# Field Test of a New Method for Determining Soil Formation Thermal Conductivity and Borehole Resistance

**John A. Shonder**
*Member ASHRAE*

**James V. Beck, Ph.D., P.E.**

## ABSTRACT

*A new method of determining soil thermal properties from in-situ tests has been developed. Based on a one-dimensional numerical heat transfer model, the method uses parameter estimation techniques to determine soil thermal conductivity and borehole resistance from field-collected data. This paper presents the results of analysis of data from three tests performed in Lincoln, Nebraska, in order to validate the method. The one-dimensional method was found to agree well with line source and cylindrical source thermal conductivity estimates derived from the same data sets. The method was also able to measure the resistance of the three borehole heat exchangers. The measured resistances lie within the expected range of resistances for the given grouting materials. A further benefit of our method is its relative insensitivity to changes in power input caused by short-term voltage fluctuations.*

## INTRODUCTION

The design of a ground heat exchanger for a geothermal heat pump system requires, at a minimum, the operating characteristics of the heat pumps, estimates of annual and peak block loads for the building, and information about the properties of the heat exchanger, such as the size of the u-tubes, the grouting material, etc. The design also requires some knowledge of the thermal properties of the soil, namely, thermal conductivity, thermal diffusivity, and undisturbed soil temperature. In the case of a vertical borehole heat exchanger (BHEx) these properties generally vary with depth, and what is usually sought are effective or average thermal properties over the length of the borehole. When the cost of doing so can be justified, these properties are measured in an in-situ experiment: a test well is drilled to a depth on the same order as the expected depth of the heat pump heat exchangers; a u-tube heat exchanger is inserted and the borehole is grouted according to applicable state and local regulations; water is heated and pumped through the u-tube; and the inlet and outlet water temperatures are measured as a function of time. Data on inlet and outlet temperatures, power input to the heater and pump, and water flow rate are collected at regular intervals—typically one to fifteen minutes—for the duration of the experiment, which may be as long as 60 hours.

Two common methods for determining soil thermal properties from such measurements are the line source method (Morgensen 1983) and the cylinder source method (Kavanaugh and Rafferty 1997). Both are based on analytical solutions to the classical heat conduction problem of an infinitely long heat source in an infinite homogeneous medium. Although there are some differences in the way the two methods are implemented, the only difference between the two models is whether the heat source is considered to be a line or a cylinder. In both methods, power input to the water loop is assumed to be constant. This assumption can result in inaccurate conductivity measurements in cases where the voltage (either from the power line or from a portable generator) varies significantly. Another drawback to both methods is that they provide no information about the borehole resistance.

In a previous paper (Shonder et al. 1999), the authors presented a new method for determining thermal properties from short-term in-situ tests. Based on numerical solutions to the heat conduction equation in cylindrical coordinates, the method includes the effect of grout inside the borehole, allowing borehole resistance to be estimated in addition to soil thermal conductivity. This is significant because after soil thermal conductivity, borehole resistance is the most important param-

**John A. Shonder** is a project manager at Oak Ridge National Laboratory, Oak Ridge, Tennessee. **James V. Beck** is professor emeritus, Michigan State University, East Lansing.

eter in the design of a vertical BHEx. In the absence of a method to measure borehole resistance, this parameter is usually calculated based on assumed thermal properties of the grout and u-tube piping and the assumed spacing between the u-tube pipes (which some authors refer to as the shank spacing). Since the shank spacing is never accurately known once the u-tube goes into the ground, and the thermal properties of the grout are rarely measured on site, a borehole resistance calculated in this manner may be very different from the actual value. Measuring borehole resistance at the site will reduce this uncertainty.

Another benefit to the method we have developed is that because the heat conduction problem is solved numerically rather than analytically, it is not necessary to assume constant heat input to the water loop. The heat transfer model uses the field-measured power input data rather than an average value. This feature is particularly useful in situations where unstable voltage (either from the power line or from the output of a portable generator) causes the power input to the water loop to vary over time. Because the line source and cylinder source methods both assume constant power input, their estimates of soil thermal properties tend to be inaccurate when the power input varies significantly.

A further benefit of our method is that it provides statistical estimates of the confidence intervals for the parameters estimated. Other methods of determining effective thermal properties have traditionally reported only the parameter value itself, with no estimate of accuracy. Obviously, the accuracy of a particular parameter value determined from a field experiment depends upon the accuracy of the data collection equipment, the length of the experiment, and other factors. The model we propose uses a statistical technique to provide a quantitative estimate of the confidence interval for the parameters measured.

