly consistent at ~17 mW as shown in Fig. 19.

Fig. 19: Optical power out of each fiber before alignment to the sensor for 240 mA laser drive current.

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An example of a resonance trace on the network analyzer for a 9 VDC drive offset and 70 mV RF drive peak-to-peak amplitude is shown in Fig. 20. As the RF output from the network analyzer scans in frequency, the signal amplitude reaches a peak and then drops suddenly at the resonance frequency into a deep notch. Above the notch frequency, there is a period of rapid oscillation in amplitude, before the signal again decays.

It was previously hypothesized that for small resonator vibrations, the signal response is mostly linear at the fundamental frequency as shown in Fig. 21(a). However, as the resonator approaches its resonant frequency, the amplitude of the resonator displacement increases to the point that the cavity response becomes nonlinear, as shown in Fig. 21(b). The dominant result of this nonlinearity is to excite the second and higher order harmonics. As signal power is diverted into the harmonics, it is subtracted from the fundamental and a minimum occurs in the signal spectrum at the fundamental frequency. This hypothesis has been verified by direct capture of the signal trace on the oscilloscope as shown in Fig. 22 at the frequencies marked by the red and magenta circles in Fig. 20. These scope traces are each actually an average of 100 successively captured traces.

Fig. 20: Resonance as measured on the network analyzer with a 30 Hz IF bandwidth. The red circle denotes the frequency of peak signal amplitude. The magenta circle denotes the notch frequency. The signal modulation at slightly higher frequencies is reproducible (i.e., it is not noise) but it can be greatly affected by changes in IF bandwidth.

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Fig. 21: (a) For small drive amplitudes and variations in gap distance between the resonator and cover, the response is approximately linear around the operating point (black dot). (b) For larger drive amplitudes, the response becomes nonlinear and higher harmonics are generated.

Fig. 22: (a) Off resonance (red circle in Fig. 20) the drive amplitude is small enough to operate in the nearly linear regime. (b) On resonance (magenta circle in Fig. 20) the drive amplitude is so large that nonlinearities in the signal response generate a large second harmonic component and correspondingly reduce the fundamental amplitude.

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The evolution of the scope trace as the frequency is scanned across the resonance is shown in Fig. 23.

Fig. 23: A scan from the network analyzer is shown in the upper left. The scope trace of the raw detector signal was captured at nine different frequencies along this scan (the ten scope trace occurs at a +60 Hz offset from the 35.440 kHz “zero” frequency in the network analyzer trace).

We can infer the amplitude of the resonator from the scope traces as shown in Fig. 24. The operating point is apparently not at the optimum location, but rather is close to a minimum. As a result, even 15 Hz away from the resonance, in scope trace #1, flattening can be observed at the bottom of trace as the resonator swings through the reflectance minimum of the Fabry-Perot interference fringe. By trace #4, the drive frequency is only about 3 Hz from resonance and the amplitude of the resonator oscillation is now large enough that it is almost crossing the first Fabry-Perot interference maximum. At trace #5, on resonance, the amplitude is large enough that the resonator swings through two Fabry-Perot maxima.

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Fig. 24: The extent of the resonator displacement from its operating point (black dot) at each different frequency in Fig. 23 is plotted in this figure.

The initial plan was to adjust the operating point to an optimum position by varying the temperature (wavelength) of the read laser or the power level of the drive laser, but ultimately it was found that the laser wavelength could not be varied over a sufficiently large range and instead an alternate method involving the higher harmonics of the read back signal was adopted as will be described subsequently.

This instrument shown in Fig. 14 was also used to validate the optical models. Several additional predictions of the models were verified, including the inverse square drop off of signal amplitude with fiber-to-sensor spacing as shown in Fig. 25, a 3 dB point at $\sim 75 \mu\text{m}$ fiber-to-sensor spacing, a spot size on the resonator of the sensor from SM cleaved fiber of $\sim 20 \mu\text{m}$, a signal amplitude which saturates with increasing RF drive power as shown in Fig. 26, the growth of higher signal harmonics past the saturating drive power, and the ability to tune the operating point by changing the wavelength of the readback laser.

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Fig. 25: (a) Model of dependence of signal amplitude on fiber-to-cover gap, and (b) experimental measurement.

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Fig. 26: Signal amplitude with increasing drive amplitude exhibits saturation.

The optical readback instrument in Fig. 14 was then modified so that the resonator could be driven and read back optically through a single fiber as shown in the block diagram of Fig. 27 and photo of Fig. 28.

Fig. 27: Block diagram of the all-optical interrogation system for the MEMS pressure sensor.

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Fig. 28: Breadboard layout of apparatus for optically driving the MEMS resonator and reading back the signal.

An example of the signal amplitude and phase as measured by the network analyzer for this setup is shown in Fig. 29. SNR is >30 dB at resonance with an IF bandwidth of 30 Hz. The phase signal is used in the electronic feedback loop to maintain the drive frequency at the resonant frequency of the sensor.

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Fig. 29: Amplitude and phase of resonator signal when driven and read back optically.

Difficulties were encountered in exciting the resonance of the first MEMS devices to be fabricated with the optical drive. After some investigation, the most likely cause was identified as an insufficient level of boron doping in the optical target region. Either insufficient doping was delivered by the ion implantation process or the subsequent processing steps to cap the wafer caused the implanted boron to diffuse away. A number of uncapped wafers remained in stock and were coated with an additional absorptive coating to improve the optical drive efficiency.

Further experiments were then carried out with this apparatus to examine the effect of the separation between the top of the sensor and the tip of the multimode cleaved fiber, as manufacturing tolerances can cause this gap to change by as much as 300 μm . Fig. 30 illustrates the dependence of signal power on this separation, where a gap of $\sim 400 \mu\text{m}$ causes the signal to merge with noise. The change in resonant frequency as a function of gap size is attributed to a corresponding change in the temperature of the sensor. Pulling the fiber away from the chip reduces the DC heating effect of the laser light. Addition of index matching gel in the gap improves the signal as shown in Fig. 31.

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Fig. 30: Effect of fiber tip – chip separation on readback power and resonant frequency.

Fig. 31: Improvement in peak signal due to index matching gel.

At this point, there was some work on attempting to control the frequency of oscillation of the RPT pressure sensor by using a vector network analyzer (VNA) and a software control loop. The software control loop controlled the frequency of modulation of the drive laser via the VNA output driving the oscillation of the RPT sensor. The read laser reading back the oscillation of the sensor was converted to an electrical signal with a photodiode/transimpedance amplifier (TIA) and fed back into the VNA input where its phase was measured. The software closed loop

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controller constantly adjusted the frequency of the drive laser modulation so that the phase of the read back signal was a constant (e.g. 0). This technique showed some success but was deemed to be insufficient for this project since the resonant frequency of the RPT sensor was not stable. Also, even under closed loop control the phase of the read back signal could not be controlled to better than about $\pm 10^\circ$.

The next step, therefore, was to switch from a software-based closed loop control to a hardware-based closed loop control whereby the overall system was closed on itself and allowed to find and oscillate at its own natural resonance. This system is shown in Fig. 32. A 1310 nm laser was used to drive the sensor. A 1550 nm laser was used to read back the oscillation of the sensor. Closed loop oscillation was achieved by directly feeding back the output of the read laser (converted to an electrical signal), with amplification and phase shift applied, to the modulation drive of the drive laser. The first stage of amplification of the read back signal was achieved with an SRS SR645 high pass filter and amplifier. The phase shift was applied with a National Instruments NI-PXI 7853R FPGA board with a 16-bit ADC and a 16-bit DAC.

Fig. 32: Closed loop control of RPT sensor

In order to get the closed loop system to oscillate, the gain must be greater than the loss and the phase shift must be properly selected. As shown in Fig. 33, a variable phase shift was achieved by first digitizing the amplified read back signal, using a 16-bit ADC on the NI-PXI 7853R card. Once digitized, the read back signal was fed into an FPGA, where selectable units of digital delay could be applied. Once the delay was applied, the signal was converted back to an analog

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voltage and used to modulate the laser driver. The LabView-based FPGA code that applies the variable delay is also shown in Fig. 33. The screen shot in the figure shows the A/D converted input signal to the NI-PXI 7853R card being fed to a unit delay block, where the digital samples are held for a selectable number of FPGA clock cycles before being D/A converted and sent out. The FPGA also allows for applying additional gain to the signal before D/A conversion.

Fig. 33: NI-PXI 7853R FPGA based variable phase shift.

The closed loop system was verified by moving the fiber away from the resonating position, and also by switching off the drive laser. In addition, the resonant frequency obtained from the electrical leads of the resonator coincided with that from the optical signal, as shown in Fig. 34(a), further confirming that the resonant frequency was that of the sensor rather than some other component in the loop. Fig. 34(b) is an oscilloscope trace of the FPGA output which gets fed back to the laser driver.

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Fig. 34: (a) Spectrum analyzer scan of signal amplitude as a function of drive frequency indicating the resonant mode at ~35.68 kHz. (b) Oscilloscope trace capture of the drive signal in the closed loop.

This simple variable digital delay (phase shift) scheme enabled searching for the optimum gain/phase shift setting that would allow the sensor to oscillate at its natural resonance. Fig. 35 shows open loop and closed loop resonance data taken for the RPT sensor using this setup. The SNR in this experiment was > 40 dB.

Fig. 35: Open and closed loop oscillation of RPT sensor

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After successfully achieving closed loop oscillation with the RPT sensor, this feedback loop was applied unsuccessfully to operate the newly fabricated sensors, apparently due to the lack of absorbed laser drive power as described previously.

The RPT sensors are electronic MEMS pressure sensors for low pressure applications (<50 psi) that were used to initially develop the optical readback system, but are not suitable for the high pressures in a geothermal well. The RPT sensor was mounted on a heater and placed in the pressure vessel in Fig. 13 that could be pressurized up to 50 psi. The sensor exhibited high peak powers and SNR in the open loop configuration. Figure 36(a) shows the highly linear response of the RPT sensor to ambient pressure variations. The data were recorded for chip temperatures of 24°C and 50°C. The RPT sensor was unaffected by the 25°C rise in chip temperature and exhibited a linear response with the same pressure sensitivity (slope of the line) of approximately 130 Hz/psi in both cases.

Fig. 36: (a) Plot showing the change in resonant frequency of the RPT sensor as a function of ambient pressure at room temperature (24.2 C) and at 50C. The sensor exhibits a very linear response and the slope (sensitivity) is nearly identical at both temperatures, ~130 Hz/psi. (b) Plot showing a variation in the observed peak power of the open loop resonant spectrum for the RPT sensor as a function of the applied pressure.

During the experiment, it was observed that the peak signal power varied as the ambient pressure was changed (Fig. 36(b)). Over the 20 psi pressure range, the peak signal varied by more than 20 dBm. In order to determine whether this variation was wavelength dependent, the variation in the peak signal power as a function of the laser wavelength at a fixed pressure was investigated at two different ambient pressures, 8 psi (corresponding to the lowest peak power for the plot at 24°C) and 16 psi (corresponding to the highest peak power for the plot at 24°C).

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Fig. 37: Effect of changing laser wavelength at low SNR point – 8psi (a) Plot showing a further decrease in the SNR with increasing read laser current (increasing wavelength) (b) Plot showing variation in the peak power as the read laser TEC temperature is tuned over 30C, corresponding to a ~14 nm wavelength change.

At an ambient pressure of 8 psi, the peak power and SNR varied as the read laser wavelength was tuned via current (smaller wavelength shift of ~1 nm) and by temperature (larger wavelength shifts of ~14 nm) as shown in Figs. 37(a) and (b). However, at an ambient pressure of 16 psi (corresponding to the highest peak power in Fig. 36(b)), the minor variation that was observed can be explained by the increase in read laser power with increasing laser drive current, and a decrease in read laser power with increasing device temperature, as shown in Figs. 38(a) and (b)

Fig. 38: Effect of changing laser wavelength at high SNR point – 16 psi (a) Plot showing an increase the peak power with increasing read laser current (increasing wavelength) (b) Plot showing variation in the peak power as the read laser TEC temperature is tuned over 30 C, corresponding to a wavelength change ~ 14 nm.

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Although finite element modeling had been previously used to design the new MEMS resonators, the variation in the mechanical properties and dimensions of the resonators made it impossible to predict with high accuracy their resonant frequencies. The new sensors, consisting of 2-beam and 4-beam designs described previously, were tested and characterized. Initial attempts to excite the sensors by a modulated laser beam were unsuccessful, so both mechanical tapping and high frequency vibration induced from a piezoelectric actuator were employed. This approach was used successfully to identify the resonant frequencies of the new resonator designs. While the piezo drive provided a good optical read back signal at the fundamental resonant mode, it was unable to excite higher order modes of the 2-beam and 4-beam sensors. Due to limitations in the testing setup, the piezo could not be incorporated directly below the sensor and as a result, it was clamped some distance away from the sensor. The inability to excite higher order modes via the piezo was most likely due to this distance between the piezo and the sensor.

Subsequently, *with careful alignment and higher laser drive powers (~10 mW), both the 2-beam and 4-beam sensors were able to be tested in an optical read, optical drive configuration* as had been previously demonstrated with the RPT sensor. Of the three methods of driving the resonator (mechanical tap, piezo, optical), the peak signal and SNR was found to be the best in the case of optical read and drive and it was also found to be the best method for exciting higher order modes of the sensors, as long as there was no tilt between the fiber and the sensor. Figure 39(a) shows a plot of the open loop resonance data for the fundamental mode of the 2-beam sensor using both a piezo and optical drive. Figure 39(b) is a plot of the third mode of the 2-beam sensor with optical read and drive.

(a)

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Fig. 39: (a) Plot showing resonant spectrum of the fundamental mode of a 2-beam sensor that is actuated by a piezo and by an optical signal. (b) Resonant spectrum of the third mode of the 2-beam sensor.

1. Results for two beam sensor

The pressure sensitivity of the 2 beam sensor was measured at various chip temperatures. To vary the chip temperature, a resistive heater was placed below a copper plate on which the sensor was mounted. By varying the applied voltage to the heater and measuring the temperature of the copper plate using a type-K thermocouple, a calibration curve for temperature was obtained. The thermocouple was also kept in place when the pressure chamber was sealed and pressurized to enable continuous monitoring of the plate temperature and to ensure that the temperature had reached steady state before any data was collected.

Initial testing indicated that heating of the copper plate resulted in a misalignment of the sensor and optical fiber due to the expansion of the copper plate on which the sensor was mounted. By changing the method of clamping the copper plate, and by placing the chip at the center of the plate, this effect was mitigated, thus enabling data collection across a range of chip temperatures and ambient pressures.

Fig. 40(a) and (b) shows the measured data and linear fits of the resonant frequency as a function of pressure at 24, 50, 75 and 100°C for the first and third resonant modes, respectively. In all cases, the sensor shows a fairly linear response. The slope of these plots represents the pressure sensitivity of the 2-beam sensor at these different temperatures, and this is shown in Fig. 41(a). The observed variation in Fig. 41(a) demonstrates that the third resonant mode of the sensor is approximately 1.4 times more sensitive than the first resonant mode.

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(a)

(b)

Fig. 40: Plot of resonant frequency as a function of ambient pressure for 2 beam sensor at 24, 50, 75 and 100 C for (a) first resonant mode (b) third resonant mode.

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(a)

(b)

Fig. 41: (a) Pressure sensitivity (slope of plots in Figs. 40(a) and (b)) of the 2-beam sensor as a function of chip temperature. The pressure sensitivity varies between 1.8 to 2.2 Hz/psi for the first resonant mode and 2.2 to 3 Hz/psi for the third resonant mode. (b) Temperature sensitivity of the 2-beam sensor at atmospheric pressure.

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The temperature sensitivity of the 2-beam sensor at a constant pressure (atmospheric pressure) was also characterized as shown in Figure 40(b). The temperature sensitivity is -1 Hz/C and -5.5 Hz/C for the first and third modes of the sensor, respectively. The peak signal power was observed to increase slightly while heating this chip, with a total observed change of around 1.5 dBm.

