RESEARCH SUMMARY – ASHRAE 1118-TRP
"Methods for Determining Soil and Rock Formation Thermal Properties from Field Tests"

A critical need in the design procedure of closed-loop GSHPs, or ground-coupled heat pumps (GCHPs), is an accurate knowledge of soil/rock formation thermal properties. These properties can be estimated in the field by installing a loop of approximately the same size and depth as the heat exchangers planned for the site. Heat is added in a water loop at a constant rate and data is collected. Inverse methods are applied to find thermal conductivity of the formation.

ASHRAE has supported this project to investigate details associated with these tests by collecting and adding scientific information to items currently being debated in this industry. These issues include the length of test, required heat input level and quality, analysis procedures, specifications of test methods, equipment and instrumentation, corrections for deviations from fundamental assumptions, and validation of results.

Objective

The objective of this project is to evaluate the validity of the models, estimate the accuracy and costs of the test methods, and establish a set of recommended practices for field tests to determine soil and rock formation thermal properties at ground-coupled heat pump sites.

Project Scope

The project began with a traditional search in the technical literature followed by written and oral communication with experienced thermal conductivity testers and their clients. An abundant set of test data was provided with some information regarding costs and methods. A series of tests were also conducted at a controlled site to supplement the information. Thermal properties were computed using publicly available software and methods developed specifically for this project. This has permitted comparative analysis, impact of uncertainty resulting from measurement error, variations from fundamental assumptions, test procedures, and unavoidable disturbances to the natural formations.

Summary Conclusions and Recommendations

- Test durations of 36 to 48 hours are recommended. In some cases shorter periods were adequate. However, the recommendation is due to the high frequency of data sets that required longer tests for convergence. Information collected during the project indicates that longer tests do not significantly impact total cost.

- When test data were good there was agreement among several line source methods, the cylindrical heat source method, and numerical methods. The recommendation is to apply multiple analysis methods. Higher levels of confidence will result if agreement is good and further testing and analysis is warranted if agreement is poor. The two numerical methods tested appear to offer no significant advantage over simple line source methods.

- Acceptable power quality can be obtained when the standard deviation $\leq$ 1.5% of average power and the maximum variation (spikes) $\leq$ 10.0% of average power. When the deviations are larger, acceptable results can be obtained if the maximum deviation of the average loop temperature is $\leq$ 0.5°F (0.3°C). The heat rate should be 15 to 25 W/ft (50 to 80 W/m) of bore depth, in order to reproduce the impact of typical loads on actual loops.

- A minimum delay of five days between loop completion and test start-up is recommended in formations that are expected to have low conductivity [< 1.0 Btu/her-ft-°F (1.7 W/m-°C)] and three-days for other formations. If retesting a bore is necessary, the loop temperature should return to within 0.5°F (0.3°C) of the pretest initial ground temperature. This typically corresponds to a 10 to 12-day delay in mid to high conductivity formations and a 14-day delay in low conductivity formations if a complete 48-hour test has been conducted.

- The initial ground temperature measurement should be made at the end of the waiting period by direct insertion of a probe inside a liquid filled ground heat exchanger at three locations representing the average or by the measurement of temperature as the liquid exits the loop during the period immediately following start-up.

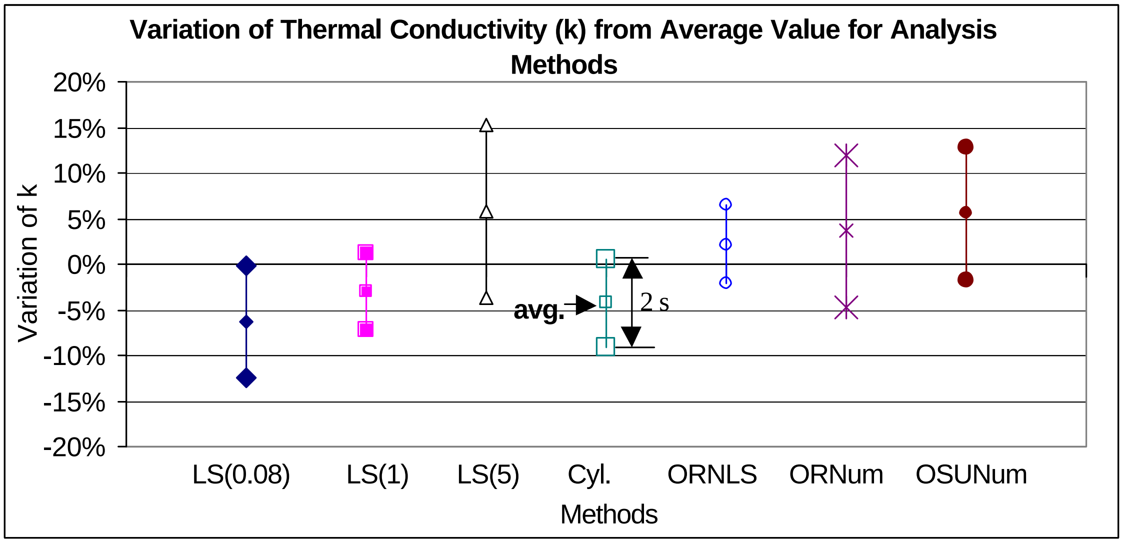
- At a minimum, the measurements required are initial ground, loop inlet, and outlet liquid temperatures [$\pm$ 0.5°F (0.3°C) accuracy], input power to heating elements and pump (2.0% accuracy of reading), and ground heat exchanger length ($\pm$1%). Suggested information for higher quality tests include liquid flow rate (5% accuracy), a drilling log, diameter of bore, depth of bore, tube dimensions and type, grout (or fill) specifications and amounts, a record of drilling fluid additives used, and a description of surface casing.