## OBJECTIVES

In the previous paper (Shonder et al. 1999), we showed that our method could accurately predict the thermal conductivity of a known material (namely, moist sand) given data collected in an experiment on a laboratory test rig. The objective of this paper is to present the results of analyses of data from a total of three in-situ tests carried out at two elementary schools (Maxey and Campbell) in Lincoln, Nebraska, in 1998 and 1999. At the Campbell school, two boreholes were drilled with the same diameter and the same approximate depth, about 60 feet apart. An additional borehole was drilled at Maxey. Three different grouts were used: thermal grout 85, fine sand, and soil cuttings. The tests were blind in that the driller did not inform us of which grout was used in which borehole. The parameters of each test are presented in Table 1.

Data from in-situ field tests provide a more rigorous test of a properties measurement technique than data from laboratory experiments, but a field test has the drawback that the true thermal conductivity of the soil formation and borehole resistance at the site are generally unknown. For the Maxey school

**TABLE 1**
**Parameters of Three *In-Situ* Thermal Properties Tests Performed in Lincoln, Nebr.**

| Test Designation | Date Performed | Borehole Depth (ft) | Average Soil Temperature (°F) | Average Power Input (W) |
|---|---|---|---|---|
| Maxey | 09/19/98 | 245 | 55.7 | 2609 |
| Campbell #1 | 09/15/98 | 245 | 54.8 | 2595 |
| Campbell #2 | 10/08/98 | 244 | 55.6 | 2606 |

site, however, analysis of one year of data from the operating borefield provided an estimate for the effective soil thermal conductivity that could be compared with the measured values.

One objective of the in-situ field tests then was to determine whether the soil conductivity estimates for the two boreholes at the Campbell school agreed with each other; and whether the conductivity estimate at the Maxey school agreed with the thermal conductivity estimate obtained from analysis of the operating data. Another objective was to determine whether the numerical method could identify the different borehole resistances resulting from the different grouts.

For purposes of comparison, the three data sets were also analyzed using the line source and cylinder source methods.

## THEORETICAL BACKGROUND

### Heat Transfer Model

Figure 1 represents a typical in-situ field test to determine the thermal properties of the soil formation. The borehole, of radius $r_b$, is drilled to depth $L$. A u-tube consisting of inlet and outlet pipes of radius $r_u$ separated by a distance $D$ is placed inside the borehole. The borehole is then usually filled with a

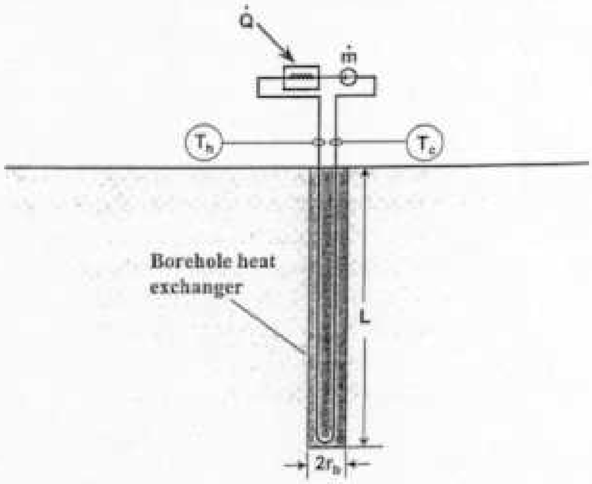


*Figure 1 Schematic of field test to measure soil formation thermal properties.*

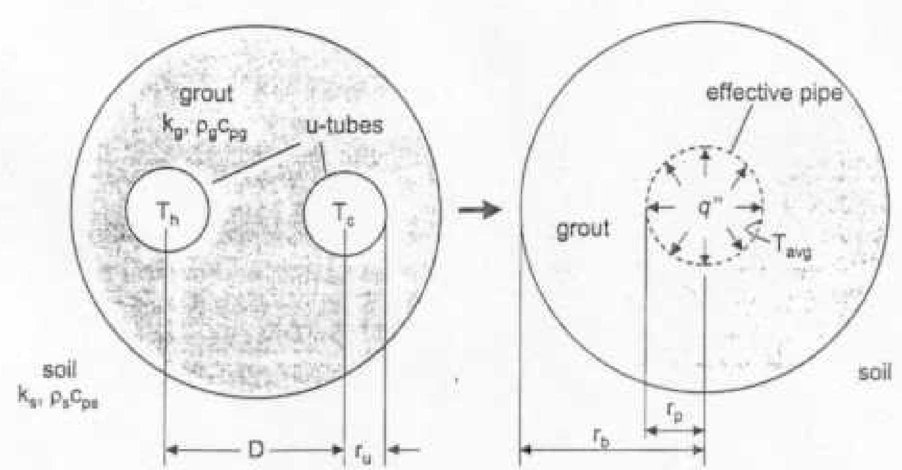


***Figure 2*** *Cross section through borehole. To make the problem one-dimensional, the two u-tube pipes are replaced by a single pipe with an effective radius.*

grouting material for groundwater protection. In general, the thermal conductivity ($k_g$) and volumetric specific heat ($\rho c_g$) of the grout are different from the thermal conductivity and volumetric specific heat of the surrounding soil, $k_s$ and $\rho c_s$, respectively.