The effect of the read laser current on the signal was also characterized at room temperature (24° C) and atmospheric pressure. Increasing the current from 50 mA to a maximum of 225 mA resulted in an increase in the peak signal power from -68 dBm to -49 dBm. This increase in current corresponded to an increase in the read laser wavelength from 1551.3 nm to 1554.7 nm and read laser power varying from 1.8 mW to 14.9 mW. This increase in read laser power also results in increased localized heating of the sensor, which causes a negative drift in the sensor frequency. The sensor frequency sensitivity to read laser current was -0.8 Hz/mA, and the response of the sensor to laser current was linear.

The lateral sensitivity of the fiber coupling to the 2-beam sensor was estimated by aligning and adjusting its tilt to get the maximum peak power. This point corresponds to the origin (i.e., $x=0$, $y=0$) in Fig. 42. Subsequent scans were conducted by moving the fiber along two orthogonal directions (axes of the translation stage on which the fiber was mounted) in the plane of the sensor as shown in Figs. 42(a) and (b). Along the x-axis, translation of the fiber over 80-100 μm still resulted in a reasonably strong peak signal power. Along the y-axis, the fiber could be translated approximately 40 μm (20 μm on each side of the origin) while maintaining reasonably high peak signal powers. These measurements have a direct bearing on the alignment tolerance for the fiber within the package.

(a)

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Fig. 42: Effect on power and frequency when scanning the optical fiber along the (a) X-direction and (b) Y-direction.

2. Results for four beam sensor

The functioning of the 4-beam sensor was tested with mechanical tapping, piezo modulation, and optical drive and read signals. As in the 2-beam sensor, the overall signal power levels were low, the SNR was much lower than the RPT sensor, and the resonator Q was in the range of 80 to 800. The effect of the read laser current and wavelength was measured at room temperature and pressure as in the case of the 2-beam sensor. It was found that the resonator frequency did not change much with the resonator wavelength (6 Hz over ~15 nm), as long as the laser power was not changing. Changing the laser current caused both wavelength and power of the laser to change, resulting in a marked change in resonant frequency due to the sensor temperature changing with the laser optical power (40 Hz over ~150 mA change in laser current). The readback signal power peaked at a read laser temperature of 26 C corresponding to a wavelength of 1559.5 nm, and a drive current of 200 mA, hence this setting was used for all subsequent measurements, with an RF power of 9 dBm for a drive laser current of 200 mA at 20°C.

The pressure sensitivity of the 4-beam sensor was measured at various chip temperatures. Chip temperature was set by means of a thermoelectric cooler (TEC). Using a TEC enabled more accurate and stable temperature profiles during the course of the experiment, as described in the temperature measurements for the 2-beam sensor. However, the greatest source of error was the limited resolution of the pressure gauge on the pressure vessel. Measurements were further complicated by a slow leak of the vessel. Fig. 43(a) shows measured data and linear fits of the resonant frequency as a function of pressure at 25, 40, 60, 80 and 100°C. Measurements repeated at 25°C and 40°C (not shown), resulted in slopes between 0.7 and 1.3 Hz/psi. It should be noted that the sensor cap thickness had been originally selected at GE Sensing to reduce the

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pressure sensitivity by about two orders of magnitude from the 130 Hz/psi of the low pressure RPT sensors. These results demonstrate that the cap thickness was indeed chosen correctly. Therefore, for the desired 220 bar pressure range of the geothermal sensors, corresponding to 3200 psi, there should be ~3 kHz frequency shift from the initial resonance at ~18 kHz. When completely packaged sensors are available, the measurements will be extended to cover the entire pressure range.

In Fig. 42(b) the resonant frequency was captured at a constant pressure but the temperature was varied. The temperature sensitivity is -1.1 Hz/C, which is consistent with the value of -0.9Hz/C calculated from the y-intercepts of the linear fits in Fig. 42(a). The temperature sensitivity is about the same as mode 1 of the 2-beam sensor and one third that of mode 3 of the 2-beam sensor.

(a)

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Fig. 43: (a) Plot of resonant frequency as a function of ambient pressure for 4-beam sensor at 25, 40, 60, 80 and 100 C. The slopes indicate pressure sensitivities of 0.7 to 0.9 Hz/psi. (b) Resonant frequency as a function of chip temperature for 4-beam sensor at ambient pressure (red), and calculated from y-intercepts of (a) (blue).

The lateral sensitivity of the 4-beam sensor was estimated by finding the alignment of the fiber at which the peak power was maximum and then scanning to the left, right, up and down from this point, as was done for the 2-beam sensor. It was possible to scan in one of the directions for 90-250 μm , depending on the particular die being tested. However, large signal variations observed in the scan along the perpendicular direction indicates the need for design changes to the resonator.

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(a)

(b)

Fig. 44: Effect on power and frequency when scanning the optical fiber along the (a) x-direction and (b) y-direction of the 4-beam sensor.

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As manufacturing tolerances can cause a separation of as much as 300 μm between the fiber tip and sensor, the RPT, 2-beam, and 4-beam sensors were tested with flat cleaved and collimated single-mode (SM) fiber tips. In the case of the RPT sensor, the collimated fiber yielded a good signal for a distance of up to 1000 μm , although a dip existed at 350 μm and 200 μm , in air and oil, respectively.

Fig. 45(a) and (b) show the vertical sensitivity of the readback signal using a cleaved SM fiber for the third mode of a 2-beam sensor and the fundamental mode of a 4-beam sensor, respectively. Commercially available index matching fluid with $n = 1.69$ was used with the 2-beam sensor, while a high temperature oil that will be incorporated in the packaged sensors with a refractive index of $n = 1.54$ at a wavelength of 589.29 nm was used with the 4-beam sensor. In both cases, the fiber could be pulled away from the sensor by up to 300 μm before the signal merged with the noise floor in a 30 Hz bandwidth. Fig. 13(c) illustrates measurements for a 4-beam sensor using a collimating fiber tip in air. The initial SNR of 30 dB in a 30 Hz bandwidth was maintained as the fiber was separated up to 1000 μm from the sensor surface. It was found that the signal variation was less sensitive to fiber tilt for the collimating fiber than for the cleaved fiber.

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(b)

(c)

Fig. 45: Effect of separation between fiber and sensor on peak power and resonant frequency for (a) SM cleaved fiber and 2-beam sensor, (b) SM cleaved fiber and 4-beam sensor, and (c) SM collimated tip fiber and 4-beam sensor.

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After testing various 4-beam sensor dies, one with a high SNR was chosen for a closed feedback loop experiment using the circuit in Fig. 32. The phase of the amplified detected signal was varied through an FPGA-based delay block, before the signal was fed back to modulate the drive laser. Fig. 46 shows the spectrum of the signal from the network analyzer as the phase was varied, and the corresponding oscilloscope trace.

(a)

(b)

Fig. 46: (a) Spectrum of detected signal for 4-beam sensor run in closed loop. (b) Oscilloscope trace of the detected signal.

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The pressure sensitivity of the sensor was measured in closed loop at ambient temperature, as shown in Fig. 47, resulting in a sensitivity value of 1.2 Hz/psi, which is close to the 0.9 Hz/psi measured in open loop, and within the margin of error.

Fig. 47: Resonant frequency as a function of pressure, at ambient temperature, for 4-beam sensor with a closed feedback loop.

The optical attenuation expected from a fiber cable that is several kilometers long was simulated by inserting an attenuator in the WDM coupler path before the sensor. The optical attenuation could then be increased until the feedback loop was no longer able to track the sensor resonance. With the noise sources in the present system, at least 4.5 mW of drive laser power and 6 mW read laser power injected into the fiber cable were required for closed loop operation. In our optical system, the drive laser has a maximum output power of 100 mW and the read laser has a maximum output power of 80 mW, so there appears to be substantial margin available to overcome any attenuation of the lasers occurring in the fiber cable in the downhole experiment.

Task 1.4—Distributed Pressure Sensor Survivability and Modeling

Associated Milestone: Demonstration of fiber-level performance on FBG pressure sensor

This task is meant to leverage the capabilities and economics of commercial vendors along with new design inputs to produce fiber Bragg grating sensors and an interrogation system.

A detailed examination was performed of different pressure sensors available on the market for the oil and gas technology sector applications. These pressure sensors mainly target downhole pressure detection with differing ranges of operating pressure and temperature. There is no a pressure sensor, which is already available on the market, which will survive temperatures as high as 374°C and measure pressure to 220 bar (~ 3200 psi).

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One available product on the market is produced by Weatherford that measures up to 10 kpsi but is limited to an operating temperature range of 150°C. The Weatherford point pressure sensor can be concatenated up to 4 sensors on one SM fiber probe to provide a distributed measurement. Another product available on the market from Sabeus Inc. measures downhole pressure, using Fabry Perot (FP) cavity principle, up to 2000 psi. Since the FP cavity based sensing technology is temperature dependent, Sabeus uses a fiber Bragg grating (FBG) sensor to eliminate temperature effects. Operating temperature limits of this approach are not known and this method cannot be concatenated. The final product examined was from Opsens which can operate to temperatures of 300°C but can measure only to 750 psi and is not concatenable to form a quasi-distributed pressure sensor. The principle drawbacks of these products stem from the use of technology that does not scale when the operating temperature goes beyond certain limits, while FP cavity-based pressure sensors are not cascable. It is evident from an examination of these products that the need exists for a novel means of monitoring downhole pressure in distributed or quasi-distributed fashion which will satisfy all of the operating conditions of the enhanced geothermal systems.

A literature survey of the different results published by academia and industry in the field of using FBG for pressure sensing in the Oil & Gas and geothermal arena has also been conducted. The performance and specifications of these pressure sensors have been compared by their operating limits, working range, and reliability etc. To overcome high-temperature and high-pressure challenges for current program, a brainstorming session among different photonics engineers and scientists working at GE Global Research Center was held. Several ideas in pressure sensors and sensing cable conceptual designs have been presented and discussed.

The approach under consideration in this project are fiber Bragg grating sensors. These distributed pressure sensors have the ability to be cascaded such that multiple single FBG-based pressure sensors can have a spatial resolution of a few ten meters to a few hundreds meters. However, fiber Bragg grating sensors have several challenges for implementation at 374°C for geothermal applications. One critical development identified is the need for a high temperature package and transduction method to convert the pressure measurement into a strain on the FBG. This requires a thorough mechanical design through the use of finite element analysis. It is also necessary to properly design the pressure sensor package, pressure-to-strain transduction mechanism, metallized fiber, and bonding adhesive that can hold fiber and package together form some of important design inputs.

The strain response properties of FBGs are utilized to measure pressure. A fiber Bragg grating is basically a strain and temperature sensor because of its mechanical and thermal sensitivity. The wavelength shift induced by mechanical and thermal strain can be expressed by,

$$\Delta\lambda = \kappa_m \cdot \varepsilon_m + \kappa_t \cdot \varepsilon_t + (\beta + \alpha_f) \cdot \Delta T; \quad (5)$$

$$\varepsilon_m \propto \Delta l / L_o, \quad \text{and} \quad \varepsilon_t \propto (2\alpha_s - \alpha_f - \alpha_b) \cdot \Delta T;'$$

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where κ_m and κ_t are corresponding mechanical strain and thermal strain sensitivity, or calibration coefficients, respectively. The mechanical strain is proportional to relative material deformation by pressure. The thermal strain is proportional to the difference in linear coefficients of thermal expansion (CTE) among support structure, bonding material, and fiber material. Thermal strain is dependent mainly upon the temperature inside the geothermal well, and the external pressure is converted into mechanical strain by the package. In the final fiber pressure sensor design, an important issue is how to provide a proper bonding strength for the FBG to a mechanical structure which responds to external pressure variation. Thus much of the lab testing work was focused on bonding methods (adhesive bonding, soldering), bonding materials that provide a sufficient bonding strength, and methods to evaluate the bonding strength.

Well-established vendors for supplying metallized fibers and for making fiber Bragg grating sensors were identified. For evaluation purposes, gold, aluminum and copper-alloy coated single-mode fiber from three vendors were chosen. These fibers have

1. High operating temperatures (Cu-alloy: 600°C, Al: 450°C, Gold: 700°C).
2. Excellent thermal conductivity
3. No outgassing at elevated temperatures.

The glass portion of the optical fiber is a standard single mode fiber (SMF) with 9/125 μm core/cladding dimensions. The typical coating diameter is 165 μm with short and long term bending radii better than 10 and 25mm, respectively.

There are several key factors in the downselection of the single mode fiber type. One drawback of the Al coated fiber is that it has an attenuation coefficient of 5.5 dB/km in comparison to 1 dB/km for Copper coated SMF. Al coated fiber could pose serious problems for the optical loss budget over a length of 10 km. This problem could be partially remedied by splicing to a lower attenuation fiber in the lower temperature regions of the well. Another important consideration in the fiber selection is the ability to write FBGs into the metallized fiber.

A key component of the package design is the method of attaching the fiber to the metal package. Several high temperature adhesives were investigated, testing for bond strength through mechanical pulling tests. To evaluate the bonding strength of the metallized fiber and adhesive, a pair of test “buttons” which can be held by an Instron mechanical pulling machine were fabricated by the GE machine Shop. Inconel was selected as the base metal for these tests since that is the packaging material for the sensor. A drawing of the button is shown in Figure 48.

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Fig. 48. Metallic buttons of Inconel manufactured for evaluating mechanical bonding strength of metalized fiber with several adhesives.

Figure 49 shows a photograph of the Instron Tensile Test Machine Model # 1125 where the adhesive buttons were tested. To test the adhesive, 6" of gold-metallized fiber was attached to the button and pulled at the rate of 5-10 mils/minute. The load prior to breaking the bond was noted in order to calculate the maximum strain that could be achieved before the adhesive bond failed. Figure 50 summarizes initial load tests for several different adhesives at room temperature.

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Fig. 49: Instron Tensile test machine used for evaluating bonding strength with inset depicting zoom-in view of the bonded metallic fiber held in tester.

Fig. 50: Load vs. Extension for Gold metalized fibers used with different high temperature functional adhesives.

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Table 2. Summary of the maximum strain for the gold-metallized SM fibers and several different adhesives.

Adhesive	Maximum Strain (μ Strain)
Adhesive_1	13173.9
Adhesive_2	13046.9
Adhesive_3	8666.2
Adhesive_4	1152.3
Adhesive_5	11523.2

Based on the package modeling, there are several adhesive candidates that can withstand a strain budget on the order of ~ 11 - $13,000 \mu$ Strain, which should be sufficient to handle the temperature-related strain caused by the FBG package design as well as the pressure-related strain. It is important to note that all of the above tests were performed at room temperature. The strain budget helps to divide the temperature- and pressure-related strain appropriately in the final pressure-to-strain transduction mechanism and final sensor package design. At the elevated operating temperature of 374°C , other factors such mismatch between the CTE (coefficient of thermal expansion) of the fiber, bonding material, and enclosure case of the pressure sensor itself will also play a crucial role in selecting the fiber, adhesive, and package material.

The FBG sensor is essentially a strain sensor that generates a wavelength shift in the reflected light that is induced by thermo-mechanical strain. Depending on the design of the package, the sensor can be used to measure strain, temperature, pressure, structural fatigue or as a chemical sensor. In this application, since the sensor operates in a harsh environment, the package must protect the fiber from the surroundings. The choice of material and the design of the package depends on the method of transduction as well the environmental constraints.

Fig. 5: Simplified schematic of a FBG sensor package.

Fig. 51 shows a simplified schematic of a FBG sensor package. In a conceptual sense, the sensor consists of a metallized optical fiber which is bonded to an outer package. It was desired to develop guidelines for component design using simplistic models. The parametric relationships aid in developing the final design of the sensor package.

