FIELD APPLICATIONS OF FIBER-OPTIC SENSORS:

1. Temperature Measurements
   In A Geothermal Well

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ABSTRACT

We have initiated a program for developing and field testing fiber-optics-based sensors to monitor in situ physical and chemical parameters in highly corrosive environments, such as geothermal wells, oil wells, and hot-water boiler reactors. Inability to sample hot geothermal wells or to measure the chemical composition of hot brines limits our understanding of in situ conditions in geothermal fields. In this communication, we report preliminary results obtained using a temperature optrode to profile the temperature in a geothermal steam well. To our best knowledge, this is the first time in situ geothermal well measurements have been made using a fiber-optic sensor.

INTRODUCTION

While technology has advanced in certain aspects of geothermal exploration, instrumentation for downhole measurements has not advanced significantly. The present methods for gathering temperature, pressure, and water-chemistry information about the fluids in high-temperature wells include measurement by mechanical instruments and by electronic instruments. There are limitations to each of these methods. Some of the limits of mechanical instruments are that (1) results are not provided on a timely basis because most chemical concentrations are determined on a batch sampling basis in laboratories removed from the site and results are not available until a few hours or a few days, (2) results for water chemistry are suspect because water from another depth may leak into the samples, and (3) immediate changes in constituents and concentrations generally cannot be assessed because only a limited number of chemical compounds can be measured in real time and those measurements can only be made under restricted conditions. Present downhole data acquisition by electronic instruments is
limited because heavy conducting cables are required and there is a high incidence of instrument failure at high temperatures.

Real-time downhole measurements are essential in the development of geothermal wells and fields. The variation of the temperature in the well as a function of depth and of time is important in determining the source of the hot water in the well and for predicting the future production of the well. These parameters as well as water chemistry in the well are also important parameters in determining the useful life of a well. Furthermore, understanding the water chemistry in a well is critical for designing equipment that is resistant to scaling and can withstand corrosive fluids.

Recently, a program was started at Lawrence Livermore National Laboratory (LLNL) to develop optical-fiber sensors (optrodes) for use in logging and monitoring geothermal wells. Research was focused on developing a temperature optrode that could be used to obtain real-time information at temperatures up to 300°C in very deep geothermal wells. This optrode was completed and has been thoroughly tested in the laboratory. The most serious limitation of this optrode is that the optical fiber must be kept dry at high temperatures.

Optical-fiber temperature measurements at LLNL are based on the temperature-dependent fluorescence characteristics of inorganic ions doped into a host matrix. A ruby-based temperature and pressure optrode that operates in the temperature range of 100° to 600°C has been reported previously. The ruby-based optrode has a temperature accuracy that is very dependent on the temperature range being measured and is better at higher temperatures. At 400 °C the accuracy is about 1 to 2°C. More recently, a temperature optrode has been developed based on dual-emission rare-earth phosphorescence. The new optrode has the advantage of working over a wider temperature range and in corrosive environments and uses simpler instrumentation. Further, it has an improved accuracy because the intensity ratio of two emission
bands are measured. The objective of the research reported here is to demonstrate that a temperature optrode can be used to obtain real-time information from a geothermal well and that it can be used interactively.

**EXPERIMENTAL**

The new temperature optrode is based on the temperature-dependent phosphorescence of the Eu$^{3+}$ ion. Briefly, Eu$^{3+}$ and Er$^{3+}$ are doped into lattice sites within an inert ceramic-like carrier matrix (CaZrTi$_2$O$_7$). The two dopants both fluoresce when excited with the 488-nm line of an argon ion laser. In the case of Eu$^{3+}$, the intensity of the fluorescence bands at 610 nm and 595 nm increases as the temperature increases, while, in the case of Er$^{3+}$, the intensity of the fluorescence bands at 548 nm and 560 nm decreases as the temperature increases (Plot A of Figure 1). The ratio of the Eu$^{3+}$ and Er$^{3+}$ band intensities is plotted as a function of temperature to produce a calibration curve for the optrode (Plot B of Figure 1). The accuracy of this optrode is about ±0.2°C in the range 100 to 300°C, using a short (1 to 2 m) optical fiber and a laboratory spectrometer. Of course, the accuracy of the sensor is related to the type of spectrometer used to make the measurement, the laser power, and many other parameters that vary from spectrometer to spectrometer.

The details of the optrode construction are shown in Figure 2. The optrode was made by modifying a standard optical-fiber connector (Ofti-brand, 250 µm hole) to hold the temperature-sensitive ceramic. The ceramic was machined into a 3-mm-long cylinder about 2 mm in diameter. For the single-fiber measurements, we used a temperature-resistant film (Kapton) on one flat end of the ceramic cylinder to hold the ceramic piece tight against the polished face of the optical fiber (Figure 2A). The single fiber was glued in the optical-fiber connector with a temperature-resistant ceramic cement (Cotronics Corporation, No. 940, zirconia-based adhesive), and this optical fiber was used both to illuminate the sensor and to
collect the resulting fluorescence signal. All well measurements were made over a single, 300-m length of high-temperature, polyimide-coated, fused-silica optical fiber (Polymicro Incorporated FHP 320/385/415) with a 320-µm core diameter.