The left-hand side of Figure 2 represents a cross section through the borehole heat exchanger of Figure 1. Water in one leg of the u-tube is at temperature $T_h$, and water in the other leg is at temperature $T_c$. These temperatures, as well as the soil thermal properties, are a function of depth. The thermal properties of the soil and grout can also vary with depth due to compaction and other factors.

In order to simplify the problem, the two u-tube pipes are then replaced by a single effective pipe of radius $r_p$, as shown in the right-hand side of Figure 2. The water temperature in this effective pipe is assumed to be the average of $T_h$ and $T_c$ (this means that the model does not directly account for the energy transported by the fluid in the axial direction). If $r_p$ is assumed to be equal to $r_u\sqrt{2}$, then the effective pipe will have the same surface area as the two u-tube pipes. With these simplifying assumptions, the problem becomes one-dimensional in the radial direction. Heat conduction within the grout is described by

$$\frac{k_g}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_g}{\partial r}\right) = (\rho c)_g\frac{\partial T_g}{\partial t}, r_p < r < r_b \quad (1)$$

and heat conduction within the surrounding soil is described by

$$\frac{k_s}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_s}{\partial r}\right) = (\rho c)_s\frac{\partial T_s}{\partial t}, r_b < r < \infty . \quad (2)$$

$T_g$ and $T_s$ are also functions of depth, but, as with the line source and cylinder source models, we assume these are average temperatures over the length of the borehole. The properties $k_s$, $k_g$, $\rho c_s$, and $\rho c_g$ then become the average thermal properties from top to bottom.

The differential Equations 1 and 2 are coupled at the borehole wall ($r = r_b$), where the temperature and heat flux in the grout must be equal to the temperature and heat flux in the soil. A heat flux boundary condition is assumed at $r_p$; the heat input to the u-tube is measured at regular intervals during the in-situ field test, and the power input per unit area $q''$ is found by dividing the measured power by the surface area of the effective pipe (circumference times length). The initial condition comes from assuming that at time zero the entire system is at the undisturbed soil temperature $T_\infty$. Note that $T_\infty$ is not equal to the deep earth temperature: it is the average temperature of the soil from the top to the bottom of the heat exchanger.

The model described above includes just two materials—the grout and the surrounding soil—but since the conduction equations are solved numerically, it is not difficult to include the effects of other materials in the model. For example, an equation similar to Equations 1 and 2 can be added to include the effect of heat conduction through the u-tube pipes and the capacitance of the pipe material. We have also attempted to model flow effects inside the pipe by including a thin film with additional capacitance on the inside of the pipe. These more complicated models offer some advantages in certain cases, but in general we have obtained very good results including just the soil and the grout.

In certain cases it may be possible to solve the system of Equations 1 and 2 analytically, but in practice it is more useful to employ a numerical technique. In order to estimate parameter values from field data, we solve the direct problem numerically using a finite difference grid and a Crank-Nicolson integration scheme.

## Parameter Estimation Technique

The problem described by Equations 1 and 2 (with the associated boundary and initial conditions) cannot be solved using classical techniques because not all of the relevant parameters (such as the soil and grout thermal conductivities) are known. However, some extra information is available that allows these and other parameters to be estimated—in addition to the power input, the inlet and outlet water temperatures are measured in the field. The average of these two temperatures is approximately equal to the average temperature of water over the length of the u-tube, which in this simplified model corresponds to the temperature at the inner surface of the effective pipe. Hence, two conditions are known at the inner surface of the effective pipe: heat flux and temperature as a function of time. For direct problems, only one condition can be used, so there is excess information. This information can be used to estimate the value of one or more of the parameters. Let these parameters be designated by $\beta_1, \beta_2, ..., \beta_n$. Given some initial guesses for the parameters, the field-measured heat flux history is imposed at $r_p$, and Equations 1 and 2 are solved numerically to determine the temperature $T_p(t)$ at the effective pipe radius $r_p$. If $T_{avg}(t)$ is the average of the field-measured inlet and outlet temperatures as a function of time, then we can define a sum-of-squared errors function as follows:

$$S(\beta_1, \beta_2, ..., \beta_n) = \sum_m (T_{avg}(t) - T_p(t))^2 , \tag{3}$$

where $m$ is the number of data points available. The objective is then to determine the values of $\beta_1, \beta_2, ..., \beta_n$ that minimize $S$.