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Typically, a metallized fiber is used to reduce the high CTE mismatch between the adhesive material and the fiber. The coating material is chosen depending on the maximum operating temperature range. Since the maximum operating temperature for the present application is 374°C, an aluminum or a copper alloy coated fiber is acceptable. If the coating material or thickness is not chosen correctly, de-bonding or non-uniform stress distributions may occur. However, if done properly, the coating also serves to improve the temperature sensitivity of the fiber.

If the fiber is metallized near room temperature, it can be assumed that there are no stresses at the initial temperature. Since the physical properties of the glass fiber and the coating material are different, strain will build up as the temperature increases. The axial strain, $\varepsilon_{thermal}$, induced by the coating material is given by the equation:

$$\varepsilon_{thermal} = \left(\frac{1}{1+y} \right) (\alpha_m - \alpha_f) \cdot \Delta T \quad (6)$$

where α_m is the coefficient of thermal expansion of the metal coating material, α_f is the coefficient of thermal expansion of the fiber, and y is given by the relation,

$$y = \frac{Y_0 \cdot r_1^2}{Y_1 \cdot (r_2^2 - r_1^2)}$$

where Y_0 and Y_1 denote the Young's modulus of the fiber and the coating material, and r_1 and r_2 are the radii of the fiber with and without coating.

A finite element modeling tool, ANSYS, is used for the simulation. A quarter-symmetry model is used to reduce computation time. The geometry used for the calculations is shown in Figure 52. A fused silica fiber, 125 μ m in diameter is considered for the fiber. In order to calculate the thermal strain induced in the fiber due to the CTE mismatch, both aluminum and stainless steel are considered as the coating materials. Stainless steel has a CTE of 12 and aluminum has a CTE of 23, which is 20 – 40 times greater than that of the silica fiber.

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Fig. 52: Geometry of the fiber with metallic coating used for thermal strain calculations.

Figure 53 shows the thermal strain for aluminum and stainless steel coating for various thicknesses. It can be seen that the thermal strain increases by increasing the coating thickness. Also, if the coating material has a higher CTE, the thermal strain is higher. For aluminum, the thermal strain values are amplified by a factor of ~ 4 by increasing the coating thickness from $3\mu\text{m}$ to $20\mu\text{m}$. These values obtained through the numerical model also match with the analytically predicted values.

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Fig. 53: Shows the thermal strain induced in the fiber due to CTE mismatch. (a) Stainless steel as the coat material with a CTE of $12 \text{ } ^\circ\text{C m/m}$ (b) Aluminum as the coat material with a CTE of $23 \text{ } ^\circ\text{C m/m}$.

The coating material and the thickness must be determined based on the specific operating conditions. A thicker coating is beneficial for a better hermetic seal if operated at a lower temperature. The bonding strength between the metal layer and the fiber will determine the thickness that can be used. Moreover, while operating at high temperatures, the bond strength could degrade due to metal grain boundary deformation, grain size growth, and dislocation formation processes. Hence, a sufficient safety margin should be employed while designing the fibers.

A simplified model of the sensor package is shown in Fig. 54. It is used to analyze the functional relationships between various parameters. A silica fiber $125\mu\text{m}$ in diameter with an aluminum coating is used for the simulations. The material of the package is stainless steel. Since most of the high temperature adhesives have alumina as the base element, the adhesive material is assumed to have the tensile properties of alumina.

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Fig. 54: Simplified model of the sensor package used for the numerical model.

As mentioned before, the sensor has to measure pressures ranging from 0 – 210 bar while operating at temperatures ranging up to $\sim 374^{\circ}\text{C}$. Pressure will be acting on the outer surface of the cylinder causing the walls of the outer package to deform. By calibrating the amount of deformation at various external pressures, the sensor could be used to measure any pressure within that range. However, since the temperature of the surrounding can vary, the entire package will experience varying thermal strain due to the CTE mismatch between the various components. A common method to overcome this difficulty is to place an additional sensor which will only measure the thermal strain and use that to offset the main sensor.

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A typical FBG sensor can withstand a maximum strain of $\sim 10,000 \mu\text{strain}$. This maximum allowable strain will be divided among the mechanical and thermal effects. The sensitivity of the sensor can be increased by increasing the mechanical component of the strain. The objective of the current analysis is to study the relative contribution of mechanical and thermal strain and their dependence on various parameters.

In order to measure the thermal strain, a uniform temperature boundary condition was set at 374°C . To measure the mechanical strain, a pressure of 210 bar was applied on the outer surface of the cylindrical wall. The thermal strain is plotted on the left y-axis and the mechanical strain is plotted on the right y-axis. Figure 55(a) shows the thermal and mechanical strain as a function of wall thickness of the package. It can be seen that, in general, the thermal strain is an order of magnitude greater than the mechanical strain. The thermal strain does not show a large variation with the wall thickness, which is expected. However, as the wall thickness decreases, the mechanical strain increases. This is due to the fact that the deformation of the wall increases when the wall thickness decreases.

Figure 55(b) shows the thermal and mechanical strains as a function of the thickness of the metal coating on the fiber. It can be seen that the thermal strain decreases as the coating thickness is increased. This behavior is different than that in Figure 53. This difference could be due to the interaction between the package, adhesive material, and the fiber. A thicker coating also helps to increase the mechanical strain.

Figure 56(a) shows the thermal and mechanical strains as a function of the CTE of the adhesive material. It can be seen that the CTE of the adhesive material does not have any effect on the mechanical strain, as the Young's modulus of the material was not changed in these simulations. However, as the CTE of the adhesive material becomes similar to that of the package, the thermal strain decreases. Figure 56(b) shows the thermal and mechanical strains as a function of the length of the overall package. As the package length is increased, it can be seen that the mechanical strain is reduced. Also, it can be seen that the thermal strain increases sharply as the length is increased.

Based on these observations certain guidelines can be formed to aid in the design of the final package, as shown below:

- 1) In general, the thermal strain is much larger than the mechanical strain
- 2) For a cylindrical package design, thinner walls produce larger mechanical strain
- 3) For aluminum coated fiber, thicker coating is better
- 4) Choosing an adhesive material with the same CTE as the package is better to reduce the thermal strain
- 5) Shorter package is better to reduce the thermal strain and increase the mechanical strain
- 6) In all the simulations it is assumed that the strain is zero at room temperature. The thermal strain can be cut in half by attaching the components at 200°C .

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Fiber	FBG Writing Capacity	Strain Budget	Possible Creep Problems	High Temp Survival
#1	?/NO	10K uStrain or better		OK
#2	Good	10K uStrain	?/OK	Oxidation
#3	OK/Damage to fiber	8K uStrain		OK
#4	?		?/OK	?/OK

Fig. 57: Results of metallized fiber testing.

The temperature dependence of the wavelength shift was measured for all four metallized fibers and fit to both a linear and cubic polynomial. The qualitative testing results are shown in Fig. 57. The results for all four fibers were similar. The linear coefficient for $\Delta\lambda/\Delta T$ between 20 to 400°C was 4.679, 4.5487, 4.6548 and 4.7254 nm/°C, respectively. An example of the data collected is shown in Fig. 58. As a result of these tests, both fiber #3 and fiber #4 are suitable for the FBG sensor.

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Fig. 58: Calibration of the Bragg wavelength as a function of temperature for a metallized fiber.

The stability of the fiber Bragg grating when written in metallized SM fiber with Cu, Au and Al was tested for 1600 hours. As shown in Fig. 59, three of the fibers exhibited a satisfactory minimal long term drift after a 72 hour anneal, which has been expressed as an equivalent temperature change in these graphs. The copper-coated fiber, Cu-2, however, exhibited a larger drift and when cooled back to room temperature, the FBG failed.

(a)

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(b)

(c)

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Fig. 59: Measurement of FBG peak wavelength drift for fibers with Cu, Al and Au metal coatings at a temperature of 400 C.

A prototype FBG sensor was constructed using a commercial bellows as shown in Fig. 60.

Fig. 60: Prototype FBG sensor using commercial bellows.

The response of this prototype FBG sensor to pressure was measured as shown in Fig. 61.

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Fig. 61: Change in FBG peak wavelength as a function of time as the external pressure on the sensor was varied between 0 psia and 1500 psia. The magenta curve is for the fiber designed to measure both pressure and temperature while the blue curve is for the fiber designed to measure just temperature.

The results of this test indicated that there was probably a permanent deformation of the sensor package, because the zero level at the end of the experiment did not go back to the initial level for either fiber. Moreover, changes in the zero level at intermediate steps indicated that there was a loss of hermeticity in the seal. A microscopic examination of the adhesive, shown in Fig. 62, indicated that it is somewhat porous.

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Fig. 62: Microscope image of adhesive seal in FBG sensor prototype.

Although *fiber level* performance of the FBG has been satisfactorily demonstrated, thereby completing this task, nevertheless, these actual prototype sensor results were disappointing. Previous experience has indicated that it is very challenging to design a package that is sufficiently sensitive to pressure changes and yet resists permanent deformation, it will not be so simple to obtain a hermetic seal with a high temperature adhesive.

Task 1.5—Cable Design

Associated Milestone: Cable design complete to meet specifications

This task has an overall design objective of developing a cable that protects and imparts reliability of the sensing fibers through installation and downhole operating conditions particular to the EGS environment. As previously mentioned, it was decided to leverage the downhole oil and gas optical sensing cable designs and supply chain, starting with a baseline all-steel protective armor cable construction used successfully in thermal wells. Consistent with oil and gas applications that can subject these cables to broad temperature cycles and dynamic mechanical stress, the cable will be engineered to maintain the sensing fiber in a low strain condition out of direct contact with well fluids under these conditions. A formal review of the geothermal well environment and well completions was undertaken by gathering information from current and planned geothermal/EGS projects. This work dovetails with the installation methods being developed in *Task 1.2—Field Installation Design*, in which the cable design form factor and mechanical handling must be appropriate for use with installation equipment and well conditions.

The cable manufacturer, AFL Telecommunications, formally joined the project team and supported several specification and cable design reviews. A candidate cable design, shown in Fig. 63, was specified based on a tube/tube design currently adopted and in use in thermal recovery wells. This cable features an inner 304SS tubing that encases the sensing fibers. The fibers are held in this first tubing assembly with a design excess fiber length that will maintain fiber in a low strain condition under cable thermal expansion cycled over 375°C. The inner fiber in metal tube (FIMT) assembly is then processed with an outer alloy 825 armor layer. To minimize potential fiber mechanical interaction and total cable cost, a minimum number of fibers, 2 multimode to operate a dual-ended Raman configuration, and a single SM fiber for the FBG and distributed Brillouin sensor, were incorporated in the cable design. AFL prepared a drawing for the cable, reference part number DNS-3634, and which was entered into a revision control system.

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Fig. 63: Cable design showing double tube and three fibers, 2 MM and 1 SM.

A short engineering review was held between GE and QOREX to review the interface and integration of the optical gauges to the cable. It was decided that QOREX would use its qualified fiber splice design and processing to connect the gauge, and adapt its all-welded splice protection package to the gauge package. The cable was subsequently fabricated by AFL Telecommunications and delivered for final assembly and system integration to the QOREX factory.

Task 2: Subsystem Procurement and Test

Task 2.1—Fiber Development and Procurement

A formal review of commercially available geophysical fibers was completed in Q2-2010, and a set of fibers identified as candidates to meet the optical and mechanical (physical) requirements of the program. Fiber suppliers considered included AFL/Fujikura Ltd., Corning Inc., Draka Communications, Fiberguide Industries, Fibertronix, IVG Fiber Ltd., Nufern, OFS Specialty Photonics, Sumitomo Electric Industries, and Verrillon Inc. Both single mode and multimode fibers were evaluated, with the latter specifically intended for Raman-type distributed temperature sensors (DTS). Major selection criterion included use of pure silica core or other waveguide designs for resistance to hydrogen-induced attenuation, and high temperature fiber coatings capable of reliable operation to 300°C as a first temperature rating, and 374°C to fully meet the requirements of the program, which narrowed the pool of available fibers to those with polyimide or metal coating materials. After review of product literature and quotations from each supplier, a set of 10 fibers was procured and received at QOREX Rocky Hill facility, and stored in a dry, room temperature controlled environment. The fibers listed in Table 3 were tested and evaluated per *Task 2.2 – Fiber Material Testing*.

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Table 5. Summary of fibers procured and tested.

Fiber	Waveguide	Coating	Rating
A	50/125 MM Step-Index Pure Silica Core	Polyimide	300°C
B	50/125 MM Graded-Index Control	Polyimide	300°C
C	50/125 MM Step-Index Pure Silica Core	Polyimide	300°C
D	50/125 MM Graded-Index Synthetic Silica	Polyimide	300°C
E	9/125 SM Step-Index Synthetic Silica	Polyimide	300°C
F	9/125 SM Step-Index Pure Silica Core	Polyimide	300°C
G	9/125 SM Step-Index Pure Silica Core	Polyimide	300°C
H	9/125 SM Step-Index Pure Silica Core	Polyimide	300°C
I	50/125 MM Step-Index Pure Silica Core	Aluminum	400°C
J	100/140 MM Step-Index Pure Silica Core	Aluminum	400°C

Task 2.2—Fiber Material Testing

Associated Milestone: Confirmation that the industrial fiber supply chain for high temperature fibers adequately addresses EGS needs

GO/NO-GO DECISION POINT: Fiber testing for material degradation that validates acceptable performance in simulated EGS environments

Associated Milestone: A fiber reliability model based on the data from fiber material testing

In Q2-2010 QOREX generated test plans for optical, mechanical, and hydrogen performance for the fibers procured in Task 2.1 above. The test plans were reviewed with the program PI for approval. The optical tests were to confirm suitability of fiber optical performance to operate the sensors, and set baseline performance to assess any degradation of optical performance in the subsequent mechanical and hydrogen tests. Mechanical testing were based on dynamic tensile tests to analyze fiber strength and assess lifetime and any aging effects of fiber conditioned under a range of thermal and chemical environments. Hydrogen testing characterized fiber spectral attenuation response to a range of thermal and hydrogen partial pressure regimes. Both transient and permanent hydrogen-induced attenuation were characterized, as well as long-term projections of hydrogen tolerance of these fibers and their suitability for the different sensors being evaluated in the program.

A fiber tensile test-bench was assembled and modified to accommodate metal fibers by affixing special gripping mandrels to avoid slippage of the fiber common during low-strain rate tensile testing. Hydrogen test equipment was ordered and installed to accommodate simultaneous hydrogen exposure of multiple test articles and perform in-situ monitoring. A ventilation hood and hydrogen source/nitrogen-purge gas system was assembled and connected to QOREX plant exhaust system. A high pressure hydrogen vessel and heater system was installed with closed loop temperature controller using a thermocouple mounted in a vessel well for in-situ thermal monitoring and control. The vessel is rated to 5,000 psi operating pressure to 300°C. Custom

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high temperature fiber feedthroughs were assembled at QOREX and mounted in two access ports exiting the vessel. The hydrogen test system was completed with an instrumentation and data acquisition shelf capable of in-situ OTDR attenuation monitoring at 850nm, 1064nm, 1310nm, and 1550nm test wavelengths. The test system was operated and commissioned using control fibers.

Mechanical testing of the fiber with test fibers listed in Table 5 began by respooling into 12 each 30m loose-coil test spools. Dynamic strength testing at three strain rates was performed on the baseline as-received fiber and aged fibers exposure at three temperatures. Baseline dynamic strength results were completed and are shown in Figure 64.

Fig. 64: Dynamic strength measurements of the as received fibers from Table 3 prior to temperature exposure.

In the case of the polyimide-coated fibers being considered for 300°C qualification, Fibers A through H, there is a large spread in mechanical performance between these fibers, with some clearly high risk (C,G). Among metal-coated fibers being considered for 375°C, Fibers I and J, the former has a tighter strength distribution and appears more promising (see Appendix 2).

