

Short Note

Fibre optic temperature sensing: A new tool for temperature measurements in boreholes

Stephan Großwig*, Eckart Hurtig†, and Katrin Kühn*

INTRODUCTION

Usually, the temperature in boreholes is determined using a standard temperature probe. The logging technique is either "stop and go", or the probe is lowered as a moving probe into the borehole using a controlled speed.

Distributed temperature probe arrays installed permanently in a borehole are an alternative to moving probes and can be applied especially for temperature monitoring even under conditions where moving probes cannot be used. The distributed optical fiber sensing technique represents a new approach for temperature measurements. The basis for this method is given in Boiarski (1993), Dakin et al. (1985), Farries and Rogers (1984), Hartog and Gamble (1991), Rogers (1988), Rogers (1993). First results using fiber optic temperature sensing in boreholes and temperature monitoring for studying geotechnical and environmental problems (e.g., waste deposits) are published in Hurtig et al. (1993; 1994; 1995) and Hurtig and Schrötter (1993).

THE DISTRIBUTED FIBER OPTIC TEMPERATURE SENSING TECHNIQUE

The optical fiber distributed temperature sensing is based on optical time-domain reflectometry (OTDR) (e.g., Rogers, 1988; Farries and Rogers, 1984; Hartog and Gamble, 1991). Coupled to the optical fiber is a pulse laser, which is the sensing element. The optical fiber laser is neodymium-doped and has a wavelength of 1064 nm, and the pulse duration is 10 ns. The light is backscattered because of the changes in density, composition, and molecular and bulk vibrations. A portion of the backscattered light is guided back to the source and is split off by a directional coupler in the receiver. The backscattered light includes Rayleigh, Brillouin, and Raman backscattering light. The Raman backscattering light is caused by thermally influenced molecular vibrations and can be used to obtain information about the temperature distribution along the fiber.

The Raman backscattering light has two components: the Stokes and the anti-Stokes component. The Stokes component is dependent only weakly on temperature, while the anti-Stokes component shows a strong relation to temperature.

The basic principle of fiber optic temperature measurements, thus, consists in filtering the Stokes and the anti-Stokes components out of the backscattering light. The ratio of the intensities of these components is calculated and transformed to temperatures using both the internal reference temperature of the equipment and an externally determined calibration function for the particular fiber type. Taking the ratio of the intensities eliminates influences such as changes of the light source or age effects of the optical fiber.

The temperature is determined as an integral value for a short section of the optical fiber and the space coordinate is obtained from the traveltimes of the propagating light pulse. Therefore, it is possible to measure the temperature simultaneously along the entire length of the fiber. Space resolution at present is 1 m (optional 0.5 m or 0.25 m).

Absolute temperature is determined using a calibration function that depends on the geometry and chemical composition of the optical fibers and their temperature dependences. These properties will differ for the different optical fibers. The calibration function must be determined for the individual optical fibers before the measurements are performed. The accuracy of the temperature measurements is 0.3 °C, and a resolution up to 0.05 °C can be reached. Accuracy is controlled by the preciseness of the fiber-specific calibration function, whereas the available resolution and precision depend on the specific material properties of the optical fiber used.

The Raman backscattering intensity is integrated for a given fiber section (1 m, 0.5 m, or 0.25 m, respectively). Thus, the measured backscattering intensity defines the integral temperature for this interval in contrast to standard temperature sensors that give the local temperature at the position of the sensor. Backscattering of light is a stochastic process, there-

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*GESO GmbH, Max-Gräfe-Gasse 10, D-07743, Jena, Germany.

†GESO GmbH Bureau Brandenburg, Rheinstraße 3, D-14513 Teltow, Germany.

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fore, it is necessary to integrate the backscattering intensity for a given time interval. Taking a geometrical resolution of 1 m, an integration time interval of 1 minute is sufficient to minimize the stochastic noise. The integration time must be increased by a factor of 2 or 4, if the space resolution is increased to 0.5 m or 0.25 m. For a large fiber length (>8 km), the optical absorption in the fiber decreases the available space and time resolution.