The model given by Equations 1 and 2 contains a total of eight parameters: the thermal conductivities of the soil and grout, the volumetric heat capacities of the soil and grout, the borehole radius, the effective pipe radius, the borehole depth, and the far-field temperature. In general it will not be possible to estimate all of these parameters with a single experiment, as some are dependent on others. Based on our experience with the model, the two parameters that can be most reliably estimated are soil thermal conductivity and grout thermal conductivity. However, because the two u-tube pipes are combined into one, the model's estimate of grout conductivity is an effective value that depends on shank spacing. For this reason, we find it more convenient to report borehole resistance, which is defined as the resistance to heat transfer between the water and the borehole wall. This parameter is required as an input by several BHEx design programs. Given the effective grout thermal conductivity estimate $k_g$, borehole resistance $R_b$ is calculated by the following formula:

$$R_b = \frac{1}{2\pi k_g} \ln\left(\frac{r_b}{r_p}\right) \tag{4}$$

Because only two parameters are estimated, the values of six other parameters must be given as inputs. The values assumed for the input parameters have an effect on the estimated soil thermal conductivity and borehole resistance. In addition to the error associated with the input parameters, there is statistical error associated with the parameter estimates. With $S_{min}$ defined as the minimum sum of squared errors, it can be shown (Beck and Arnold 1976) that the function

$$\frac{(S(\beta_1, \beta_2, ..., \beta_n) - S_{min})/n}{S_{min}/(m-n)} \tag{5}$$

is approximately distributed according to the $F_{1-\alpha}(n,m-n)$ statistic. This provides a basis for determining approximate confidence regions for the parameter estimates.

## DESCRIPTION OF TESTS

For each test, a 4.25-inch diameter borehole was drilled to an approximate depth of 245 feet. Nominal 1-inch SDR-11 u-tube pipe was inserted, and the boreholes were grouted with either thermal grout or fine sand or not grouted at all. In general, the boreholes were drilled about 75 feet from the active borefield. The two boreholes at Campbell school were approximately 60 feet apart.

The equipment used to perform the in-situ tests has been described by Austin (1998). Housed in a trailer that is towed to the site, the apparatus includes two circulating pumps, a flowmeter, and three in-line water heaters, all powered by a portable electric generator. A watt transducer measures the power consumption of the heaters and circulating pumps, and the inlet and outlet temperatures are measured using two high-accuracy thermistors immersed in the flow. The water flow rate, total power input, and inlet and outlet temperature were logged at 15-minute intervals.

Before connecting the u-tube to the test apparatus, a thermistor was inserted into one end of the u-tube and the water temperature was measured at 10-foot intervals. The average undisturbed soil temperature at each site was assumed to be the average of these measurements. The actual length of the installed heat exchanger was also determined from these measurements.

Figures 3a and 3b present the power input and average water temperature as a function of time for the two experiments at the Campbell school, and Figure 3c presents the data for the experiment at the Maxey school. The three tests are unremarkable except for the test on the second well at Campbell. Just noticeable in Figure 3b are two jumps in average temperature at 27.5 hours and at 33.5 hours. Beginning at 27.5 hours, the water flow rate through the heat exchanger dropped by about 15%, possibly due to the presence of air in the heat exchanger. This does not appear to have affected the accuracy of the parameter estimates.

## TEST RESULTS

One indication of a mode's reliability is its ability to predict the temperature rise of the water as a function of time. Although the one-dimensional numerical model includes a number of simplifications, it is able to predict the average water temperature in the heat exchanger with good accuracy. Figures 4a through 4c present plots of the residuals between the measured and predicted average temperature as a function of time. It is seen that for times after about 30 minutes, the residuals are quite small, on the order of 0.17°F. The model did not accurately follow the system behavior during the sharp

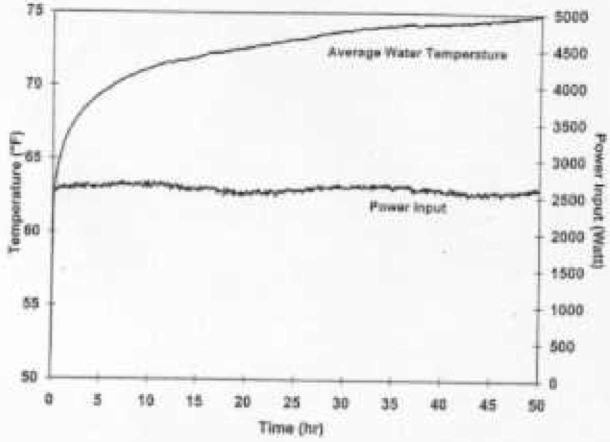


*Figure 3a* Average water temperature and power input, Campbell elementary school test #1.