Task 2.3—Distributed Temperature, Strain and Vibration Vendor Evaluation

In Q2-10 QOREX began gathering product information for Raman-type Distributed temperature sensing (DTS) equipment, Brillouin fiber strain analyzers, and distributed acoustic/vibration instruments including ones based Coherent Rayleigh OTDR and other proprietary approaches. With Raman DTS technology being the most mature and well-understood, QOREX narrowed the selection to a small set of DTS instruments with performance and features best suited to meet the

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objectives of this program and then procured an interrogator based on review of specifications and features. In matching the best performance specifications among the candidate instruments under consideration, this unit was selected for its ruggedness, ease of operation, and configuration flexibility to meet the objectives of the program. The unit was received, operating software loaded, and then installed in a test and calibration setup at QOREX and operated on a test cable to successfully test the unit performance over thermal cycles.

Brillouin fiber strain analyzers and distributed acoustic/vibration instruments were further evaluated in Q3-2010 to narrow the candidate pool of instruments. This activity also included a technical review and comparison between single fiber Brillouin OTDR versus dual-fiber/ended Brillouin Optical Time Delay Analysis to meet the objectives of the program. A further review of commercial offerings of distributed acoustic/vibration revealed two new potential sources of Coherent Rayleigh OTDR instruments. Availability of equipment and level of data processing software became the main selection criterion for this equipment.

Task 2.4—Sub-system Test at Fiber Level

GO/NO-GO DECISION POINT: Confirmation that commercial DTS, DTSS and COTDR sub-systems perform adequately in simulated EGS environments

In Q3-2010 as part of the configuration and test of the DTS unit procured in the prior task, the unit was operated on fiber calibration temperature cycles up to 300°C. Such test and calibration was repeated on metal-coated fibers in excess of 375°C. In Q4-2010 these fibers were then aged at 300°C for three different time intervals, 150 hours, 300 hours, and 500 hours. As a result of these tests, five fibers were selected for further study as shown in Table 6. Four polyimide-coated fibers were identified for use up to 300°C. An Al-coated MM fiber was found to exhibit adequate mechanical and thermal aging performance up to 400°C.

Table 6. Fibers selected for hydrogen testing.

Fiber	Waveguide	Coating	Rating
A	50/125 MM Step-Index Pure Silica Core	Polyimide	300°C
D	50/125 MM Graded-Index Synthetic Silica	Polyimide	300°C
E	9/125 SM Step-Index Synthetic Silica	Polyimide	300°C
H	9/125 SM Step-Index Pure Silica Core	Polyimide	300°C
I	50/125 MM Step-Index Pure Silica Core	Aluminum	400°C
K	50/125 MM Step-Index	Aluminum	400°C
L	9/125 SM Step-Index Pure Silica Core	Aluminum	400°C

In Q1-2011 additional fiber from different manufacturer production lots was procured, and thermal aging and dynamic strength analysis repeated to verify the initial results and assess any lot-to-lot variation. Results showed very good agreement with the first round fiber tests, and were conclusive to qualify the candidate fibers. During the period, extensive hydrogen tests were performed on all fibers to characterize hydrogen-induced attenuation performance and

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compare against manufacturer ratings. Hydrogen performance for all fibers was conclusive and positive to validate and verify these fibers for the anticipated hydrogen conditions of EGS environments.

In Q1-2011, QOREX also worked with one of the fiber manufacturers to refine their process to yield long lengths of pure silica core, hydrogen tolerant aluminum-coated fiber with uniform mechanical strength. Both fiber I and fiber K have tested positively mechanically for use at the higher program temperature of 374°C. There was no discernable hydrogen diffusion in these fibers by virtue of the Al coating exhibiting hermetic properties at hydrogen test temperatures up to 300°C.

Task 2.3—Distributed Temperature, Strain and Vibration Vendor Evaluation

As laser light propagates in an optical fiber, inelastic scattering with the molecular structure of the glass produces light at both a lower energy (wavelength up-shifted or Stokes line) and a higher energy (anti-Stokes line). In Raman DTS systems, the relative intensity of these lines is a function of the local temperature in the fiber where the light scattering takes place. A temperature profile all along the fiber can be calculated by injecting light pulses into the fiber and measuring the return time and intensity of the Stokes and anti-Stokes Raman lines. The simplicity of this effect has led to predominance of Raman DTS systems as a powerful downhole monitoring and well logging tool in oil and gas.

The main challenge to be addressed for measurements in enhanced geothermal systems is that hydrogen diffusion into the sensing fiber can create wavelength-dependent differential fiber attenuation (DFA). This effect can cause the relative intensities of the Stokes and anti-Stokes lines to vary and thereby corrupt the temperature measurement. The effect of DFA can be compensated by using two fibers in the cable that are joined at the bottom by a turn-around loop. A compensation algorithm based on the differences in estimated temperature from two common depth points on the loop distance can then be applied to the Raman data to back out the effect of hydrogen darkening and calculate the correct temperature.

QOREX has developed a compact waveguide device to provide the turnaround at the bottom of the fiber loop, and a proprietary hydrogen compensation algorithm capable of producing accurate temperature measurements by calibrating out not only the effect of hydrogen darkening, but also other DFA sources, over a wider temperature range.

A commercial Raman DTS instrument produced by AP Sensing was selected for this program. The unit features a rugged, hermetically sealed optoelectronics module, with a pump laser that stimulates Raman backscatter signals at wavelengths less prone to hydrogen absorption effects in the fiber. The Raman DTS data acquisition module includes the AP Sensing instrument, an optical switching unit for injecting laser light into either end of the fiber loop, and an electronics processor to operate the dual-ended DTS measurement protocol and compensation algorithm.

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Evaluation of compensated and non-compensated DTS measurements was performed on samples of conventional fiber and hydrogen-tolerant polyimide-coated fibers installed serially in a hydrogen test cell at 500 psi pure hydrogen at 270 C. As shown in Fig. 65, in-situ data for standard single-ended DTS and for dual-ended/compensated measurements were compared. The temperature calculated from single-ended measurements resulted in a 100 C offset from the chamber controller temperature, while the compensated DTS measurement was in excellent agreement with the controller temperature.

Fig. 65: Raman DTS: Experimental comparison of single ended DTS with dual ended/ compensated system.

Brillouin backscattering produces both temperature and strain sensitive frequency shifts due to interaction with vibrational modes in the fiber. In Brillouin distributed temperature and strain sensors (DTSS), the frequency analysis of the Brillouin spectrum is complemented with amplitude analysis to compensate the cross-sensitivity. As with Raman DTS, a pulsed time domain measuring system is used to provide distributed temperature and strain measurements along the sensing fiber. In oil and gas, temperature is used to model flow and other well operations, with strain used to monitor parameters such as casing integrity. The added complexity in discriminating between measurands with Brillouin technology has retarded commercial adoption compared to Raman DTS systems.

By contrast, emerging applications for Brillouin DTSS in long reach, high temperature, and hydrogen rich environments such as EGS can leverage its inherent advantages in frequency-encoded measurement that is not affected by hydrogen induced DFA, allowing sensing fiber to be installed single-ended. This may ultimately reduce cost compared to Raman systems that

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require dual-ended architectures in high temperature wells. Further advantages in operating on single mode fiber include longer reach and immunity to modal and other error sources that affect Raman DTS systems.

The dual-ended measurement protocol and compensation algorithm was used to successfully to address hydrogen-induced measurement error in the Raman DTS system. The dual-ended architecture also opens up the possibility to operate dual-ended single mode fibers for Brillouin Optical Time Delay Analysis (BOTDA) over single-fiber Brillouin OTDR. In Q1-2011 a detailed review compared these systems. Minor differences in meeting target program performance over the fiber distances anticipated in EGS, along with fiber constraints in the cable design in Task 1.5 were the main factors for the decision to operate BOTDR. Review of Brillouin instruments operating in BOTDR mode revealed some options, with QOREX initially selecting the Omnisens instrument for the program. However, fiber constraints of the cable design in Task 1.5 dictated a single fiber BOTDR in the trial system. The Omnisens unit, although capable of BOTDR operation, is not fully refined for such single-fiber operation. Review of Brillouin instruments operating in BOTDR then commenced with the selection between Yokogawa and Oz Optics. The Yokogawa unit has been in the commercial stream the longest based solely on the BOTDR approach, and was ultimately selected for this program.

Finally, the Rayleigh OTDR instrument was selected from the vendor Fotech, and a unit was rented for use during part of the second downhole test.

Task 2.4—Sub-system Test at Fiber Level

GO/NO-GO DECISION POINT: Confirmation that commercial DTS, DTSS and COTDR sub-systems perform adequately in simulated EGS environments

In this task, a test bed will be used to assess subsystem performance of each of the different sensing modalities (Raman-DTS, Brillouin-DTSS, COTDR/Rayleigh, point pressure, FBG/pressure) consistent with the requirements outlined in Task 1.1.

In Q3-2010 as part of the configuration and test of the DTS unit procured in the prior task, the unit was operated on fiber calibration temperature cycles up to 300°C. Such test and calibration was repeated on metal coated fibers in excess of 375°C. These tests confirmed the ability of the DTS unit to operate test fiber at the temperature regimes targeted in this program.

In Q1-2011, QOREX verified the need for operating the Raman DTS in a dual-ended architecture to apply a hydrogen compensation algorithm. Evaluation of compensated and non-compensated DTS measurements was performed on sample conventional fiber and hydrogen-tolerant polyimide coated fibers installed serially in the hydrogen test cell at 500 psi pure hydrogen at 270°C. In-situ data for standard single-ended DTS and for dual-ended/compensated measurements were compared. The single-ended temperature measurements were greater than

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100°C offset from the chamber controller temperature, while the compensated temperature measurements were in excellent agreement with the controller temperature.

Due to the expense of renting the Rayleigh COTDR instrument (~\$18K for 3 days), it was tested during the second downhole test only, not in an initial lab test.

Task 3: Component and Subsystem Validation and Issue Resolution

Task 3.1—Distributed temperature, strain and vibration issue resolution

Associated Milestone: Vendor performance for DTS, DTSS and COTDR in EGS application validated

The goal of this task is to correct any COTS sub-system anomalies via supplier interaction. In particular, issues with system integration compatibility will be corrected prior to the system level testing in Task 4.2.

In Q1-11, QOREX completed testing of a procured Raman-type distributed temperature sensor (DTS) interrogator. A dual-ended measurement protocol and compensation algorithm was shown to solve the hydrogen-induced measurement error problem. No issues were found to address with the BOTDR instrument.

The reflector package that connects the two MM fibers at the bottom of the well was spliced to the cable in Q4-2011, prior to the first downhole test.

Initial measurements of temperature as a function of well depth were conducted after the cable installation in the geothermal well. The results are shown in Fig. 66, although only a minimal amount of processing was performed on the raw data.

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Fig. 66: Preliminary results of temperature as a function of well depth from the Raman and Brillouin measurements.

Task 3.2—Point optical pressure gauge validation

Associated Milestone: Fully Functional Demonstration of Point Pressure Gauge

The goal of this task is to correct any problems found in the point pressure sensor in a second iteration after evaluation of the sensor developed in Task 1.3. The second design cycle performed in this task also includes splicing the sensor onto the cable for evaluation in Task 4.2.

Testing on the first iteration of sensors indicated that the high temperature processing steps caused a redistribution of the boron doping in the resonator such that the incident modulated laser light from the drive laser was not being efficiently absorbed. This problem could be rectified either by depositing a lossy metallic coating onto the resonator, or by increasing the boron doping and modifying the processing so that the resonator maintains its absorptance to the IR laser light. Both approaches were investigated.

Several thin materials were modeled for their absorptance at the drive laser wavelength of 1330 nm. Absorptance and reflectance as a function of film thickness is shown in Fig. 67. Relatively transparent materials like Ge and ITO exhibit a periodic variation in absorptance with thickness, and require relatively thick films to reach absorptances of 30% or more. Highly reflective materials like Au and Al, on the other hand, do not absorb a sufficient amount of IR light at any thickness. The best thin film materials are the highly lossy metals like W, Ti and Cr. Even a 50 nm layer of these materials is sufficient to absorb over 30% of the incident light. Moreover, the

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metal films are sufficiently reflective that they form a high quality optical cavity for the read laser beam.

(a)

(b)

Fig. 67: (a) Absorptance and (b) reflectance for various thin film materials deposited onto the Si resonator as a function of film thickness.

In order to apply the absorptive coating to the resonators, masks were designed and fabricated and the metallic coatings were then vacuum deposited. Tests were performed at 1000°C for 60

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hours on the coated resonators, to simulate the wafer capping process, and no degradation of the coating was observed. The remainder of the uncapped wafers in stock were then coated and capped.

The first generation point pressure sensors also did not meet the desired quality factor (“Q”) of ~20,000. The cause of the low resonator Q was identified as improper sealing of the sensor cap allowing air to leak into the resonator chamber. Efforts were undertaken to fix the problem. However, despite a number of attempts to improve the wafer bonding process, the yield of devices with a high-Q remained poor. Every wafer appeared to have areas which were well-bonded yielding high-Q devices, and also poorly bonded areas. This resulted in a large number of die needing to be tested in order to find suitable chips for packaging into sensors.

The metallized fiber must be brazed to a ferrule connector on the sensor package in order to provide a leak-tight seal under the high temperatures and pressures. Three different vendors for doing this were solicited without success. However, a vendor was eventually discovered who was able to successfully braze parts. The brazing material selected has a melting point of 800°C, which is well above the design operating temperature of 374°C.

Two packaged sensors were tested and calibrated to temperatures of 260°C and pressures of 3200 psi (220 bar). The sensors were shipped to QOREX and QOREX spliced/welded one sensor to the cable. Before shipping the cable to the test site, however, GE Global Research brought their sensor instrumentation down to QOREX to verify the operation of the sensor. Unfortunately, the sensor did not work, so it was cut off from the cable and the second sensor was spliced to the cable. The second sensor operated as expected, so it was decided to complete the welding of that sensor to the cable. Meanwhile, the first sensor was retested in the GE Global Research laboratory and still found to be not working, so it was shipped back to GE Sensing for further analysis.

Measurements have been made to determine the stability of the resonant frequency as a function of applied optical power. Two effects are apparent; one is an increase in resonant frequency with increased ac drive power, which is attributable to strain stiffening in the resonator. The second effect is a decrease in resonant frequency with increasing dc optical bias power. This is attributed to a reduction in Young’s modulus due to increased resonator temperature. Appropriate control of both dc bias and ac modulation are necessary to achieve the desired pressure readout accuracy of the sensor.

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Fig. 68: Reduction in resonant frequency with constant ac drive and increasing dc bias.

Fig. 69: Resonant frequency unchanged with increasing ac drive and deflection.

Previously, the feedback circuit for the Si resonator was described which makes use of a phase locked loop (in the lock-in amplifier). This feedback circuit was demonstrated in the lab and shown to maintain a lock at very low signal-to-noise levels. However, there were three issues identified with the method of generating a readback signal using modulation of the readback laser intensity by the vibrating optical cavity. First of all, temperature and/or pressure changes can lead to large changes in signal amplitude as shown in Fig. 70. In fact, for the original MEMS sensors that were used to develop the readback system and were only designed to operate from 0 to 50 psi, there were up to four pressures in this range at which the readback signal amplitude became extremely small. At some of these pressures, the signal amplitude became too small to retain a lock with the closed loop feedback circuit at the resonant frequency.

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Fig. 70: Signal amplitude at the resonator frequency is graphed as the pressure on the sensor is slowly decreased. At two points in time, ~3 hours and ~10 hours, the signal amplitude nearly disappears.