The fiber optic temperature sensing system operates without electronic circuits along the fiber.

FIELD EXPERIMENTS

The device used for fiber optic temperature measurements includes the transmitting and receiving unit ($450 \times 320 \times 340$ mm; total weight 20 kg), a portable computer for control and data analysis and the fiber optic cable. The fiber optic cable used for the field experiments consisted of a plastic-coated, high-grade steel tubule with a diameter of 2 mm and 5 optical fibers. The total diameter of the cable was 7 mm. The sensing cable can be installed in any configuration (simple cable, loop, coil, meander). For temperature measurements in boreholes, a loop configuration is used.

Figure 1 shows the results of comparison measurements using the fiber optic temperature method and a high precision standard logging tool. The measurements were performed in a

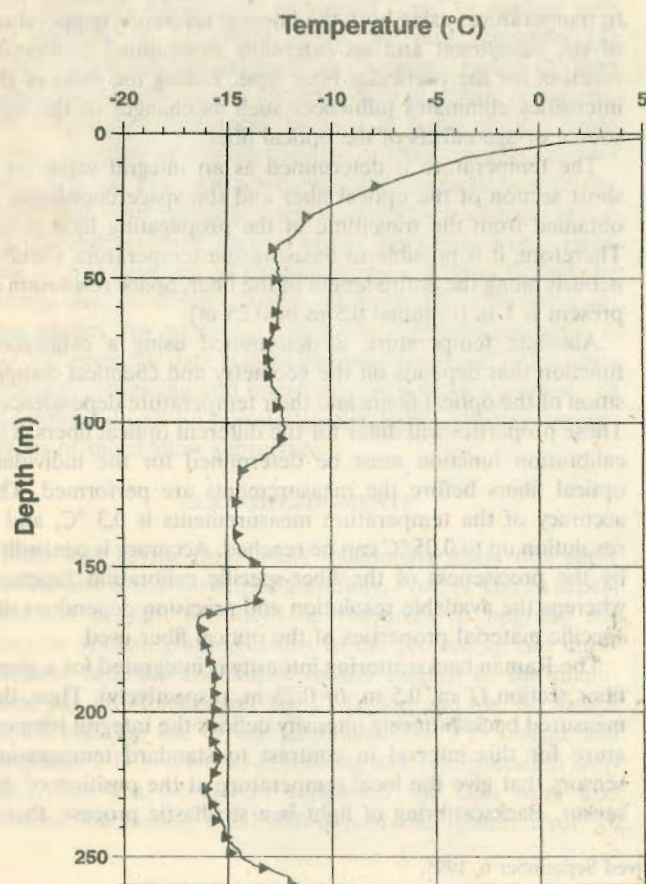


FIG. 1. Comparison between fiber-optic temperature measurements (full line) and standard thermal logging (triangles) in a monitoring well of a freezing shaft.

monitoring well of a freezing shaft with very stable temperature conditions. The temperature varied between 5°C and -16°C . The triangles give the temperature at selected depth points measured by the standard high precision borehole logging tool. Both curves fit well within a 0.1 to 0.2°C temperature range.

In many boreholes, we studied the temperature resolution of the fiber optic system. As an example, Figure 2 shows the results for a 50 m deep hydrogeological well. The temperature depth curve represents the measured unsmoothed and unfiltered data. The noise is on the order of 0.02°C . Thus, temperature anomalies greater than 0.05°C can be well detected. The temperature maximum between 15 m and 35 m is caused by contaminated groundwater.

Figure 3 gives the results for a 50-m deep borehole that penetrates a dump in a German lignite area. For the temperature scale used, the courses of the temperature-depth curve are very smooth. The measurements show that the temperature distribution can be well reproduced. The temperature changes in the uppermost part of the well are caused by the seasonal temperature variations. The temperature maximum at a depth of about 11 m is caused by exothermal reaction (both organic and anorganic) in the dump material.