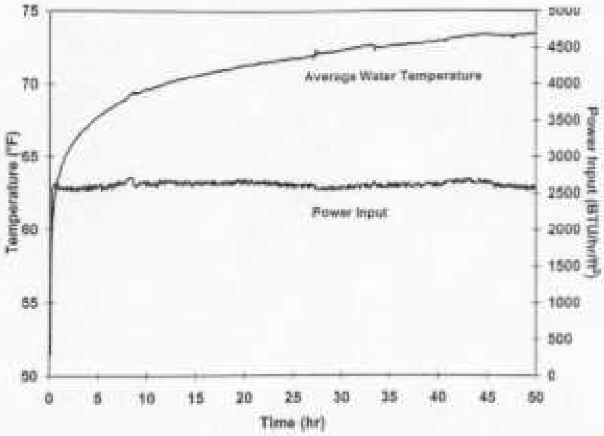


*Figure 3b* Average water temperature and power input, Campbell elementary school test #2.

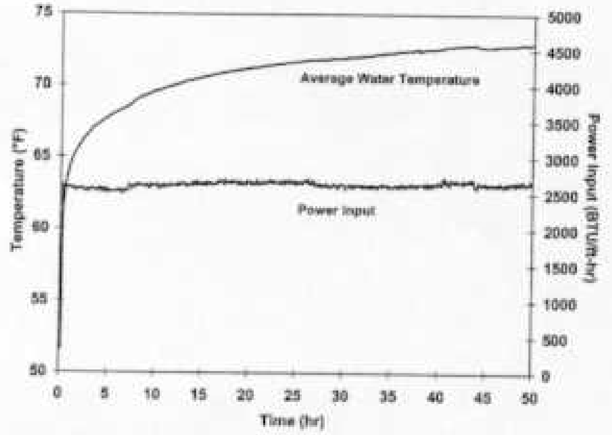


*Figure 3c* Average water temperature and power input, Maxey elementary school test #1.

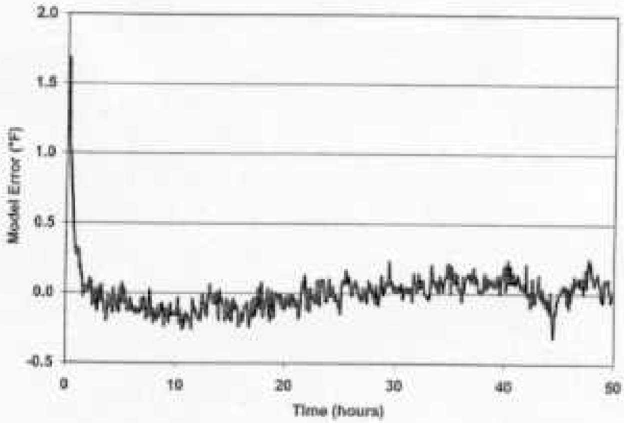


*Figure 4a* Model error ($T_{measured} - T_{calculated}$) for Campbell elementary school test #1.

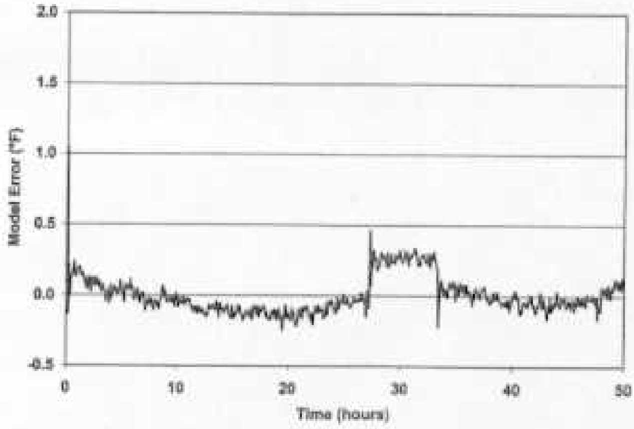


*Figure 4b* Model error ($T_{measured} - T_{calculated}$) for Campbell elementary school test #2.

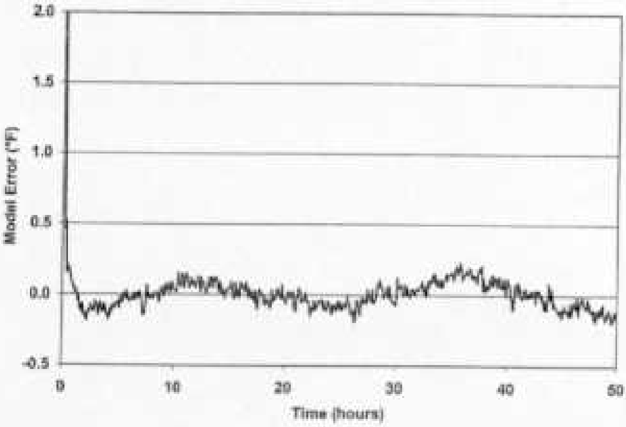


*Figure 4c* Model error ($T_{measured} - T_{calculated}$) for Maxey elementary school test.