Secondly, as temperature and/or pressure changes, when the fundamental signal frequency goes through a minimum, the signal amplitude at the second harmonic generally increases. The reflectance from the sensor die is graphed in Fig. 71 as a function of the distance between the resonator and the cap of the sensor. The periodic reflectance change with the gap is a result of the optical cavity, which is essentially a low finesse Fabry-Perot. The period of the oscillation in Fig. 71 corresponds to a half wavelength change in the distance between the resonator and the cap. This gap can vary slowly in time over several periods of oscillation as the external temperature and pressure change. It also varies at the frequency of the resonator over a small fraction of a period as the resonator vibrates. It can be noted that the minima are substantially sharper than the maxima in the reflectance curve. Under normal operating conditions, the resonator vibrates about a resonator-to-cap distance that is on the steep side slope for which the reflectance changes approximately linearly with resonator position, such as point “A” in the figure. Due to pressure and/or temperature changes, however, the operating point of the average resonator-to-cap distance may shift to either a maximum or minimum of this reflectance curve. In this case, vibrations of the resonator cause small reflectance variations which modulate the reflected signal at *twice* the resonator frequency, rather than at the fundamental frequency. This is the cause of the large drop in fundamental signal amplitude at three and ten hour points in Fig. 70. Furthermore, by reference to Fig. 71, the second harmonic readback signal will be larger, and the period for which the fundamental signal drops out will be shorter, if the operating point occurs at a narrow minimum rather than at a broad maximum.

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If the reflectance variation at the extrema is sufficiently gentle, the signal amplitude at both the second harmonic and the fundamental frequency can be extremely small. Experimentally, it has been found that the fundamental signal amplitude can easily vary by over a factor of 200 at a constant drive laser power, and at the minima both fundamental and second harmonic may be within 5 dB of the noise floor, which makes locking the feedback loop difficult.

Fig. 71: Calculated reflectance variation with distance between the resonator and cap.

Finally, the third issue is that after the pressure and/or temperature changes have shifted the operating point from “A” to “B” and the fundamental signal has been recovered, there is a 180° phase shift in the readback signal relative to the drive signal due to the change in the sign of the slope of the reflectance curve. If the phase in the feedback loop is not adjusted, the feedback becomes positive instead of negative and the loop again unlocks.

In order to address these issues, several approaches have been tried. Originally, it was believed that the operating point on the reflectance curve could be stabilized at point “A” by varying the wavelength of the readback laser. If pressure and/or temperature changes caused the operating point to move such that the average reflected light signal began to increase, then a feedback loop could be implemented to cause the temperature of the laser to also increase. This would cause the laser cavity to slightly grow and the laser wavelength to also slightly increase, thereby increasing the wavelength spacing of the periodic reflectance variations, and causing the operating point to shift back down to its original reflectance level. When this feedback process was implemented in the laboratory, however, it was found that the maximum wavelength shift of the laser obtainable by varying its temperature was only ~ 10 nm. As shown in Fig. 72, which is a theoretical calculation of the reflectance as a function of resonator-to-cap distance for two different wavelengths, a 10 nm wavelength shift is generally not sufficient to maintain the

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operating point at the same high slope region of the reflectance curve as the resonator-to-cap spacing varies with temperature and/or pressure.

Fig. 72: Calculated reflectance variation with distance between the resonator and cap at wavelengths of 1540 nm and 1550 nm.

When the fundamental signal amplitude nearly disappears, there is generally still sufficient signal amplitude at the second harmonic to use as a feedback signal. However, it is essential that noise levels be minimized. The electronic system that has been developed in the laboratory has successfully maintained its lock to signal levels below 20 μV . Moreover, an intelligent servo loop can decide when to switch between fundamental and second harmonic signals. When switching between different input signals, however, the feedback loop must be temporarily opened. In order to successfully reacquire a lock when the loop is closed, the electronics must be operated so that there is no frequency drift during the short time that the loop is open. Finally, the intelligent feedback loop must also know when to adjust the phase in the loop by 180° . This process is shown in the flowchart in Fig. 73, and was implemented within a LabView program for the equipment.

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Fig. 73: Flowchart for algorithm to maintain feedback circuit lock by making use of fundamental and second harmonic signal amplitudes.

This algorithm has been fully implemented in LabView and tested in the laboratory on a sensor that exhibits several nulls in the fundamental signal over its full scale pressure range. As shown in Fig. 74, the frequency and signal amplitude of an RPT sensor were measured between 2 and 50 psi. The fundamental signal has nulls between 9 to 11 psi, 21 to 22 psi, 31 to 32 psi, and 42 to 43 psi. As the pressure was reduced continuously from 50 psi to ambient, the LabView program automatically selected the appropriate harmonic and phase shift to maintain the feedback loop lock and track the resonant frequency.

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Fig. 74: Closed loop measurement of RPT sensor frequency over its full pressure range.

The entire laser optical system was mounted inside a safety interlocked box to meet the Class 1 laser requirements for operation at the Ormat well site. A photo of the instrumentation is shown in Fig. 75. The pressure vessel in the lower left is used to apply pressures of up to 50 psi to the sensor die. Electrical and optical fiber feedthroughs are used to adjust the temperature of the die and drive/interrogate the sensor frequency, respectively. The large aluminum box in the bottom center contains the two lasers and the feedback electronics. A single optical fiber is seen connected to the front center of the box. The single mode fiber from the fiber cable is connected to this point during the field test. On top of the feedback unit is a laptop that operates the data collection via a custom LabView program. The laptop also operates the Micron instrument (not shown) for fiber Bragg grating sensor measurements through a separate LabView program to determine the temperature in the vicinity of the pressure sensor. On the left side of the center shelf above the pressure vessel is a Tektronix scope. This is extremely useful in the lab for monitoring the drive and readback signals. A portable PC-based oscilloscope ([DS1M12](#)) was purchased for use in the field. The small unit on the extreme left of the center shelf is a power supply for the small digital pressure meter barely visible on top of the pressure vessel. To the right of the oscilloscope is another power supply for the feedback electronics, which will be transported to the test site. Beneath this power supply is a network analyzer used for open loop measurements on the sensor. To the right of the network analyzer is a laser power supply, which will also be transported to the test site. Directly above the power supply is a high pass filter/amplifier that is used for open loop measurements. Above this unit is a lock-in amplifier which forms part of the feedback loop, and will be transported to the test site. Therefore, at the

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test site, there is a laptop, the aluminum box with the lasers and feedback electronics, a power supply, a laser driver, the Micron box for the fiber Bragg grating temperature sensor, and a lock-in amplifier.

Fig. 75: Photograph of laboratory sensor test instrumentation.

The goal of this task is to correct any problems found in the point pressure sensor in a second iteration after evaluation of the sensor developed in Task 1.3. The second design cycle performed in this task will also include splicing the sensor onto the cable for evaluation in Task 4.2.

The sensor cable was finally deployed on June 21, 2012 with the help of Scott Lindblom from Sandia National Laboratories, Andre Williams from QOREX, Stephanie Konefat from Ormat, Bill Challenger from GE Global Research, and Pacific Process Systems at the same Ormat geothermal well at the Brady site in Nevada that was used for the first field test. Data from the MEMS sensor attached to the single mode fiber and from the Raman distributed temperature sensor attached to the multimode fibers were collected on June 21, 22 while QOREX and GE Global Research personnel were on the site. Data collection continued after this with the help of a local technician in Fernley, NV.

The MEMS sensor that was finally attached to the cable exhibited five resonant modes between 10 kHz and 100 kHz when tested in the laboratory under ambient conditions. These modes were at 18.865, 22.45, 43.19, 43.45 and 69.90 kHz. The signal from the 43.45 kHz mode was extremely strong. The 18.865, 22.45, and 43.45 kHz modes had moderate signal strength. The

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69.90 kHz mode was very weak. After deployment in the geothermal well, only three modes could be observed and the signals were ~5 to 10 time weaker. It was subsequently discovered that the interrogator apparatus was connected to the downhole fiber cable by a MM fiber instead of a SM fiber. This fact was not realized until after the personnel had left the well site and, therefore, could not be rectified. This is undoubtedly the cause of the loss of signal amplitude from the additional optical losses associated with transitioning back and forth between MM and SM fiber, which affects both the drive laser power that reaches the sensor and the readback laser signal amplitude. Indeed, it is quite remarkable that the readback signals were as large as they were.

The three observed modes in the downhole test were at 24.682, 43.65, and 44.031 kHz. Although the interrogator could lock to all three resonances, measurements were made primarily on the first and third resonance because the temperature and pressure dependence of the first resonance had been calibrated in the lab and the third resonance was the strongest and easiest for an unskilled operator to lock to. The sensitivity of the first resonant mode was 1.4 Hz/psi, which was 3.84 times greater than that of the third resonant mode, although the signal amplitude of the third mode was ~8× larger than that of the first mode.

An example of the time dependence of the first resonance is shown in Fig. 76. These data were collected on 6/22/12, the day after the cable deployment. The average frequency was 24.68208 kHz and the standard deviation was 0.1257 Hz. Using the measured temperature of 200°C from the Raman DTS system, and the laboratory calibration of the sensor, the deduced pressure was 1568.64 psia (measured with respect to vacuum) with a standard deviation of 0.09 psi. The variation of pressure with frequency was ~0.7 psi/Hz.

Fig. 76: Resonator frequency of the lowest frequency mode is graphed as a function of time. The red trace is the raw data. The green and blue traces are smoothed data by taking a running average of 10 and 100 points, respectively, of the raw data. The raw data themselves are 10 point running averages of frequency samples collected at about 1 second intervals.

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As reported in an earlier quarterly report, the geothermal well was logged for both temperature and pressure in the first field test. The results are shown in Fig. 77.

Fig. 77: Well log of temperature (red) and pressure (blue) for Ormat geothermal well measured during the first field test on 12/13/2011.

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The actual data from the well log at the sensor depth of 4000 feet is shown in Table 7. Interpolating between the two nearest depths to 4000 feet gives a pressure of 1566.04 psia, which is within 2 psi of the MEMS sensor measurement.

Table 7: Well log data at depths near 4000 feet.

Depth (feet)	Temperature (°F)	Pressure (psia)
3960.3	400.0	1550.2
3966.3	400.1	1552.6
3972.3	400.2	1555.1
3978.4	400.2	1557.5
3984.4	400.3	1559.9
3990.5	400.4	1562.2
3996.5	400.5	1564.7
4002.5	400.6	1567.0
4008.6	400.7	1569.6
4014.6	400.8	1572.1
4020.6	400.8	1574.6
4026.7	400.9	1577.1
4032.7	401.0	1579.6
4038.8	401.1	1582.2
4044.8	401.2	1584.6

Task 3.3—Distributed pressure cable design optimization

Associated Milestone: Cable Integration of Distributed Pressure Sensor

In Phase 2, the distributed pressure FBG design is to be optimized based on the work in Task 1.4, and then subsequently validated. A key aspect of this task is to determine how to integrate the sensor package into the overall cable design.

Metallized pure silica core fibers were identified in which fiber Bragg gratings can be written that exhibit satisfactory stability at high temperatures as previously described. A bonding adhesive was also identified that achieved 10,000 μ strain at high temperature, sufficient for bonding the fiber to the metallic package in spite of differential thermal expansion. However, a prototype FBG sensor, though sensitive to pressure, did not return to the baseline at ambient pressure indicating a porous adhesive seal and/or irreversible deformations in the sensor package.

To address one concern previously identified, a glass or metal solder was investigated as a means to seal the porous adhesive. Although brazing a metallized fiber to the package is also an option, this is extremely difficult to do with a micro torch without damaging the metal coating.

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A new FBG package was also designed to greatly reduce stress on the fiber from differential CTE while maintaining high rigidity for reducing the possibility of irreversible package deformation.

The FBG package was modified to better transduce pressure into fiber strain without causing irreversible deformation of the package. The prototype sensor package is shown in Fig. 78. The external spring is designed to ensure that the package returns to its initial state after the pressure is released. As such, the spring strength can be adjusted for the desired pressure range of the sensor.

Fig. 78: Second generation FBG sensor package.

The sensor was tested in the laboratory by repeatedly cycling it between low and high pressures. Results from two sets of measurements are shown in Fig. 79.

Fig. 79: Variation in wavelength of FBG sensor as the pressure is repeatedly cycled (a) from ambient to high pressure, and (b) from ambient to a lower pressure.

In the first generation sensor, as described in previous reports, the baseline of the measurements did not return to zero after the pressure was removed, indicating either diffusion of the external gas into the sensor package and/or irreversible deformation of the sensor package. The latter issue was addressed in this device by not relying on the elasticity of the bellows itself for reversibility, but rather making use of the external spring around the bellows. The initial positive results of this test indicate that it is suitable for further extensive testing of repetitive cycling at

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elevated temperatures and pressures. Prior to integration within a fiber cable, an outer package will also need to be integrated onto the sensor. This package will also have to ensure a hermetic seal between the fiber and fiber package.

One of the FBG fibers that were fabricated for this sensor was annealed and calibrated and then installed in the fiber cable for the first downhole test. The FBG reflectance spectra are shown in Fig. 80. The spectra are seen to shift uniformly to the right and downward over time. The shift over time of the reflectance peak in the spectra towards longer wavelengths indicates that the grating period is getting longer, which could be due to small temperature changes in the well corresponding to ~ 3 C or perhaps to some additional strain on the fiber. Unfortunately, as a result of this shift, the temperature calibration of the FBG sensor performed in the laboratory was no longer accurate after insertion of the cable into the well. Using the laboratory calibration, the FBG sensor predicted a temperature of 250°C , rather than the value of $\sim 205^{\circ}\text{C}$ obtained from both Raman measurements and the initial well log. The fiber was inserted in the cable just loosely in the cable terminator. Although it is possible that the fiber became entangled around other fibers or parts in the cable terminator and was experiencing some strain, it is more likely that the high temperatures continued to anneal the polyimide recoating put over the FBG sensor.

Fig. 80: FBG spectra measured periodically after cable installation in the geothermal well. The uniform drift of the spectra to the right and downward indicate ~ 3 C increase in temperature and ~ 3 dB signal loss over time.

The downward shift of the spectra indicates a loss of reflected signal amplitude, which could be due to reversible hydrogen darkening in the fiber. Over the five week period, the signal drop was ~ 4.5 dB. The rate at which the signal was dropping over the course of the field test is shown

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in Fig. 81. It appears to be reaching an asymptotic level, which would be expected for reversible hydrogen darkening.

Fig. 81: Peak amplitude of the reflectance spectra for the FBG sensor over the five week downhole test.

A third generation FBG pressure sensor was designed and fabricated, and is shown in Fig. 82. Because the original contract milestones did not explicitly require a downhole test of this sensor, and because it would need to be placed in series with the MEMS pressure sensor on the cable, it was decided to forego downhole testing of this sensor. If the FBG sensor failed in the downhole field test, then it would likely cause a fiber breakage that would preclude testing of the MEMS sensor. The MEMS sensor, however, is considered to be the more accurate and important sensor for which to obtain downhole data. The mechanical design of the FBG sensor was focused on five requirements:

1. the package must be extremely stiff to prevent any strain from being transmitted to the FBG fiber
2. the package must be designed so that the weight of the cable does not get transferred to the fiber
3. the differential coefficient of thermal expansion (CTE) between the fiber and the metal package must be minimized or eliminated so that the thermal stress on the fiber is minimized
4. the diameter of the sensor must be as small as possible, preferably less than 1/2", for integration into the cable and winding on the spool
5. water should not have a pathway into the cable

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Fig. 82: FBG pressure sensor with 1/2" outer diameter and containing polyimide-coated fiber with two FBGs, one for pressure measurement and one for temperature measurement.