- Water flow rates that result in 6 to 12°F (3 to 7°C) differential are recommended, as this is the temperature differential for an actual heat pump system. The heat source cabinet and connections to the loop should be well insulated to limit heat loss to less than 2% of total heat input at the minimum outdoor temperature possible during testing.

Summary - Analysis Methods

The seven methods used to analyze were the Line Heat Source Source Method, ignoring initial 0.08 hrs (**LS**(.08), **b**), initial 1 hrs (**LS**(1), **c**) and initial 5 hrs (**LS**(5), **d**), the Line Source Method (**ORLS**, **e**) and the Numerical Method (**ORNum.**, **f**) from Oak Ridge Lab, the OSU Numerical program (**OSUNum.**, **g**), and Cylindrical Heat Source Method (**Cyl.**, **h**).

The average value and the standard deviation (σ) of k were found for each method applied to over 50 data sets. Figure 5.1 demonstrates the results of the comparison. The midpoint of each vertical segment is the % variation for each method from the average value of all methods. The height of each vertical line segment (2σ) is included as an indicator of the consistency of the method. It is emphasized that the value of zero in the figure is an average using all methods and no procedure for determining "true" values for thermal conductivity was established.



*: Not include Test #34, #35, #36, and #37.

Figure 5.1. Variation of Thermal Conductivity (k) from Average Value for Analysis Methods

The analysis indicates the following.

- Average values of variation of k found using **LS**(.08), **LS**(1) and **Cyl.** were normally less than zero. These three methods were more likely to give values of thermal conductivity lower than the average value obtained from all of the methods.
- Average values of variation of k found using **LS**(5), **ORLS**, **ORNum.,** and **OSUNum.** were normally greater than zero. These four methods were more likely to give values of thermal conductivity greater than the average value obtained from all of the methods.
- **ORNLS** gave the closest average variation of *k*. The methods that gave a variation of k, in order of closest to farthest from average, were: **LS**(1), **ORNum.**, **Cyl.**, **OSUNum.**, **LS**(5) and **LS**(.08).
- **LS**(1) gave the smallest range of variation of *k* ($\pm$ 4.2%). **ORNLS** gave the next to the smallest range of variation of ($\pm$ 4.3%). The methods that gave a variation of k, in order from the smallest to the greatest, were: **Cyl.**, **LS**(.08), **OSUNum.**, **ORNum.**, and **LS**(5).

Line-Source Method of Analysis

The following is a discussion of the most simple analysis method. Required information is the bore length, the heat rate, and the average temperature of the loop $[(t_{in} + t_{out})/2]$ over time. In order to determine the thermal conductivity of the soil, the inverse method has been used to analyze field test data by applying,

$$\Delta t = Slope * \ln(t) + B$$

Where $Slope = \dfrac{q}{4pkL}$, thus, $k = \dfrac{3.412 * P}{4pL * Slope}$ 1.

A power transducer is used to record the heat rate (P) into the ground and the unit is *watts*, which must be converted to *Btu/h* if English units are used. The power used is the average over the time period in question. For example, if the time period in question is 5-48 hours, then the power used is the average over that period. Any data before the fifth hour is not used. It is recommended that 5 to 10 hours of the initial data be ignored in order to comply with the requirement that the results generated with a line source of heat (the assumption) approach those generated with a cylinder heat source (the actual ground heat exchanger).

The basic procedure to plot the average loop temperature using field test data (Test #32, 2606 watts, 244 ft. bore) as shown in Figure 1 and discussed in Step 1. Then plot data as log (time) vs. temperature and find the slope of the resulting line (Figure 2, Step 2). The conductivity (k) is determined from Equation 1 (Step 3).