**TABLE 2**
**Results of Soil Thermal Conductivity and Borehole Resistance Estimates from Three *In-Situ* Tests**

| Test Designation | Soil Thermal Conductivity (Btu/hr·ft·°F) | Borehole Resistance (hr·ft·°F/Btu) | Grout Material |
|---|---|---|---|
| Maxey | 1.358±0.02 | 0.185±0.003 | thermal grout 85 |
| Campbell #1 | 1.204±0.043 | 0.226±0.015 | soil cuttings |
| Campbell #2 | 1.188±0.028 | 0.158±0.008 | fine sand |

decrease in flow rate that occurred during the second Campbell experiment, but again, this did not seem to affect the property estimates in that case.

## Thermal Conductivity

Table 2 presents the estimates for soil thermal conductivity and borehole resistance. There is good agreement between the two thermal conductivity measurements at each site. The value of 1.36 obtained for the Maxey test agrees well with the value of 1.3 obtained from analysis of one year's operating data from the borefield (Thornton 1999). The average of the two Campbell measurements is 1.20 Btu/h·ft·°F, and the two tests were consistent with one another (the thermal conductivity estimates differ by only 2%), so it appears there is a definite difference between soil thermal conductivity at the two schools.

## Borehole Resistance

Although Table 2 indicates a definite difference between the borehole resistances measured at each site, it is difficult to say whether the measured borehole resistances correspond to the expected values. For a given u-tube size, borehole resistance is a function of grout thermal conductivity and shank spacing. Spitler (1996) has developed a spreadsheet program that is useful for calculating borehole resistance given shank spacing and grout conductivity. As an example, for a 1-inch SDR-11 u-tube grouted with thermal grout 85 (nominal thermal conductivity of 0.85 Btu/h·ft·°F) the spreadsheet calculates borehole resistances between 0.176 and 0.313, depending on the shank spacing assumed. The measured borehole resistance for heat exchanger #1 at Maxey school does lie within this range, and the fact that it is closer to the lower limit may indicate that the u-tube legs are close to the borehole wall.

Determining the borehole resistance of the heat exchangers grouted with fine sand is more problematic since the thermal conductivity of sand depends on moisture content. With a nominal value of 1.5 Btu/h·ft·°F for the sand thermal conductivity, the calculated borehole resistance is between 0.139 and 0.237. The measured resistances for Maxey #2 and Campbell #2 are both within these limits, and both are closer to the lower limit that the higher one, indicating again that the u-tube legs may be close to the borehole wall.

**TABLE 3**
**Fifty-Hour Thermal Conductivity Estimates from the One-Dimensional Numerical Method, the Line Source Method, and the Cylinder Source Method**

| Test Designation | Numerical Method | Line Source Method | Cylinder Source Method |
|---|---|---|---|
| Maxey | 1.36 | 1.30 | 1.39 |
| Campbell #1 | 1.20 | 1.24 | 1.19 |
| Campbell #2 | 1.19 | 1.18 | 1.22 |

Heat exchanger #1 at Campbell school was grouted with soil cuttings. If the grout is assumed to have the same thermal conductivity as the soil, the calculated borehole resistance would lie between 0.151 and 0.248. The measured borehole resistance does, in fact, lie between these limits, but certainly further experiments would have to be conducted to determine whether borehole resistance can be measured reliably with this method.

## Comparison with Other Analytical Techniques

Table 3 compares the thermal conductivity estimates from the three tests using our method and the values obtained using the line source and cylinder source methods. These are 50-hour estimates. For the line source method, data prior to four hours were ignored. In general, the parameter estimates agree well with the estimates using the line source and cylindrical source methods; the differences are on the order of only 2% to 3%.

In addition to comparing the 50-hour thermal conductivity estimates, it is also informative to examine plots of sequential estimates from the three methods. These plots show, for every time, the estimate of thermal conductivity obtained by using all the data up to that time. A plot of sequential parameter estimates can indicate whether the method is converging to a particular value or whether the estimate changes significantly over time. Sequential plots are also useful for estimating how long the data must be collected in order to obtain an accurate parameter estimate.