A package design was indeed realized that achieved these five requirements. As the design is proprietary, it will not be described in detail here. However, as can be seen, the outer sensor package is 1/2" diameter, and composed of very stiff Inconel to resist bending. Holes in the outer package allow water to enter to exert pressure on the inner bellows design. The inner bellows contains two FBG sensors, one which is under strain that varies with the applied pressure, and one which hangs loosely within the sensor package. The second FBG measures only temperature, while the first FBG measures both temperature and pressure. The two measurements combined are then able to determine temperature and pressure separately as is commonly done in the industry. A fiber can barely be seen emerging from the left hand side of the package, which is where the fiber splice would be made for calibration. Unfortunately, the fiber on the right hand side of the package where the continuation of the cable would have occurred was broken off. Unlike the second generation package design described in an earlier quarterly report, the outer package in this case is designed to be spliced into the cable by being welded to the cable at both ends and the outer package supports the entire cable weight below the sensor package so that this weight does not get transferred as strain into the fiber. The inner package is also designed so that thermal expansion transfers minimal strain to the pressure-sensing FBG, so this sensor does predominantly measure pressure. This design reduces the requirements for the high temperature epoxy that binds the FBG on both sides. Alternatively, a metallized fiber could have been used and the fiber attached to the metal sensor package by brazing as was done for the MEMS pressure sensor.

Although this third generation FBG was designed and fabricated, and should in principle address the shortcomings of the two earlier FBG pressure sensor designs, nevertheless, the experience with the drift of the FBG temperature sensor in the first downhole field test led us to be very

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skeptical of the ultimate feasibility of using FBG sensors to measure either pressure or temperature under these harsh conditions with the necessary degree of long term accuracy. There was great concern also about splicing the sensor in between the MEMS pressure sensor and the fiber cable, in that any fiber breakage due to FBG sensor failure would have also precluded testing of the MEMS sensor. Finally, as the project neared completion, the resources required to complete the field test of the MEMS sensor and the Rayleigh instrument did not leave sufficient resources for even the lab testing and calibration of this FBG sensor. So this aspect of the project was not fully completed.

Task 4: System Integration and Test

Task 4.1—Cable fabrication and test

Associated Milestone: Cable fabrication process demonstrated and mechanical properties validated through thermal and mechanical tests

The purpose of this task is to fabricate the cable structure as designed in Task 1.5. The cable length was chosen to be 2 km, which is sufficient for the depth of the geothermal wells under consideration by Sandia National Laboratory and which minimizes the cable cost, but which is also of sufficient length to test the cable design for supporting fiber over long vertical drops which are typical of geothermal wells. Sections of cable were tested against strain relief specifications such as "excess fiber length" (EFL) at core and armoring stages of manufacturing. The final cable system will undergo thermal cycling and testing for baseline optical and mechanical performance characteristics as well as retention and strain over temperature.

As documented previously, commercially available single and multimode fibers with all-silica cores and polyimide and metal coatings were evaluated for resistance to hydrogen darkening, and tensile strength at high temperatures. Two temperature ratings were considered: 300 C, which enables operability in a majority of the EGS resources, and 374 C for the specific targets of this program. Of the fibers tested by QOREX, metallized MM fibers of type "I" and "K", and SM fiber of type "L" were found to perform adequately up to 400 C, while polyimide-coated MM fibers "A" and "D" and SM fibers "E" and "H" were adequate to 300 C.

The fiber optic cable for the EGS environment must survive a high temperature, corrosive environment and the rigors of installation. The proposed cable structure consisted of an outer ¼" metal tube that utilized IncoloyTM 825 material with a wall thickness of 0.035". Incoloy 825 is commonly used for fiber optic and tube encapsulated copper (TEC) instrumentation cables for downhole monitoring in the oil and gas sector. This material is used where H₂S or high CO₂ levels make corrosion a concern. The wall thickness of the tube was selected based on the pressure in the well, the type of completion and the desired ruggedness to account for upsets during installation. For more severe environments, a 0.049" wall thickness could be used.

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There is a stainless steel tube inside of the ¼” Inconel tube that houses the selected fibers – two 50 μm graded index multimode fibers with a carbon polyimide coating and one pure silica core single mode with a polyimide coating. The optical fibers were pulled into the stainless steel tube making process in such a way that they were not exposed to the laser welding process which seals the tube. One of the key design parameters for the stainless steel tube manufacturing is to ensure that there is adequate excess fiber in the tube to keep the optical fibers from being exposed to strain in the target environment. Fiber strain can lead to increased attenuation, termination difficulties, contamination of certain fiber optic sensing technologies, or worse, broken fibers. Mechanical and thermal strain must be considered when determining the appropriate level of excess fiber. Through AFL’s proprietary methods, excess fiber can be incorporated into the design to keep the fiber strain free up to the designed temperature limit of the cable.

A series of mechanical tests were performed on a separate section of cable that had been cut from the fabricated cable for the downhole tests. The four tests are:

1. Stress strain test
2. Crush test
3. Impact test
4. Installation or sheave test

The purpose of the Stress Strain Test is to tension the cable while monitoring cable strain, tension, fiber strain and fiber attenuation. The single mode fiber was used for monitoring fiber strain while the 50 μm multimode fibers were monitored for attenuation. The cable tension was increased in 75 lb increments up to 2000 lbs. At the 2000 lb level, the cable strain was 0.39%. The average optical attenuation increase from baseline on the two 50 μm multimode fibers at this level was 0.01%. The designed excess fiber length exceeded the cable strain at this level, ensuring a strain free fiber in deployment.

The purpose of a Crush Test is to determine the level of deformation of the cable with a defined load and to characterize the optical loss on the optical fibers under such load. The test method used for guidance was TIA/EIA-455-41A, Crush Test. The cable is located between two metal plates that are 100 mm long on which the crush load is applied. The optical fibers are monitored for a change in optical loss during the testing. The starting load was 909 kg or 2000 lbs. After each test, the cable was shifted 150 mm to a new location and the load increased by 455 kg. At each test location, the deformation in the tube and the optical loss on the fibers were recorded. The first point of deformation occurred at 1818 kg or 4000 lbs with tube deformation measuring 0.04 mm. There was no incremental optical loss at this level. The balance of the test is shown in Fig. 83. Note that the fibers did not break up through the final measurement. At 5000 kg, the optical loss on one fiber jumped notably but dropped back to baseline for the balance of the test. This loss is probably a result of the optical fiber undergoing a microbend during the application of the force. Once the load was removed, the microbend was relieved. Although the optical loss results were low throughout most of the test, the cable was severely compromised at ~2700 kg and would be considered unusable subsequently.

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Fig.83: Crush test on optical cable indicating deformation (blue) and optical loss (red).

The purpose of the Impact Test is to characterize the effect on the cable from an impact load. The test method used for guidance was TIA/EIA 455-25C, Impact Test. The point of contact on the cable was a rounded metal semi-circle with a radius of 25 mm. The weight was dropped from a height of 150 mm with the striking surface perpendicular to the cable. The weights used for this test were 5 kg, 10 kg and 15 kg, translating to a test impact energy of 7.3 N*m, 14.6 N*m and 21.9 N*m. The deformation and optical loss for two impacts at three locations were recorded at each level of impact energy. Fig. 84 captures the results of the tests showing the highest deformation and optical loss at each level. There was essentially no optical loss throughout the test on any of the three fibers. At the conclusion of the test, the number of impacts was increased until at least one fiber broke. At 10 impacts with a weight of 15 kg, one of the multimode fibers broke – the other two fibers had no optical loss at this point.

Fig. 84: Impact test on optical cable indicates that no optical loss is seen till the fibers break.

The Installation or Sheave Test was intended to characterize the mechanical and optical effects on the cable during installation. The cable was passed over a sheave under load multiple times while attenuation was monitored on each of the optical fibers. Cable deformation during the test was also captured through measurement with a caliper. For this test, the cable was passed over a 16" sheave with a 13" root diameter at a 30° angle with a tension of 177 kg, which is ~15% of

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the rated breaking strength of the cable. The cable was cycled back and forth over the sheave under tension fifteen times. There was no change in optical performance of either the single mode or on the two multimode fibers throughout the test.

Task 4.2—System level hardware integration and test

Associated Milestone: System level hardware validated

In this task an environmental test bed is to be used to assess the performance of each sensor system after integration into the final cable form factor. The FBG temperature sensor and Raman and Brillouin DTS equipment were integrated with the cable in the first downhole test as previously described. The MEMS point pressure sensor was tested in the second field test. A Rayleigh COTDR instrument from Fotech was rented to make distributed acoustic measurements on the cable during the second field test. A third generation FBG pressure sensor for distributed pressure sensing was fabricated, *but not tested* in the downhole test due to the risk that its failure would also preclude testing of the MEMS pressure sensor, which was considered to be the more important and reliable of the two sensors. Due to the previously observed unreliability of the FBG temperature sensor in the first downhole field test, the project resources were directed more towards successful testing of the MEMS pressure sensor than the FBG pressure sensor.

The sensor cable was previously shipped by Qorex out to the Ormat test site and deployed on June 21, 2012, with the help of Scott Lindblom from Sandia National Laboratories, Andre Williams from QOREX, Stephanie Konefat from Ormat, Bill Challener from GE Global Research, and Pacific Process Systems. This was the same Ormat geothermal well in Nevada that was used for the first field test in the December, 2011 to January, 2012 time frame. The initial data from the MEMS pressure sensor attached to the single mode fiber and from the Raman distributed temperature sensor attached to the multimode fibers was that had been collected in the previous quarter after initial deployment was presented in the previous report. Data collection from the pressure sensor continued for 2½ weeks with the help of a local technician in Fernley, NV, who made periodic visits to the test site to operate the readout equipment. On July 17th, Bill Challener returned to the test site to complete the pressure sensor test prior to removal of the cable from the well.

1. Pressure sensor test

As previously reported, after deployment of the cable, three resonant modes for the pressure sensor were observed at 24.682, 43.65, and 44.031 kHz. Although the interrogator could lock to all three resonances, measurements were made primarily at the 24 and 44 kHz resonances because 1) the temperature and pressure dependence of the 24 kHz resonance had been previously calibrated in the laboratory, and 2) the 44 kHz resonance was the strongest and easiest for an unskilled operator to lock onto during the course of the field test when GE personnel were not present. The response to pressure of the 24 kHz mode was found to be 1.4 Hz/psi, which was estimated to be ~3.84 times greater than that of the 44 kHz resonant mode by considering the change in resonant frequencies of these two modes measured at ambient pressure and temperature in the laboratory to those measured at the bottom of the well. However, the signal

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amplitude of the 24 kHz mode was only $\sim 1/8$ that of the 44 kHz mode. At the field site, the 24 kHz mode had an amplitude of ~ 0.2 mV, which was about ten times smaller than its amplitude had been previously measured in the laboratory. The 44 kHz mode had a signal amplitude about ten times larger than this, but its amplitude was also about ten times smaller than had been previously measured in the laboratory. The third resonant mode at 43.6 kHz was extremely weak, with an amplitude < 100 μV , although the readout electronics were also able to successfully lock onto this resonant mode for short periods of time in spite of its small amplitude and proximity to the much stronger 44 kHz mode. Signal traces captured from the output of the lock-in amplifier of the 44 kHz and 24 kHz modes are shown in Fig. 2, along with Fourier transforms of those signals. The 44 kHz mode signal was very nonlinear, leading to strong higher harmonics in the Fourier transform. The feedback loop was designed to lock onto either the fundamental mode or the second harmonic because of this nonlinear response, as described in the previous quarterly report, and indeed during the course of this field test the feedback loop was used successfully to track the 44 kHz mode at both the fundamental and second harmonic frequencies.

(a)

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(b)

Fig. 85: Scope trace of modulated readback signals at (a) 44 kHz, and (b) 24 kHz during the field test. In the upper graph of each screen capture, the yellow traces are the signal. The magenta traces exhibit the sync pulses from the voltage-controlled oscillator in the feedback loop, which are used to trigger the scope capture. In each figure, the Fourier transform of the yellow trace in the upper graph is displayed in the red trace the lower graph.

It was discovered after the field test that the ~50 m fiber optic patch cable that had been used to connect the downhole cable at the well head to the readout optoelectronic equipment in the trailer had been incorrectly spliced by a subcontractor, such that a *multimode* fiber in the patch cable was connected between the single mode fiber in the downhole cable to the pressure sensor and the single mode fiber in the readout optoelectronic system. As a result, much of the light entering the MM fiber from a SM fiber was converted into higher order modes and was then unable to be coupled back into the SM fiber at its output. When a 10 m multimode fiber was later patched between the cable and electronics in the laboratory, the resulting transmission through the fiber was undetectable. Therefore, it was extremely fortunate that the signal amplitude at the well site was *only* ten times smaller than had been anticipated from the laboratory measurements. This also is a good indication of the robustness of the readback system, which when properly spliced to the cable should be able to easily handle 10-20 dB of additional signal loss if the fiber cable should experience hydrogen darkening, for example.

The original well log from December, 2011, measured the well pressure at a depth of 4000' to be 1566 psi and the well temperature at this depth to be 205°C. The frequency of the 24 kHz mode was measured at the beginning and end of the field test (6/22 and 7/11) as shown in Fig. 86. The Raman DTS system indicated a well temperature at this depth of 200°C, not significantly different from the original well log. This temperature was used in the frequency-to-pressure conversion of the 24 kHz mode.

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A slight change in calculated pressure over the course of the test is apparent from the two graphs in Fig. 86. There are four possible explanations for the apparent change in pressure between these two measurements, 1) an actual change in well pressure, 2) a change in well temperature, 3) hydrogen darkening of the fiber causing a temperature change of the sensor itself from a reduction in the laser power that is absorbed by the sensor, or 4) a phase setpoint change in the feedback loop electronics. The last two explanations are the most likely ones leading to the apparent change in measured pressure for reasons that will be described subsequently. However, it should be recognized that the calibration accuracy of the sensor is $\pm 0.1\%$ full scale, corresponding to ± 3 psi. If these two graphs are replotted for a full y axis scale range of ± 3 psi, as shown in Fig. 87, then it is apparent that, within the calibration accuracy of the sensor, there is no change in pressure during the course of the 2½ week field test, and the pressure measurements at the beginning and end of the field test are both consistent with the original well log of 1566 psi.

(a)

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Fig. 86: Pressure measurement from frequency data collected at beginning and end of field test.

Fig. 87: Pressure measurement from frequency data collected at beginning and end of field test (Fig. 2) replotted with a y-axis scale range of ± 3 psi ($\pm 0.1\%$ f.s.), which is the calibration accuracy of the sensor.

Because the electronic feedback loop was being operated during most of the field test by an unskilled technician, and because the signal amplitudes of the resonant modes were about ten

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times smaller than anticipated, it was decided that the stronger 44 kHz signal would be monitored during the course of the 2½ week field test, rather than the 24 kHz mode, even though the 44 kHz mode had not been calibrated for pressure readings. The lower signal amplitude of the 24 kHz mode made it more difficult to locate and lock onto than the 44 kHz mode. If the proper fiber in the patch cable had been used to connect the equipment to the well cable, then this would not have been an issue, and the 24 kHz mode could have been easily monitored.

Approximately every other day during the 2½ week field test, the pressure sensor electronics were turned on, allowed to warm up, and then locked to the 44 kHz mode. The mode frequency was then monitored for ~1 hour. The results are shown in Fig. 88. The mode frequency varied between 44.03 and 44.1 kHz during this time. This corresponds to a variation of $\pm 1.2\%$.

Fig. 88: Resonant frequency of 44 kHz mode measured for ~1 hour intervals at every 2 – 3 days during field test.

