Differential Thermal Fiber Optic Sensors: A New Approach to Distributed Soil Moisture Monitoring for Landfill Covers and Barriers

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Introduction

The current state of monitoring approaches is described in several sources such as Wilson and others (1994) and Scanlon and others (1997). Any monitoring system such as proposed for the Mixed Waste Landfill (MWL) at Sandia National Laboratories, Albuquerque, NM, or landfills in general face several significant challenges. (1) The monitoring system must be effective in that it determines performance accurately (e.g., minimize false negatives and positives. (2) Any monitoring system must be cost effective. (3) The monitoring system must be durable with suitable longevity (e.g., 30+yrs.).

Differential Thermal Fiber Optic Method

To support the Mixed Waste Landfill, we have designed a soil moisture monitoring system based on a commercial differential-thermal optical fiber system used in oil and geothermal wells. This fiber-optic system will be used in conjunction with a baseline system of monitoring wells and neutron moisture logging boreholes. The DOE ASTD program facilitated the incorporation of this distributed moisture sensor system. The optical fiber for landfill monitoring consists of a continuous line of optical fiber and electrical conductor (see Figure 1, 2, 3), which is emplaced along horizontal layers in the landfill cover and a mobile differential thermal monitoring system, which can be used as multiple sites. As the water content of a soil increases so does the thermal conductivity. When constant power is dissipated from a line heat source (in this case electric current through stainless steel tubing), the temperature increase near the heat source will depend on the thermal conductivity of the material surrounding the heater. This method is similar to electrical thermistor-based methods (Campbell 299 Soil Water Potential Probe). The optical fiber system was calibrated to the expected ranges of soil moistures in a field test adjacent to the MWL.

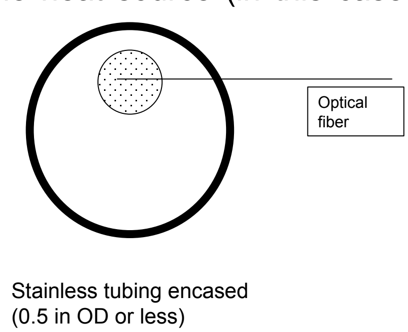

Figure 1: Cross-section of Bundled Optical Fiber and Electrical Conductor

Differential thermal fiber-optic systems are used in industrial, oil field and geothermal applications in the United States through companies such as Pruett. These systems are both intrinsic (sensors based on environmental effects on the fiber itself) and distributed (based a continuous length of fiber up to kilometers in length and taking advantage of the propagation delays of light traveling through the fiber that can be related to distance along the fiber). Measurement accuracy is +/- 1^{o}C with resolution of

**Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000* about <1 m over lengths up to 10km. The optical fiber sensor is placed continuously within stainless steel tubing. These bundled cables can be placed horizontally between landfill layers. The physical basis of this method is that measurement of the ratio of Stokes and anti-Stokes back-scatter of light in a fiber provide an absolute indication of the temperature of the surrounding medium regardless of light intensity, launch conditions, fiber geometry and materials. Raman Distributed Temperature Systems (DTS) are now well-established practical sensors with applications to electrical machines, cables and transformers, location of fires, and sensing of industrial plants.

Deployment:

Bundled optical fiber and stainless steel tubing can be placed horizontally within lifts in an engineered landfill cover. For the MWL, a 2.6 acre landfill, and in general, the optical fiber is placed in an individual lift as a grid with 10 m horizontal spacing between grid lines and 5 m radius turns at the end of the lines at the lift boundary. The MWL will deploy bundled optical fiber and stainless steel tubing in two lifts. The first grid will be placed in the prepared subgrade surface. To achieve redundancy and increased spatial resolution, additional optical fiber grids will be placed orthogonal to the first in subsequent lifts, 30–45 cm above the initial deployment (see figures 2 and 3).

Costs of Deployment:

- Optical Fiber Sensors and Stainless Steel Tubing: (Cost <$5/linear meter).
- $5000 per acre (double layer system) and $2500 per acre (single layer system)