Figures 5a-5c present sequential thermal conductivity estimates for the three experiments, from 10 to 50 hours, using the one-dimensional numerical method, the line source method, and the cylinder source method. Data prior to the fourth hour were ignored for the line source analysis, and a volumetric heat capacity of 30 Btu/ft$^3$·°F was assumed for both the one-dimensional numerical method and the cylinder source method. For the two Campbell tests, all three methods converged to within about 5% of their 50-hour values within 24 hours. However, this was not the case with the Maxey test. Although the estimates from the three methods agree among each other, Figure 5c suggests that had the measurements continued beyond 50 hours, the thermal conductivity estimate at the Maxey site would have continued to rise. One possibility is that there is modest groundwater flow at the site. Conditions such as these, which vary from site to site, make it difficult to

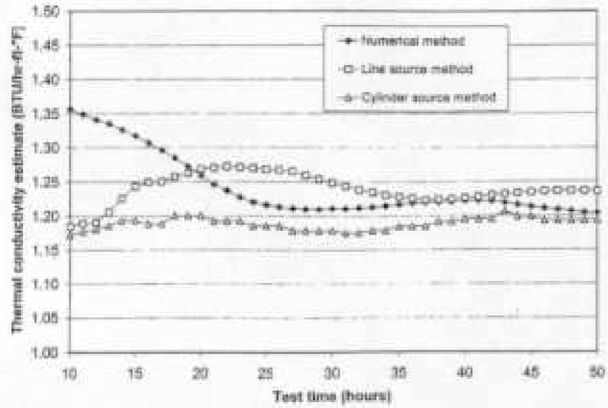


*Figure 5a Campbell school test #1. Sequential thermal conductivity estimates using the proposed numerical method, the line source method, and the cylindrical source method.*

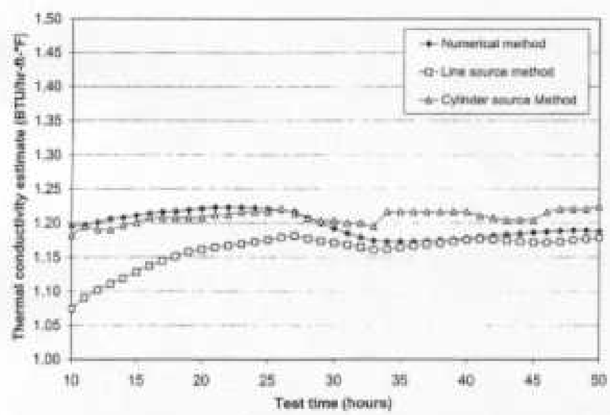


*Figure 5b Campbell school test #2. Sequential thermal conductivity estimates using the proposed numerical method, the line source method, and the cylindrical source method.*

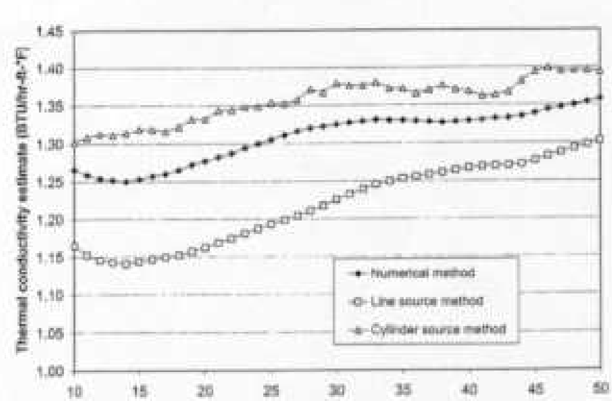


*Figure 5c Maxey school test. Sequential thermal conductivity estimates using the proposed numerical method, the line source method, and the cylindrical source method.*

make general recommendations as to how long thermal conductivity tests should proceed.

The comparisons indicate that there is little difference between the thermal conductivity estimates derived from our method and the line source method. However, the stable power supply and otherwise good quality of the three data sets tends to mask the usefulness of the method we have developed. Figure 6 presents data from a thermal conductivity test carried out at another site. During this test, the field generator developed mechanical problems (Remund 1999). Based on conversations with field personnel, short-term voltage spikes are not uncommon, even when line power is used in place of a generator. These spikes can cause significant problems if the line source or cylinder source methods are used to estimate thermal conductivity. This is because both methods assume that the power input is constant. The one-dimensional numerical method we have developed does not assume constant power. Because the model is driven with the field-measured power input, voltage spikes cause very little change in the thermal conductivity estimates.