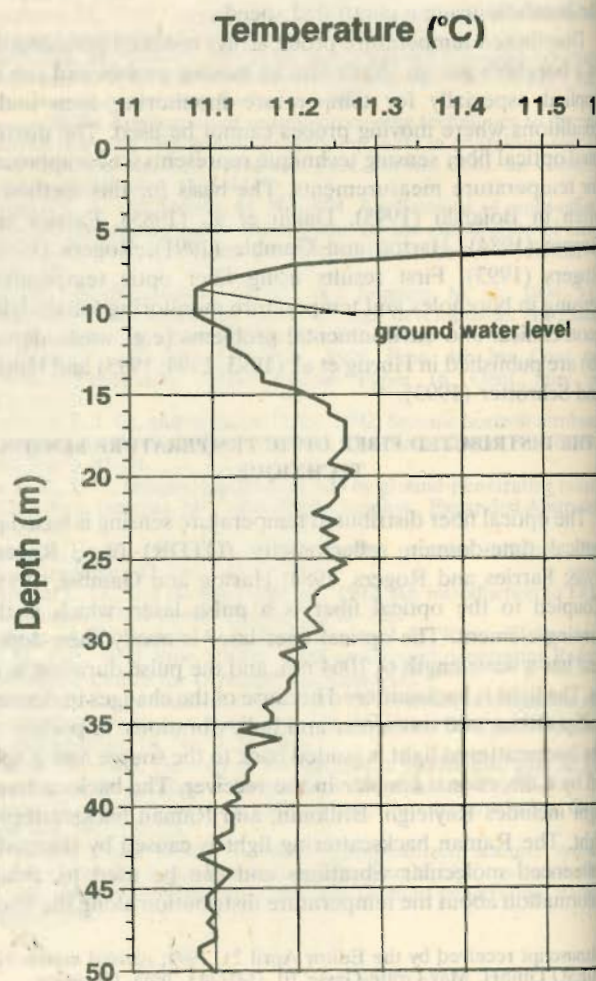


FIG. 2. Temperature resolution of the fiber-optic system installed in a hydrogeological well for monitoring the contamination of groundwater.

Depth (m)

FIG. 3. Fiber optic temperature measurements in a 50-m deep borehole penetrating a dump in a German lignite area. The temperature distribution can be well reproduced. The temperature changes in the uppermost part of the well are caused by the seasonal temperature variations. The temperature maximum at a depth of about 11 m is caused by exothermal reaction (both organic and anorganic) in the dump material.

Figure 4 shows the results of a fiber optic temperature monitoring cable was used to monitor the temperature distribution between the dump and the groundwater. The temperature distribution is very smooth. The temperature changes in the uppermost part of the well are caused by the seasonal temperature variations. The temperature maximum at a depth of about 11 m is caused by exothermal reaction (both organic and anorganic) in the dump material.

A fiber optic temperature monitoring cable was used to monitor the temperature distribution between the dump and the groundwater. The temperature distribution is very smooth. The temperature changes in the uppermost part of the well are caused by the seasonal temperature variations. The temperature maximum at a depth of about 11 m is caused by exothermal reaction (both organic and anorganic) in the dump material.

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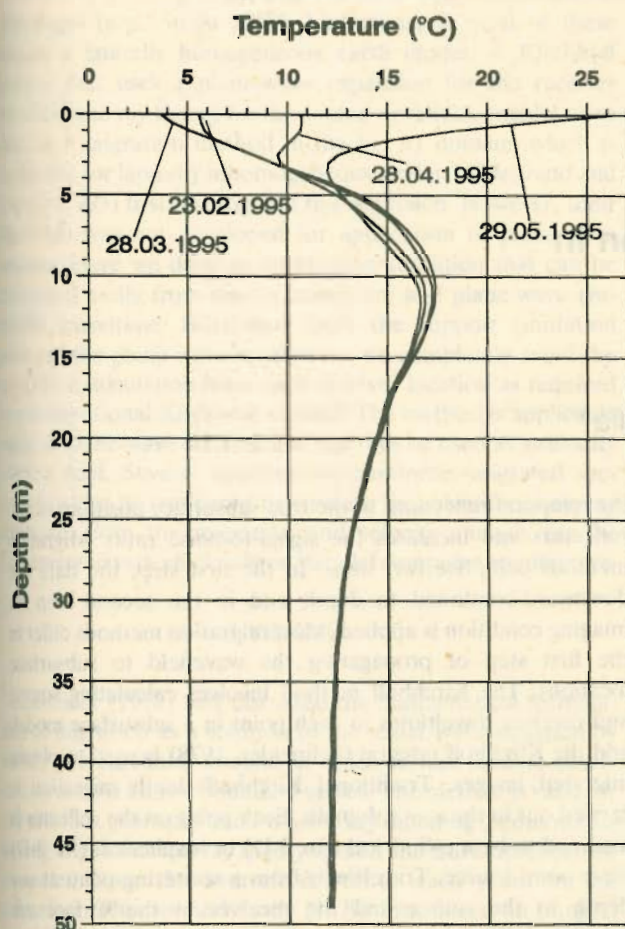