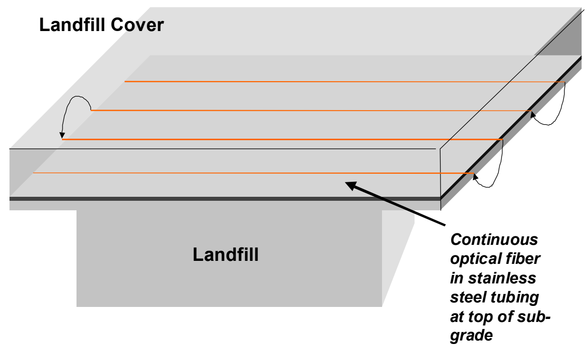

Figure 2: Continuous Fiber Optic Sensor Placed on Top of Landfill Subgrade

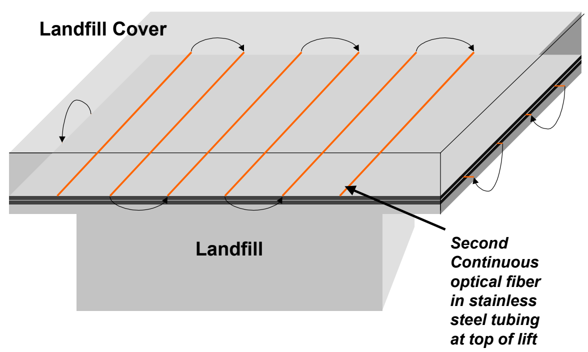

Figure 3: Continuous Fiber Optic Sensor Placed in Lift 30-40 cm above subgrade

Field Implementation

In December 2000, measurements were performed to quantify the thermal response of the fiber-optic moisture sensor system to a certain soil moisture content. This experiment was a follow-up to earlier measurements that qualitatively demonstrated the viability of this method to detect moisture penetration essentially anywhere below the surface of a landfill. For the December implementation, six parallel pits were excavated adjacent to the MWL. Soil of various moisture content (0.2. 7.5, 8.1, 10, 13, and 16 weight % dry volume) were poured into each of six pits about 15' x 3' x 3'. The values for moisture content were obtained by sampling the soil prior to emplacement in each pit, weighing each sample, heating the soil to drive off the moisture, and re-weighing the dry soil. A standard 50/125 micron graded index fiber, used for the distributed temperature measurements, was threaded through a stainless steel tube, having a

.100" I.D. and a .160" O.D. The tube served both as a protective enclosure and an electrical heater. The fiber-tube combination led from the DTS system to pit 6, centered within the pit as closely as possible. After it emerged from the other side of pit 6, it was fed successively into the other pits in a similar manner. At the far end, the excess tubing was rolled onto a large spool. A gasoline-powered generator, supplying 120 V AC, was the power source for these experiments, which is shown in figure 4, connected so as to heat pits 3-6. In all cases, it supplied about 14.5 amps of heater current. Previous measurements confirmed linear scaling with electrical power.

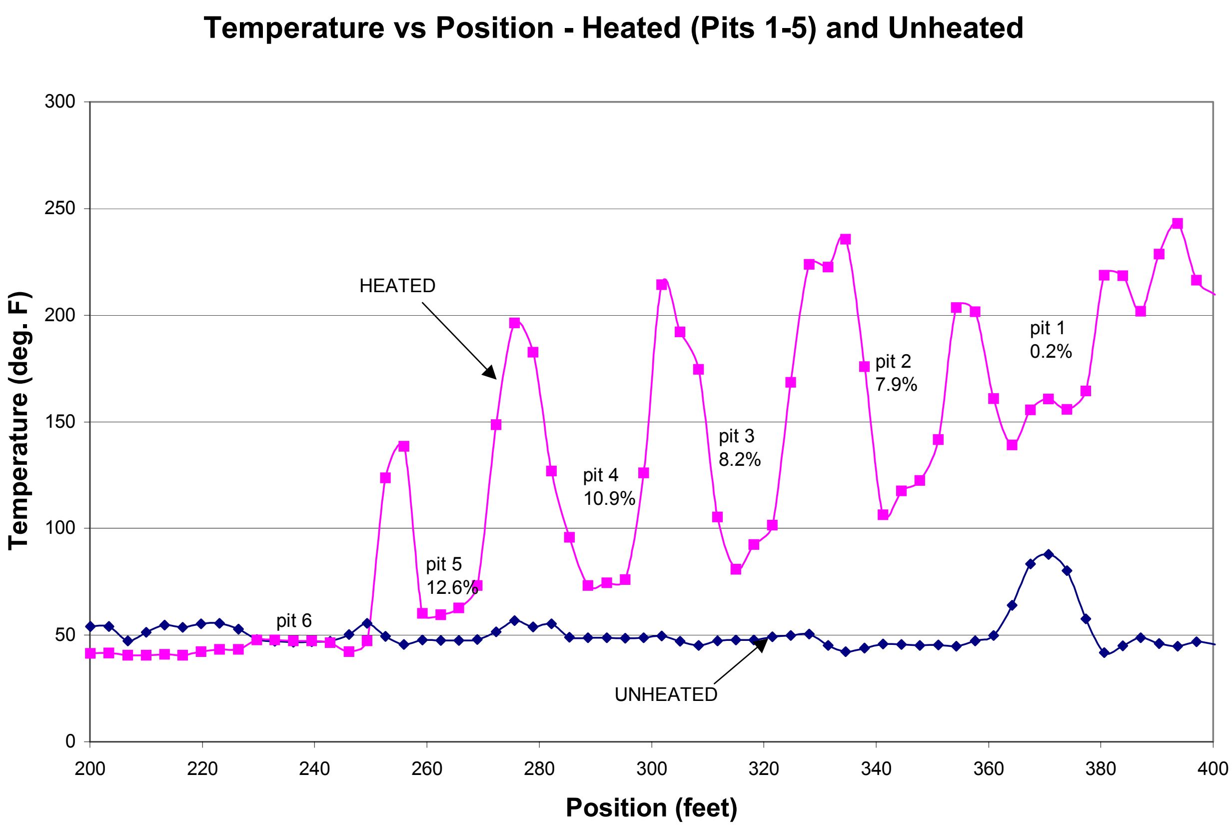

Figure 4: Temperature Rise Measured by DTS System in Heated Pits 1 through 5 (6 unheated), each with different moisture contents

Discussion of Implementation:

The differential thermal response at known heat flux for each heated pit with a different moisture content is shown in Figure 4. The figure also shows the lateral resolution of the sensor system of +/- 1m along the fiber length. From the heat rise, thermal conductivity and diffusivity are calculated. These parameters are correlated to the moisture content and used in calibrating the system. The question remains regarding the resolution of the system in terms of moisture content; e.g., whether the moisture content of the soils can be determined within +/- 1%, +/- 2%, or +/- 3%. In this implementation we did not control the soil density or porosity through compaction as would be done in MWL. Variations in porosity and density will add uncertainty.