The double-fiber probe was 100-m long and used two 200-µm-core diameter optical fibers (Diaguide brand 200/250 glass on glass optical fiber). The optrode was constructed as described above with the exception that a 2-mm spacer was used to separate the temperature-sensitive ceramic from the end of the two optical fibers (Figure 2B). This permitted good overlap between the fields of view of the two optical fibers at the optrode end, thus providing optimal collection of the fluorescence generated in the optrode. The two fibers were held in a single Ofit connector with minimum separation between them.

The field spectrometer setup is shown in Figure 3. The 488-nm line from an air-cooled argon-ion laser was used for excitation. Typical laser power was 30 mW at the laser. The collimated laser beam was first filtered to remove plasma emission using a narrow-band-pass (NBP) filter (F1 in Figure 3). Then, the beam was turned at right angles by a long-wavelength-pass (LWP) dichroic turning mirror (DM in Figure 3) into a 0.2-NA microscope objective, MO1 in Figure 3 (Newport Model M-10X), which focused it into the optical fiber (OF1 in Figure 3). The laser excitation light produces fluorescence at the optrode tip, and the fluorescence light is returned over the same optical fiber and is collected and collimated by microscope objective MO1. This collimated fluorescence light then passes through the LWP dichroic turning mirror and is focused by an f/4 lens (L1 in Figure 3) onto the slit of the monochromator. A narrow-band rejection filter (F2 in Figure 3), between the microscope objective and the focusing lens, was used to separate scattered laser light from the fluorescence signal and was also selected to attenuate a strong optical-fiber Raman band at about 600 nm. For the dual-fiber experiments, the dichroic mirror was removed and the laser beam was launched by a different microscope objective (MO2 in Figure 3) into the excitation fiber.
(OF2 in Figure 3). In the dual-fiber experiments, the fluorescence signal produced by the optrode is collected by a second fiber (OF1 in Figure 3) and returned to microscope objective MO1 for collection and collimation. The collimated beam is focused onto the slit of the monochromator by lens L1.

The detection system consisted of a 0.22-m, f/4, single-beam monochromator (SPEX Model 1681B) with a 1000-channel, intensified-diode-array detector (Princeton Instruments Model IRY-700G detector and Model 110 controller). A 300-grooves/mm grating, blazed at 500 nm, was used for all measurements described here. A personal computer was used for data acquisition and spectrometer control.

The laser and spectrometer were installed in a large moving van and were mounted on a small optical table. The van was parked along the roadside near the well site during testing. All power for the experiments was supplied by an Onan gasoline generator. The fiber-optic cable was laid out from the van to the well site and was protected by placing it inside Teflon tubing. The tubing joints were connected by heat-shrink tubing and reinforced by wire wrap. A Chromel-Alumel (K-type) thermocouple was used as a reference in the data collected, and its line probably served a more important role as a support line for the fiber-optic cable. The thermocouple line was secured to the fiber-optic line, at roughly 3-m intervals; with wire. This was important because the force of the steam from the GTW-2 well was strong enough to cause damage to the fiber-optic cable. A 0.9-kg lead weight was attached to the end of the cable to facilitate getting the fiber into the well against the force of the steam coming out of the well. The optical fiber cable assembly was lowered into the well with a pulley that was equipped with a wire-line depth gauge that was used to measure the depth of the probe in the well.

The Teflon tube used to protect the fiber-optic cable was translucent, and we found that sunlight leaked into the sides of the optical fiber, resulting in very high background signals. This background was constantly changing due to cloud movement, and, therefore, it was very difficult
to accurately subtract from each spectrum. The problem was mostly eliminated by wrapping the above-ground portion of the fiber-optic cable with aluminum foil where possible; however, some small amount of signal variation always remained due to incomplete elimination of the sunlight signal. This led ultimately to lower accuracy in our temperature measurements. However, because the main purpose of these tests was to demonstrate interactive real-time optical-fiber measurements, we did not attempt to completely solve this problem or to obtain maximum accuracy in our measurements.*

DESCRIPTION OF THE TEST SITE

The well-logging tests were made in a geothermal exploratory well, Geothermal Test Well 2 (GTW-2, USGS No. 2686-02), located on land that is owned by Amfac Corporation. In 1961, several shallow test wells were drilled in the Kilauea Volcano East Rift Zone to explore any geothermal potential. Well GTW-2 was drilled to a depth of about 169.5 m. A 14-inch (0.356-m) diameter casing extends from the surface to a depth of 32.6 m. The well is located 30.5 m from the northern side of the Pahoa-Kalapana road, just across a scenic volcanic vent turnoff. The elevation of the well site is about 41.8 m. The maximum temperature recorded in this steam well is 97.1°C.*