FIG. 3. Fiber-optic temperature measurements in a borehole penetrating a lignite dump. The temperature changes in the upper few meters are caused by seasonal effects.

Figure 4 shows the capability of the fiber optic system to monitor underground gas storages. The fiber optic sensing cable was permanently installed in the narrow (2 cm) annulus between the casing and the tubings. The figure gives the temperature changes with time after stopping the extraction of gas from a deep well and pumping into an underground gas storage reservoir. The first measurement was done immediately after stopping the gas extraction. From these data the formation temperature was determined along the whole borehole section.

CONCLUSIONS

A fiber optic temperature sensing technique can be used under field conditions. There is a good reproducibility of the data, long-term and short-term temperature changes can be detected easily, and there is good fitting between standard thermal measurements in boreholes and fiber optic measurements. It is of special advantage that the fiber optic sensing cable can be installed permanently even under conditions where standard thermal borehole probes cannot be used.

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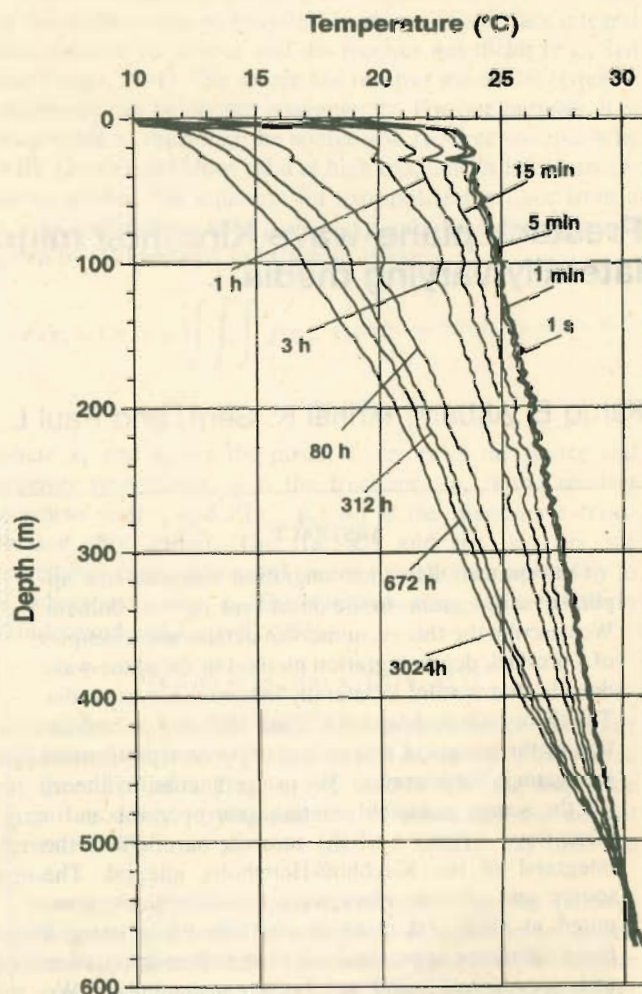


FIG. 4. Fiber-optic temperature measurements in a deep production well of an underground gas storage. The measurements show the capability of the system to obtain short-term (seconds to hours) and long-term (days to months) temperature changes. The numbers give the time after stopping the extraction of gas from the underground storage.