The average frequency was determined for each scan as well as the standard deviation. These values were graphed as a function of time for both the 24 and 44 kHz modes as shown in Fig. 89. When plotted in this manner, it can be immediately seen that the $\pm 1.2\%$ variation in measured resonant frequency is primarily due to a linear drift during the course of the field test. It should be noted that the error bars, marking ± 1 standard deviation, are in many cases much smaller than the deviation of the data point from the linear fit. This difference of the data point from the linear fit probably is due to the finite Q of the resonator and the accuracy to which the feedback loop is set to lock onto the peak signal of the resonator. This can be better understood by

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Fig. 89: Resonant frequency of the 24 and 44 kHz modes over the course of the field test. Data points at 24 kHz are only available at the beginning and end of the test.

reference to Fig. 90. As the driving frequency is swept through the resonant frequency of the sensor, the relative phase shift between the drive frequency and the response of the sensor varies by 180°. This phase shift is used to generate the error signal for the feedback loop. Ideally, the feedback loop should lock to frequency at which the readback signal amplitude is maximized. In practice, the feedback loop is locked to a frequency near the peak of the resonance, and then the relative phase shift that is output from the lock-in is varied in order to maximize the signal amplitude. However, due to nonlinearities in the system response as well as noise on the signal,

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there is always some ambiguity in the precise phase and, hence, the frequency which maximizes the signal. If we consider the four data points in Fig. 6 for the 24 kHz mode on days 18 and 19 of the field test, for example, the spread in frequency is < 2 Hz. The “Q” of this sensor was ~ 8000 , so the expected full width at half maximum (FWHM) of the resonance is ~ 3 Hz. Therefore, it is likely that the spread in these data points is due in large part to the frequency width of the resonance and to the feedback circuit locking to a frequency that was not at the precise center of the resonant mode. In principle, these MEMS sensors can be manufactured with much higher Q’s for higher precision in the measurement of the resonant frequency if necessary.

Fig. 90: The resonant amplitude and phase shift relative to the driving force are plotted as a function of frequency for a typical resonance of the MEMS sensor.

One other factor that led to a lower precision in the resonant frequency measurement was the digitation noise of the lock-in amplifier. The smallest frequency increment that the lock-in amplifier could output was ~ 2 Hz. In many cases, the readback system was actually much more stable than this, as shown in Fig. 8. In this figure, each data point represents 100 samples from the lock-in output. There were clearly periods of time when all 100 samples were identical at frequencies of ~ 44.03775 or 44.03585 kHz. Other data points at frequencies in between these values are due to averages of some points at one frequency and some at the other. If the lock-in frequency output had provided higher precision, then the measured resonant frequency of the sensor would not have exhibited the ~ 2 Hz step changes as seen in Fig. 91.

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Fig. 91: Example of frequency data exhibiting digitation noise. Each data point is an average of 100 frequency samples from the lock-in output. Flat sections of the graph indicate regions where many 100's of samples were identical. The frequency difference between the flat sections is the smallest digital increment output of the lock-in amplifier.

Returning to the data in Fig. 89, if the linear drift is due to a real effect or a systematic effect that can be corrected, then the accuracy of the frequency measurement of the 44 kHz mode is not $\pm 1.2\%$, but rather $\pm 0.005\%$. Similarly, after removing the linear drift from the measurements of the 24 kHz mode, the accuracy is $\pm 0.0026\%$. Therefore, it is of great interest to understand if possible the cause of this linear frequency drift. The frequency drift of the two resonant modes is seen to be in the opposite direction. Any pressure changes at the location of the sensor affects the two modes similarly, i.e., if the pressure increases, the resonant frequencies of the two modes both increase. Therefore, this drift in frequency cannot be due to a pressure change. The other possibility for the frequency drift is a temperature change of the sensor. Changes in temperature cause changes in the thermal expansion of the sensor and its package, which in turn change the strain on the resonator and its resonant frequency. For this reason, the pressure sensor must be calibrated as a function of both pressure and temperature. It is not too surprising that changes in temperature could affect the frequencies of the two resonant modes in an opposite manner, though this has not yet been experimentally verified or verified through modeling (only the mode at 24 kHz was calibrated in the laboratory). The temperature of the geothermal well did not change over the course of this field test within the accuracy of the Raman DTS measurement (~ 1 to 2°C). However, during the course of this field test there was a drop in the signal amplitude from the pressure sensor. This is most likely due to a “reversible” hydrogen darkening of the fiber, an effect that was also observed in the first field test. As shown in Fig. 92, the signal amplitude dropped over the course of the $2\frac{1}{2}$ week field test by on average 51% or 2.9 dB. The

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(a)

(b)

Fig. 92: Amplitude drift of both resonant modes over course of field test. (a) The amplitude of the 44 kHz mode at the end of the test was ~55% of the initial amplitude. (Three anomalously low signal amplitude data points in this graph were not included in the least squares fit.) (b) The amplitude of the 24 kHz mode at the end of the test was ~47% of the initial amplitude.

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amount of laser power incident upon the sensor, therefore, also dropped by ~30% (considering that the light incident upon the sensor travelled only down the fiber, not round trip), which could have changed the temperature of the sensor due to the change in laser power absorption by the sensor, and may have been the factor leading to the change in resonant frequency. We note that the loss in signal amplitude measured in this second field test for the pressure sensor was consistent with that measured in first downhole field test for the FBG temperature sensor after 20 days exposure as shown in Fig. 93. Also, it appeared from the first field test that the hydrogen darkening effect was asymptotically approaching a maximum attenuation of ~5 dB, but this limit, if it exists, still needs to be confirmed through a much longer field test. Further tests will also be necessary to verify the cause of the frequency drift during this field test, but a possible explanation appears to be the effect of hydrogen darkening on the fiber. If the effect can be determined and mitigated, then extremely precise pressure measurements should be possible at the level of $\pm 0.003\%$, but even without this mitigation, the pressure measurement over the course of the field test was still much more precise than the laboratory calibration accuracy of $\pm 0.1\%$.

Fig. 93: Loss in signal amplitude previously reported for the FBG sensor signal during the first downhole field test.

The cable was removed from the well on July 19, 2012, and shipped back to GE Global Research. The cable was then reattached to the instrumentation and a longer term stability test was performed. As shown in Fig. 94, with the sensor now at room temperature and pressure, the low frequency resonance occurs at ~22.451 kHz. The resonant frequency measurement drifted by ~2 Hz during the course of this test, corresponding to a pressure drift of ~1.8 psi. There are a

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number of spikes apparent in the data corresponding to momentary loss of lock in the feedback circuit. As the instrument was essentially left unattended during this experiment, it was not known what caused the data glitches. The fiber cable was located in a hallway outside of the laboratory in which the optoelectronic circuitry were located, and there was a fiber optic patch cable strung along the floor from the laboratory to the cable spool. During this time there was also a significant amount of maintenance being performed on the building facilities. In any case, the circuit was able to recapture lock in every case but one instance as noted on the graph. The instance noted occurred during a weekend, and the readback circuit was manually reoptimized and relocked on the following Monday. The reoptimizing for maximum signal amplitude also resulted in a different phase shift error being chosen for the lock-in setpoint, which in turn caused the average frequency measurement of the resonator to increase by ~ 0.8 Hz. The overall frequency drift during this time was much smaller than the $\pm 0.1\%$ f.s. (± 3 psi) calibration accuracy, however. During the first half of this test, there is also clearly a daily signal modulation which is apparently due to a small ($\sim 1.2^\circ\text{C}$) temperature variation of the sensor between night and day. There is also a four day periodicity in the signal which is currently not understood. This periodicity still seems to be present after relocking the circuit for the second half of the test, although it is not as apparent. There was no thermometer set up at the location of the sensor during this test to provide input to the calculation of pressure from the resonator frequency, but clearly this information is necessary to obtain the highest measurement precision and accuracy.

Fig. 94: Measurement of low frequency resonant mode at ambient temperature and pressure in the laboratory over a five week interval. Glitches in the signal represent instances when the feedback circuit lost "lock" momentarily. At one point near the middle of the test, the readback circuit lost lock and did not recover, but had to be manually reset. The circuit was apparently relocked to a slightly higher frequency setpoint.

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2. Rayleigh COTDR acoustic measurements

A Rayleigh COTDR unit was rented from Fotech in order to perform distributed acoustic measurements on both the MM and SM fiber in the cable during this field test in partial fulfillment of the contract requirements. Michael Pearce from Fotech arrived at the well site with most of the Fotech equipment on July 17, 2012, and began to setup the instrument. A test of the Fotech instrument on both multimode and single mode fibers in the cable was conducted all day on the July 18. The results were relatively disappointing. There were two factors that made this experiment nonideal. Rayleigh COTDR is designed to operate with SM fiber. Our SM fiber, however, was connected to the pressure sensor at the bottom of the well. As a result, there was a strong reflected signal from the end of the fiber. This signal caused the detector in the Fotech instrument to saturate. A delay then had to be inserted at the end of each pulse to allow sufficient time for the detector to recover. As a result, the repetition rate of the pulses was relatively low even though the fiber was only slightly more than 4000' long. The second issue was the fact that the cable was designed without gel to support the fiber inside. The gel generally acts as a transducer to conduct acoustic waves outside the cable to the fiber. In our case, however, we had to rely on physical contact between the fiber and the metal tube for the fiber to sense acoustic waves.

When using the MM fiber, the Fotech instrument could be operated at 10 kHz with either 50 or 100 ns pulses. A scope capture of the reflected signal is shown in Fig. 95. There are actually two MM fibers in the cable which are connected at the bottom of the cable forming a loop with two separate inputs at the top of the cable for the Raman DTS measurements. The Fotech instrument injects a pulse into one of the MM fibers and then measures the reflected pulse at the same fiber input. The first half of the reflected pulse represents the scattered light from the injected pulse propagating down the cable, and the second half of the reflected pulse represents the scattered light from the injected pulse propagating back up the second MM fiber to the surface. At the bottom of the cable, there is a substantial optical loss where the two MM fibers are joined by a fiber loop, and so there is a large drop in signal amplitude at this point. At the end of the pulse, there is a small spike in the signal due to back reflection from the end of the MM fiber.

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Fig. 95: Scope trace of reflected Rayleigh COTDR signal from the MM fiber in the cable. The pulse represents backscattered light along the total length of the MM fiber. The first half of the pulse is the backscattered light from the light pulse propagating down the first MM fiber. The second half of the pulse is due to backscattered light from the light pulse propagating back up the second MM fiber. The drop in amplitude at the center of the pulse is due to high losses at the turnaround point at the bottom of the cable. The small spike at the end of the pulse is due to reflections from the end of the second MM fiber at the top surface.

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(a)

(b)

Fig. 96: Two examples of acoustic waterfall plots from the MM fiber in the cable.

The reflected trace was captured for each pulse, and then changes in the trace from pulse-to-pulse were monitored and Fourier transformed as a function of depth along the fiber in order to look for acoustic energy along the fiber. No signals were observed on the MM fiber in spite of the fact that there was heavy equipment operating at the surface within 100' of the well. Two

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examples of a “waterfall plots” from the MM fiber are shown in Fig. 96. Well depth is plotted along the horizontal axis. Time is plotted along the vertical axis (with earlier times at the bottom and later times at the top). Each horizontal line represents the acoustic energy at a particular instant in time as a function of distance along the fiber. In this case, the random pattern is indicative of noise without any signal.

Somewhat more success was obtained for the SM fiber. In this case, the maximum pulse frequency was limited to 1 kHz to allow sufficient time for detector recovery due to the large spike at the end of each pulse. The large signal spike at the end of each pulse is the reflection from the pressure sensor, which saturated the detector. As a result, the maximum acoustic frequency that could be measured was only 500 Hz. A screenshot of the scope trace of the reflected signal from the SM fiber is shown in Fig. 97.

Fig. 97: Example of reflected Rayleigh COTDR signal from the SM fiber in the cable.

Surprisingly, although the heavy equipment had stopped operation before the SM fiber was tested, it was still possible to demonstrate detection of an acoustic signal as shown in the waterfall plot in Fig. 98. In this case, on the horizontal axis at a depth of ~639 m, there is a vertical line of yellow and red dots. There are also two other intermittent lines at well depths of ~135 m and ~215 m. These are clear acoustic signatures of something happening to the cable at these specific depths. The exact well depth is somewhat uncertain because the horizontal scale indicates a fiber cable length of ~1400 m, while the actual fiber was 1220 m below the surface and then connected to the Fotech instrument at the surface via a patch cable. A great deal more work is necessary to identify the source of these acoustic signatures, but at least it was

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discovered that even in gelless fiber cable, it is possible to measure an acoustic wave in a relatively quiescent geothermal well with the Rayleigh COTDR instruments.

Fig. 98: Waterfall plot from the SM fiber in the cable exhibiting a clear acoustic signature at an apparent well depth of 639 m and two other intermittent acoustic signatures at 135 and 215 m depths.

Task 4.3—Field deployment planning

Associated Milestone: Concrete field deployment plan in place to support an actual field test

This task builds upon the framework of Task 3.2. Hardware was procured to enable system level testing. In particular, the "splice box" or "junction box" that forms the interface between the downhole cable and the point sensors was procured and tested. In addition, a list of suitable candidate geothermal wells for field test of the system was generated and annotated with any unique requirements they might pose for deployment. Although downhole field testing was not specifically part of the original contract, we planned to actually deploy the fiber for two separate downhole field tests.

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Joe Henfling at Sandia National Laboratories identified several wells at either the Desert Peak, or the Brady, NV geothermal sites of Ormat for the test. The wells are ~2 km deep and reach peak temperatures of ~200 C.

A field deployment plan was drafted as shown in the Appendix and was used to solicit bids for operating the equipment for cable insertion and removal.

Although the installation process was carefully planned prior to the field installation, nevertheless, there were several unexpected events that occurred during the deployment. For example, the dimensions of the end cap on the cable were somewhat different than those which had been communicated to Sandia, so the sinker bar fabricated by Sandia did not fit over the end of the cable. This required a half-day diversion to a “local” machine shop to modify the sinker bar. Once the cable had been deployed and the bottom sheave was being removed, the cable was accidentally released and it snapped up until it was stopped by a cable clamp. In the process, the outer Inconel ¼” cable was partially cracked at the clamp. Fortunately, the fibers inside the cable were not severed and a secondary cable clamp could be installed to maintain the integrity of the cable. The well itself was located in a hollow area that was a potential trip hazard for humans and animals, so lumber from a local hardware store was procured and nailed over the hole and around the well pipe. Ormat indicated that there had been several recent instances of local thievery aimed at removing copper for resale, so the trailer had to have additional locks and other precautions installed, as well being set up on blocks after having its tires removed.

On the other hand, the trailer provided by Sandia with built-in solar power and an auxiliary gas generator was ideal for setting up and powering the equipment. Once the cable was installed and the cable spool fully situated by the well, the breakout box and fiber cable extension were easily installed and connected to the equipment inside the trailer. After completing the installation, the equipment was working well and data was being collected on a regular schedule.

As a result of this installation experience, one lesson learned was to clamp the cable at the top of the well prior to attempting to remove the lower sheave so that there would be no tension on the cable. Nevertheless, it seems that one must be prepared for the unexpected.

After the cable was removed in January, 2012, it was shipped back to QOREX for repair, respooling, and for splicing the Si resonator pressure sensor onto the bottom end. The cable was subsequently shipped back to Ormat and deployed into the geothermal well for the second field test.

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Fig. 99: Fiber cable installed downhole in an Ormat well in Nevada in December, 2011.

Fig. 100: Fiber cable installed downhole for second field test in an Ormat well in Nevada in June, 2012.

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Task 5: Program Management

In Q2 of 2010, General Electric presented an overview of this program and participated in the peer review organized by the Dept. of Energy. Several connections were made with other companies and DoE performers. General Electric visited two of the subcontractors (Qorex and GE Sensing) for detailed discussions of their technical work. Weekly and biweekly meetings were set up between GE and their subcontractors.

In Q3, 2010, the quarterly report and the final report for 2010 year were generated. In addition, an abstract was submitted to the 2011 Stanford Workshop in order to provide an update on the technical progress of the program in accordance with the terms of our SOW.

In Q4, 2010, the paperwork was initiated to transfer project management from Dr. Aaron Knobloch to Dr. Bill Challener, both located at General Electric Global Research in Niskayuna, NY. The project was reviewed at a quarterly internal GE project meeting. A presentation was put together for the Stanford Geothermal Workshop, January 31 – February 2, 2011, and submitted for DOE approval. This paper/presentation will satisfy an item in the project SOW. The annual report was submitted to DOE. Discussions were held with Alta Rock, a leading producer of geothermal energy, and with Sandia and AFL Telecom in preparation for the work to be performed in 2011. Weekly and biweekly meetings continued to be held between GE Global Research, GE Sensing and Qorex.