RESULTS AND DISCUSSION

The optrode was calibrated prior to the well tests using the same 300-m optical fiber that was used in the experiments. In Figure 4 is shown the response of the optrode using the 300-m optical fiber. The optrode spectra measured with a long optical fiber (Figure 4) are different from those measured with a short optical fiber (see Figure 1A) because of strong optical-fiber

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*The background can be easily eliminated by using an opaque cable. If this is not possible the background signal can be accurately subtracted by chopping the laser beam and using a lock-in amplifier with the detection system.
Raman bands that appear at 550 nm, 600 nm, and below 535 nm. In Figure 4, the Raman band at 600 nm is blocked by the narrow-band rejection filter; this filter also blocks the 595-nm Eu³⁺ emission band. The calibration was done in the dark and without subtracting the Raman background component of the optrode signal. A 38-L temperature-controlled water bath was used for the calibration, the temperature calibration range was between 31.8°C and 91.0°C. The water temperature, as measured by a K-type thermocouple, varied by ±2°C at different positions in the bath, and this limited the accuracy of the optrode calibration. Optrode measurements were made while the temperature of the water bath was increased from 31.8°C to 91.0°C and again as the water bath cooled back down to room temperature. In Figure 5 is shown the resulting calibration curve. The solid curve in Figure 5 represents a polynomial fit of the optrode response. The polynomial equation was used to relate the optrode response in the well to the temperature in the well.

The well measurements were made by lowering the temperature optrode to a particular depth while monitoring the real-time response of the detector on an oscilloscope. This was found to be very useful for quickly locating and examining interesting spots in the well. After positioning the probe to a particular depth, the sensor response was allowed to reach equilibrium (almost immediately), and three spectra were measured. One spectrum was measured with the sensor illuminated (fluorescence signal plus background signal), followed by one with the laser shuttered (background signal only), and a second spectrum with the sensor illuminated. The shuttered spectrum was used for subtracting the variable background signal that was due to sunlight leaking into the optical fiber. A thermocouple reading was also recorded at each depth. After completing the measurements at a particular depth, the probe was repositioned and the procedure was repeated. Measurements were taken as the probe was lowered down the well as

**The polynomial equation used to fit the temperature optrode response is:**

\[
\text{Response} = 0.4684 + (0.0069 \times T) + (1.57 \times 10^{-5} \times T^2)
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well as when it was raised back to the surface. When results from a region appeared to be interesting, measurements were repeated several times. In this way, a depth versus temperature profile (well log) was obtained very quickly.

In Figure 6 are shown spectra that were measured with the fiber in the well at a depth of 15.2 m (50 ft), including the Raman and sunlight components. In Plot A of Figure 6 is shown the spectrum that results from the combination of optrode fluorescence, Raman signal generated in the optical fiber, and sunlight background. Plot B of Figure 6 was obtained by removing the optrode and measuring the signal that resulted only from illumination of the optical fiber. This spectrum was measured with the optical fiber in the dark and is due only to the Raman signal generated in the optical fiber. Finally, the spectrum shown in Plot C of Figure 6 was obtained by shuttering the laser and is due only to the sunlight background component.

The temperature in the well is determined by subtracting Plot C of Figure 6 (sunlight background) from Plot A of Figure 6 (Optrode signal plus Raman signal plus sunlight background) and calculating the ratio of the Eu²⁺ band intensity at 610 nm and the Er³⁺ band intensity at 560 nm from the resulting spectrum. The ratio is then related to the calibration curve (Figure 5) to obtain the temperature. It is not necessary to subtract the Raman component because it is constant with respect to the fluorescence signal generated by the optrode and is taken into account in the calibration curve.

In Figure 7 is shown a temperature profile that was obtained for well GTW-2 using the optrode versus the thermocouple profile. The optrode response was converted to temperature by relating the response to the calibration curve shown in Figure 5. The optrode temperature value is plotted in Figure 7 as open diamonds and the thermocouple readout is plotted as open squares connected by a solid line. Measurements were made to a depth of 150 m (about 490 ft). The agreement between the optical measurements and the thermocouple measurements is within the error of the calibration data (±2°C). These results are not as accurate as those obtained in the
laboratory. This is partly because of errors in the calibration data and also because of the
difficulty of accurately subtracting the varying background signal.

The accuracy of the single-fiber optrode measurement depends to some extent on the
ability to remove or subtract the Raman background signal generated in the optical fiber itself.
The Raman signal is generated in the optical fiber by the exciting laser light and propagates in
both directions within the fiber. Thus, in a single fiber probe the Raman signal travels directly
back to the spectrometer and for long optical fibers is a major source of background signal. The
use of separate optical fibers to illuminate the optrode and to collect the fluorescence eliminates
a direct path for the Raman signal to get back to the detector and results in a lower background
signal.