Figure 7 is a plot of sequential thermal conductivity estimates from the data of Figure 6 derived using the line source method, the cylinder source method, and our one-dimensional numerical method. Because the cylinder source method calculates thermal conductivity based only on the measured temperature rise for a particular time, it is much more sensitive to short-term variations in power. For example, between 30 and 33 hours, the cylinder source estimate of thermal conductivity drops by almost 10% due primarily to fluctuations in the power input. The line source method is somewhat less affected by short-term fluctuations because it uses all of the temperature data up to a given time. Nevertheless, the line source method still assumes constant power input, and this can cause abrupt changes in the thermal conductivity estimate. Our one-dimensional numerical method is the most stable of all because it uses all of the power data and all of the temperature data. As shown in Figure 7, the estimate of thermal conduc-

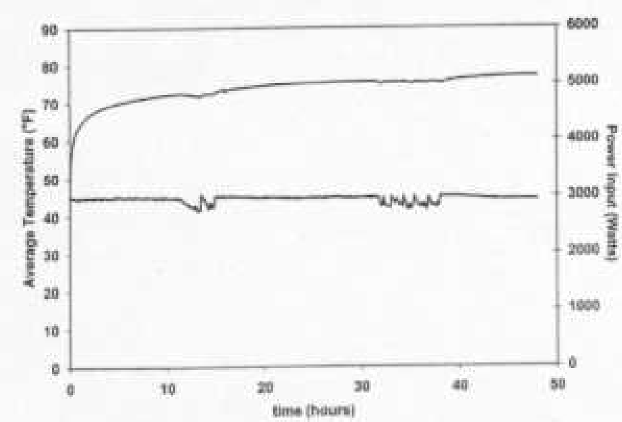


*Figure 6 Temperature and power input vs. time for a case in which the generator developed mechanical problems.*

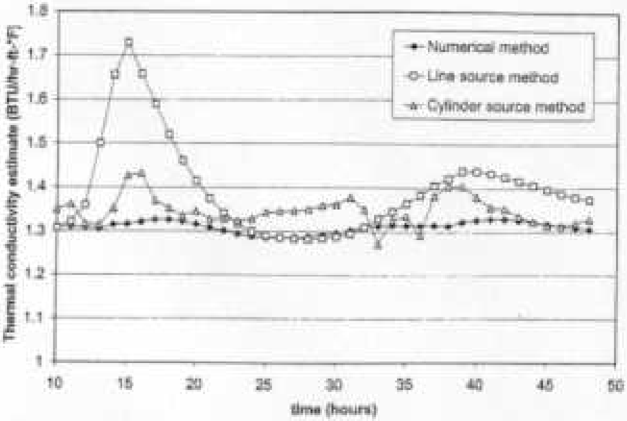


***Figure 7*** *Sequential estimates of soil thermal conductivity from line source, cylinder source, and the proposed numerical method.*

tivity from our method changes by only 1% to 2% over the entire experiment.

## CONCLUSIONS

A new method of determining soil thermal properties from in-situ tests has been developed. Based on a one-dimensional numerical heat transfer model, the method uses parameter estimation techniques to determine soil thermal conductivity and borehole resistance from field-collected data. Tests were performed in Lincoln, Nebraska, in order to validate the method. A total of three borehole heat exchangers were installed, two at Campbell elementary school and one at Maxey elementary school. The thermal conductivity test at Maxey agreed to within 4% with a separate thermal conductivity value for the site derived from one year of operating data from the borefield. The two tests at Campbell agreed with each other to within about 2% but were lower than the values obtained for the Maxey site.

The borehole resistance of the three heat exchangers was also estimated from the field data. The values measured were within the range of borehole resistances calculated for the grout materials, but, because of uncertainty in shank spacing and the actual conductivity of the grout, we recommend that further experiments be performed to determine the reliability, accuracy, and repeatability of the borehole resistance measurements.

The thermal conductivity measurements from our method agree with the values obtained from the line source and cylinder source methods. This is to be expected because the power input was relatively stable during the course of the three experiments. Analysis of a separate data set showed that thermal conductivity estimates from the line source and cylinder source methods are significantly affected by variations in power input, while the thermal conductivity estimate from the method we have developed varied by only about 1% over the course of the experiment.

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## DISCUSSION

**Joel Goss, President, Goss Engineering, Lowell, Oreg.:** Is not the $\Delta t$ used in the tests a critical assumption? Very high flows-low $\Delta t$ have limited exchange between two pipes (L.M.T.D.) and if it's significantly different from ground, measure ground conductivity. Low flows-high $\Delta t$ have significant exchanges between pipe down and pipe up, which means you are measuring a significant apperture loss as well as soil conductivity.

**John A. Shonder:** Since we have not tested the model with data from a low flow experiment, it is difficult to give a definitive answer. Certainly, however, at very low flow rates some of the assumptions we make in the heat transfer model are no longer valid. In these tests, we recommend that the test borehole be as similar to the planned boreholes as possible, e.g., borehole diameter, u-tube size, depth, grouting, etc. This would also include flow rate: the flow rate for the test should be the same as the maximum flow rate per well expected in the application.