At this point, it was determined that Task 1.3, “Point Optical Gauge Pressure Development” had slipped ~1 to 2 months due to a later than expected start in the device fabrication process. The first device die were expected in the mid to end of March, 2011. Efforts were made to accelerate the fabrication process, but it was recognized that if the parts did not arrive before mid-March, there would be insufficient time to test the parts before the end of the quarter to complete the task. However, the second iteration of the device and package design was scheduled to begin in June in order to obtain parts for down hole testing by Q1, 2012, so even with parts arriving in mid-March, we still expected to be able to complete the second generation design phase and maintain the schedule for the project.

In Q1, 2011, the project was reviewed at a quarterly internal GE project meeting at the end of January. A paper was presented at the Stanford Geothermal Workshop (January 31 – February 2) on the results of the first nine months of the project as specified in the project SOW, and the paper was submitted to DOE. The Q4-2010 report was also prepared and submitted to DOE. Weekly and biweekly conference calls continued to be held between GE Global Research, GE Sensing, and Qorex. AFL Telecom and Sandia National laboratories were also invited to begin participating in the conference calls.

There were several first year tasks remaining to be completed. Most of those involved tasks on which Qorex was working and would be completed prior to the first downhole test in Q3, 2011,

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and should not delay the project. Moreover, Qorex had remaining funds designated for these tasks from phase 1 of the project. Final details of the installation still needed to be completed pending identification of the actual rig and procedural review with the service provider, which would occur closer to the first downhole test in Q3-2011. In order to conserve resources, some testing that required the leasing of commercial instruments was delayed until just prior to the downhole test.

In Q2, 2011, periodic project reviews continued to be performed to ensure all key milestones were met. The project management plan was kept current during the duration of the project and shared with the DoE. During this quarter both the Q1 quarterly report and the annual peer-review report and presentation were completed and delivered. The project was reviewed at a quarterly internal GE project meeting at the end of April. Weekly and biweekly conference calls continued to be held between GE Global Research, GE Sensing, Qorex, AFL Telecom and Sandia.

Fiber cable manufacture was scheduled to be completed in Q2-2011, but was delayed by the manufacturer until the end of August. This has in turn delayed the first downhole test until the second half of September. This was not expected to impact the completion of any project milestones, however.

In Q3, 2011, the Q2 quarterly report was completed and delivered. The project was reviewed at quarterly internal GE project meetings in both June and September. Weekly and biweekly conference calls continued to be held between GE Global Research, GE Sensing, Qorex, AFL Telecom and Sandia. An abstract of the work for this year was prepared and submitted, per the contract requirements, to the Stanford annual geothermal conference.

A number of issues arose during this quarter requiring management attention. QOREX used up their entire allotted labor budget in August, 2011. With approval from DOE, a portion of their materials budget was reallocated to labor. Sandia required a new statement of work, leading to a new contract and purchase order, with necessary approvals at each step from Sandia, GE, and/or DOE. This unexpected delay reduced the amount of time that Joe Henfling at Sandia was able to spend on soliciting bids for performing the actual downhole installation and removal of the cable. This delay was partially mitigated, however, by the fact that AFL also experienced several delays in the cable manufacture and had not delivered the cable to QOREX by the end of this quarter. The original delivery date was the end of July, and it was first extended into mid-August, then mid-September, and finally early October.

In spite of these delays, a well was identified that is owned by Ormat in Bentley, Nevada, for the first downhole test and it was still expected that this test would be completed by the end of 2011. The second downhole test was originally scheduled for February, 2012, leaving January for turnaround and splicing the MEMS pressure sensor to the cable. There were indications from the team at GE Sensing that the second generation sensor fabrication was proceeding more slowly than anticipated, however. Moreover, the sensor package, which was originally planned to be

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completed by June, was still being fabricated. The package was expected to be completed by November, but there was a good chance that the sensors would not be finished by January. However, the interim sensors with metal films were expected to be tested in November and might be used in place of the second generation sensors. At the beginning of January, 2012, it was decided that the project timeline would be reassessed to determine if a no cost extension should be requested.

In Q4, 2011, weekly conference calls were held this quarter between GE Global Research and all subcontractors. The decision was made to attempt the first downhole test before the end of the year, in spite of the nearness to the holidays, due to the repeated delays from the original field test schedule of August, 2011. A decision was made to request an extension of the project by at least one quarter in order to provide time for the pressure sensor package to be completed and so that a well stimulation could be monitored in the field.

The final quarterly report for 2011 was written. The abstract that was submitted to the 2011 Stanford Geothermal Workshop according to the requirements of the contract, was accepted, so an in depth report and presentation on the technical progress of the program has been written and is undergoing the internal GE publication approval process.

In Q1, 2012, weekly or biweekly conference calls were held between GE Global Research and the subcontractors. The second downhole test was tentatively scheduled for deployment during the week of May 21, 2012. This date was subject to the MEMS pressure sensor arriving at QOREX in time for splicing and subsequent cable shipping to the test site.

The slides were prepared for the DOE peer review conference in May. A presentation of the results from the past year of the project was delivered in accordance with the contract requirements at the Stanford Geothermal Workshop at the end of January.

In Q2, 2012, weekly or biweekly conference calls were held between GE Global Research and the subcontractors. The second downhole test began on June 21, 2012, about a month later than originally scheduled due to delays in MEMS sensor fabrication and unavailability of the Ormat well.

The primary aspect of program management this quarter was coordinating the second downhole test with Qorex, Sandia National Laboratories, Pacific Process Systems, and Fotech to complete testing of both the pressure sensor and the Rayleigh COTDR acoustic system. After completion of the test on July 18, 2012, the equipment was removed from the well and shipped back to GE Global Research. The pressure sensor while still on the cable was reconnected to the readout equipment in the laboratory and a longer term stability test was conducted. After the conclusion of the project on September 30, 2012, the final program management tasks include the quarterly report, the final report, and the final equipment inventory.

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The project technical team is listed below.

1. General Electric Global Research

William Challener, final P.I.
Aaron Knobloch, initial P.I.
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James Lopez
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2. General Electric Sensing, Measurement and Controls

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3. QOREX, LLC.

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Paul Sanders
George Sarkizi
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Andre Williams

4. AFL Telecommunications

Brian Herbst
Brett Villiger

5. Sandia National Laboratories

Joseph Henfling
Scott Lindblom
Frank Maldonado

6. Ormat

Stephanie Konefat

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PRODUCTS / PUBLICATIONS / PATENTS

[W. Challener, et al. “Subsystem design and validation for optical sensors for monitoring enhanced geothermal systems,” Proc. 36th Workshop on Geothermal Reservoir Engineering, Stanford Univ., 1/31/2011 – 2/2/2011, SGP-TR-191.](#)

[S. Palit, et al. “A multi-modality fiber optic sensing cable for monitoring enhanced geothermal systems,” Proc. 37th Workshop on Geothermal Reservoir Engineering, Stanford Univ., 1/30/2011 – 2/1/2011, SGP-TR-194.](#)

[W. Challener et al., “Optical MEMS pressure sensors for geothermal well monitoring,” to be presented by A. Knobloch at MOEMS SPIE Photonics West conference in February, 2013.](#)

No patent applications have been filed during the course of this project. Two patent applications are currently under development related to the design of the MEMS pressure sensor.

No new products have been introduced during the course of this project.

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Appendix 1: Field Trial of Hydrogen-Tolerant Fiber

Program Objective:

The overall objective of the field trial is to evaluate field performance of the program optical sensor cable in a geothermal well. Testing will encompass cable design robustness to handling and well installation procedures, and the downhole environment. The program will integrate multiple sensors and optical sensor cable for installation in a test well. A test program will evaluate sensor performance over the trial period to validate the suitability of the cable to operate these sensors with high measurement performance and reliability in the intended geothermal well application. Specific objectives include the following.

- Injury and damage incident free deployment and operation of the sensor system.
- Successful deployment of the system into a geothermal well using conventional installation methods and equipment.
- Evaluate sensor performance relative to baseline specifications and laboratory tests.
- Validate the cable design for operating the suite of sensors in the geothermal application.
- Create better understanding of downhole geothermal well conditions and characterize any cable or fiber aging due to the downhole environment.
- Generate an initial reliability model for the downhole sensor cable in geothermal well environments to project lifetime and performance under a range of conditions.

Test Site:

Test well #XX at Ormat Desert Peak facility near Reno Nevada.

Work Plan Details:

The newly developed fiber cable system consists of multiple fiber housed in 1/4 tubing, 3/8" termination tubing (approximately 24" long, located at the downhole end of the tubing), and a suitable sinker bar. As with any tubing deployment, success depends on careful handling due to the unforgiving nature of tubing. Any bends imposed on the tubing during installation that are less than the recommended bend radius can lead to early failure of the cable system. The fiber termination tubing is welded at the bottom-hole end of the tubing and is not field repairable and is an additional motive for careful handling. The tubing is housed on a wooden spool with an integrated partition (to ease the surface termination difficulties and to enable both ends of the cable to be accessed prior to deployment). It is expected the contractor will provide an adequate truck/ trailer to enable 10000 feet of tubing to be deployed/extracted at a controlled rate of approximately 50 feet per minute. Once deployed, the wooden spool is to be removed and placed near the well site for long-term monitoring (6 to 14 weeks). Once the testing is complete, the contractor is to remove the tubing. A lubricator and sheave wheels will be supplied by the contractor. A generator is required for the duration of the testing and is also to be supplied by the contractor. Due to seismic sensor in the immediate area near the well, a generator designed for quiet and continuous use is necessary. Prior to deploying the cable system, a TPS log will be

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performed to determine the baseline temperature and pressure. After the completion of the test, another TPS log will be performed. Sandia will supply the TPS tool. The TPS log can be deployed using slickline or braided cable (braided cable preferred). Monitoring of depth is required and Sandia will work with contractor to interface a depth encoder to the deployment system.

Cable specifications

- Diameter: 1/4"; except termination module at the end of the tubing, which is 3/8" diameter and 24" in length
- Length: 3km
- Maximum temperature 250C
- Minimum recommended sheave wheel diameter 26"; preferred 30"
- Maximum pressure: 10000 psi
- Drum core diameter 27 1/4" (see Figure 1)
- Drum flange diameter 48" (see Figure 1)
- Maximum processing tension (steady state) < 50 lbs
- Maximum Operating Tension; >500 lbs
- Minimum buckling force; > 200 lbs
- Minimum bend radius when handling tubing while rigging up is 15"
- Spool weight:

Contractor-Supplied Components

- Adequate trailer/truck to deploy and remove 10,000 feet of cable at a controlled rate of 50 feet per minute
- Adequate trailer/truck to accommodate and drive the wooden spool (see Figure 1)
- Lubricator as required by Ormat
- Ability to fully release packing around tubing when the cable is to be removed from the well
- Boom truck (required for deployment and for removing spool from truck/trailer after installation)
- Generator designed for continuous duty and is quiet (required to minimize influence of existing surface seismic sensors)

Sandia/GE/Qorex Supplied Components

- Cable system
- Spool (see Figure 1)
- Sinker bar
- TPS Tool
- Encoder for reading depth and the recording system
- Trailer to house surface electronics
- All necessary surface electronics

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Tasks for Deploying Cable System

- Mobilize trucks, etc. at chosen well site
- Rig sheaves, lubricator, etc. to prepare for TPS log
- Log well with TPS tool
- Load wooden spool onto truck/trailer
- Rig sheaves, lubricator, etc. to prepare for cable deployment
- Deploy fiber cable system
- Make 500 foot stops to check fiber integrity using an OTDR
- Prior to removing spool from truck/trailer, check fiber integrity
- If ok, remove spool from truck/trailer and prepare site for long-term deployment
- Setup generator
- Setup up monitoring equipment and verify fiber functionality
- Demobilize equipment not required for long-term testing

Tasks for Removing Cable System

- Mobilize equipment to well site
- Perform any additional tests on fiber (as required)
- Load spool onto truck/trailer
- Rig sheaves
- If packoff used, make sure it can be backed off without damage to tubing
- Remove fiber cable system from well
- Check fiber integrity
- Remove spool from truck/trailer
- Rig up for TPS log
- Log well
- Demobilize from well site

General Notes:

- Target Deployment Date: mid-October, 2011
- Allow two days for deployment and two days for removing the cable system

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Fig. 101: Dimensions of supplied wooden spool.

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Appendix 2: Statistical analysis of optical fiber performance

To impart reliability and a predicted application lifetime, optical fiber is subjected to a tensile proof test procedure at the factory to screens fiber and ensure a minimum mechanical strength. This assures a maximum flaw size to allow a lifetime prediction for a given maximum application stress. Measured strengths of identically prepared glass fibers show a statistical distribution. It is customary to plot the measured strength distribution on a Weibull plot. Since failure in brittle materials is a statistical process, numerous samples must be measured in order to adequately represent the distribution of flaws (and strength) throughout the fiber.

The Weibull function is represented by:

$$\ln \bullet \ln (1 - F) - 1 = m \ln \sigma_f - m \ln \sigma_0$$

Where F is the cumulative failure probability, m is the Weibull slope, σ_f is the failure stress, σ_0 is the Weibull scale. The Weibull distribution provides a measure of the median or mean strength of the fiber, and a slope or Weibull modulus m that is a measure of the scatter in strength and relates to the standard deviation. A fiber with tight distribution and high Weibull modulus indicates a well-controlled fiber manufacturing process and associated uniform strength distribution. In contrast a broad distribution or low Weibull modulus indicates a poorly controlled process and fiber with low potential reliability.

Under tension, corrosive chemical environments will accelerate this crack growth. A key design element for fiber mechanical reliability is the quality and conformance of its protective outer coating, in which polymers are the most common material applied to maintain the as-produced fiber surface condition and allow handling without inducing further flaws to the glass surface. For the challenging chemical and thermal environments, mechanical reliability becomes dependent upon the stability of fiber coating under application conditions; in which the material needs to maintain its elastic and mechanical properties, as well as prevent ingress of any corrosive agents from attacking and degrading the fiber surface condition. This forms the basis for characterizing and testing fiber for a particular application thermal or chemical environment. Comparison of pre- and post-conditioned fiber subjected to design application environment, will reveal and quantify degradation of intrinsic fiber strength and lifetime prediction.

Dynamic tensile testing and Weibull analysis provides a useful tool to assess fiber quality and aging effects for this program. Baseline as-produced fiber Weibull distribution provides initial characterization of the fiber process based on the Weibull modulus. Extending the analysis to conditioned fibers can provide critical insight into fiber performance under design conditions and flag potential problems.

Referring to the figure below, a range of performance can be seen in the examples of intrinsic and aged Weibull plots. In (A), intrinsic fiber Weibull distribution is low with high modulus, showing a well controlled process without the presence of low strength flaws. The aged fiber

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Weibull plot, a virtual overlap to that of the intrinsic plot shows no gross aging effect or degradation of intrinsic fiber strength after conditioning. The presence of low strength flaws is shown in (B) which features a low strength “tail” indicative of a poorly controlled process or material contaminant. Here the “tail” tends to grow and shows aging after conditioning. This Weibull spectrum would raise significant concern for using the fiber in critical applications such as thermal wells. In (C) the intrinsic Weibull is similar as in (A) with tight distribution and high Weibull modulus. Upon conditioning however, the Weibull plot features a low strength “tail” indicating that the conditioning has introduced a flaw or experienced flaw growth from stress or corrosion (as seen in the previous figure) that degraded the fiber mean strength and reliability, therefore the fiber not well-suited for use under the conditioning environment it was subjected. In a worst case the conditioning introduces a flaw that promotes a bi-modal strength degradation effect shown in (D) where flaw introduction couples with flaw growth.

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