A two-fiber optrode was tested to reduce the optical-fiber Raman signal. In Plot A of
Figure 8 is shown the response at 25.5 and 85°C of the single-fiber temperature probe described
above. The Raman bands appear at 550 nm and below 535 nm. These Raman bands are reduced
with respect to the fluorescence signal from the optrode in the dual-fiber probe (Plot B of Figure
8), as shown by the reduction of the Raman band at 550 nm and the elimination of the band
below 535 nm. The lower curve (dotted) in Figure 8B shows the Raman signal that is generated
in the 100-m excitation fiber. This was measured in the same way that the single-fiber
measurements were made. The disadvantage of the dual-fiber probe is that less fluorescence
signal reaches the detector. The amount of fluorescence signal returned by the double-fiber
optrode, in this particular case, was about four percent of that returned by the single-fiber probe.
The smaller signal was partly because the diameter of the collection fiber used in the
double-fiber probe was smaller than that in the single-fiber probe (200 µm versus 320 µm). But,
it is mostly a result of the smaller overlap between the fields of view of the illumination and
collection fibers.
CONCLUSIONS

These experiments demonstrate the feasibility of optical-fiber temperature measurements over 300 m of optical fiber in a geothermal steam well. It was further demonstrated that this optrode can be used in situ in an interactive manner to obtain real-time information in geothermal wells. The Raman signal generated in the optical fiber can be a major source of background noise when long optical fibers are used with a single-fiber optrode. It was shown that the Raman background can be greatly reduced by using a dual-fiber optrode; however, only at the expense of greatly reduced signal levels.

FUTURE DIRECTIONS

In the future, other types of optrodes will be tested to measure chemical parameters in geothermal wells. High-temperature pH and Eh optrodes are already being tested for this purpose. In the more immediate future, the temperature optrode will be tested in hotter and deeper geothermal wells. It has been tested in the laboratory to 320°C at several thousand-PSI pressure for extended periods of time. However, to be used at such high temperatures, the optical fiber has to be well shielded and kept from directly contacting the well fluids. Based on the magnitude of the fluorescence signal generated by the optrode using 300 m of optical fiber and the known attenuation of the optical fiber, it is believed that wells up to 1000 m in depth can be logged. Using the present instrument configuration, spectra can be obtained at a rate of about 30 per second. This will allow very high spatial resolution measurements to be made as the probe is continuously lowered into the well.
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REFERENCES

FIGURE CAPTIONS

Figure 1. Single-fiber temperature optrode response using a short (2-m) optical fiber: (A) the optrode fluorescence response at 37.3°C (Dashed) and 138°C (Solid); (B) response curve for the temperature optrode using a 2-m optical fiber, plotted as the ratio of the intensities of the Eu³⁺ and the Er³⁺ fluorescence peaks, versus temperature.

Figure 2. Optrode Construction: (A) Single-fiber optrode construction; (B) Double-fiber optrode construction.

Figure 3. Field spectrometer setup.

Figure 4. Single-fiber temperature optrode response using a 300-m optical fiber and a narrow-band rejection filter to attenuate the Raman band at 600 nm: (Dashed) 25.5°C; (Solid) 85°C.

Figure 5. Calibration curve from 31.8°C to 91.0°C using a 300-m optical fiber and the single-fiber optrode. The solid line shows the polynomial curve fit to the calibration data as described in the text.

Figure 6. Fluorescence response of the temperature optrode, at a depth of 15.2 m in the well, showing the Raman and sunlight contributions to the total signal. (A) the total signal comprised
of the optrode fluorescence signal, the Raman background, and the sunlight contributions; (B) the Raman contribution obtained by removing the optrode from the fiber with the fiber in the dark; (C) the sunlight contribution obtained by shuttering the excitation laser.

Figure 7. Optrode temperature profile for well GTW-2: the optrode response is shown by the open diamonds. The error bars indicate the error in the calibration curve; the solid line with the open squares shows the thermocouple response. The thermocouple well measurements varied by as much as ±1°C.

Figure 8. Comparison of the single-fiber and dual-fiber optrode responses. The single-fiber measurement was made with a 300-m fiber and the dual-fiber measurement was made with a 100-m fiber: (A) single-fiber optrode response at 25.5°C (dashed) and 85°C (solid); (B) dual-fiber optrode response at 25.5°C (solid) and 85°C (dashed). The lower curve shows the Raman signal generated in the 100-m excitation fiber.
Temperature Optrode Calibration

![Graph showing the relationship between temperature (C) and ratio1. The graph appears to be a straight line, indicating a linear relationship.](image-url)