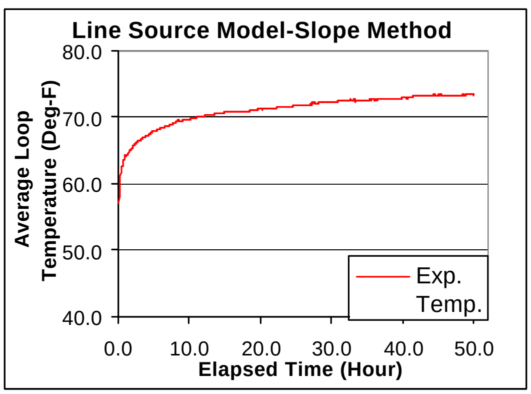


Figure 1. Linear Time – Temperature Plot

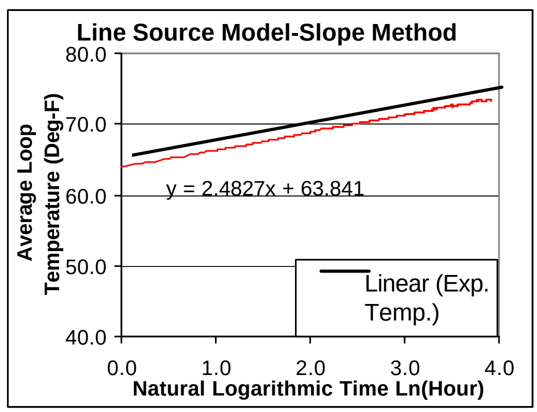


Figure 4.2. Log Time – Temperature Plot with Equation

Step 1:
Set up the spreadsheet of field test data in Excel, which include times and loop temperatures (t_{loop}) into the ground and from the ground. Make X-Y Chart of average loop temperatures (t_{loop}) versus time (τ), as shown in Figure 1.

Step 2:
Click the right button of the mouse on the curve and choose **Add Trendline….** The **logarithmic regression type** is chosen in the **Type** window and **Display equation on chart** is checked in the **Options** window. The value of slope is shown in the regression equation.

Step 3:

Equation 1 is applied to find the thermal conductivity with the value of power (P), slope and length of the borehole (L).

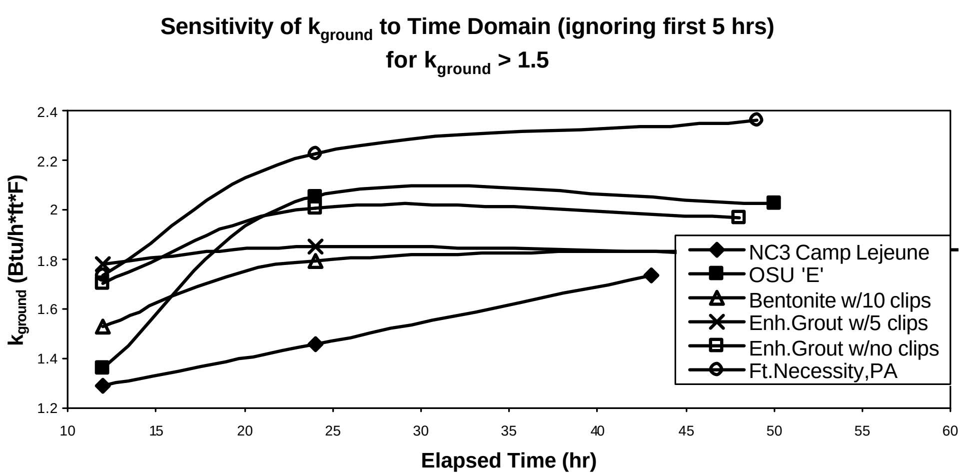
$$k = \frac{3.412 * P}{4pL * Slope} = \frac{3.412 * 2606(watts)}{4 * p * 244(ft) * 2.4827}$$ = 1.17 Btu/hr-ft-°F (2.03 W/m-°C)

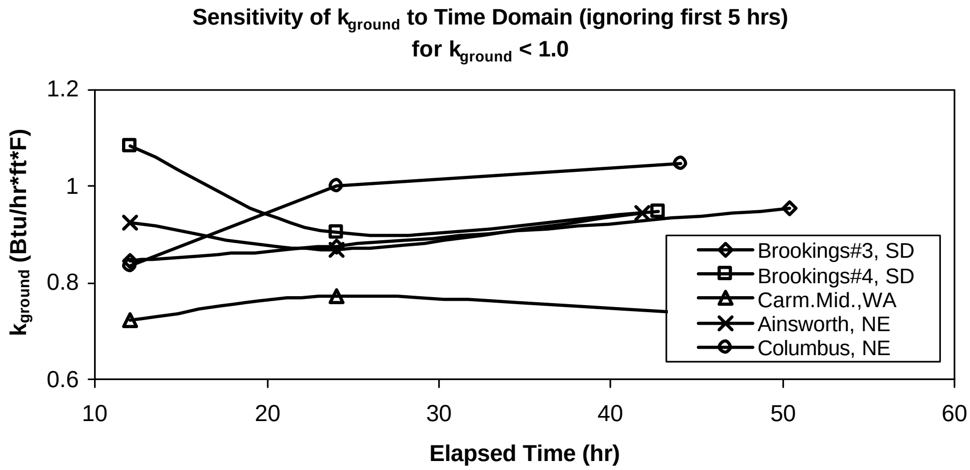
This can be also done graphically

Summary - Test Duration

Proponents of short-term tests (12 hours or less) claim the data can be screened to arrive at accurate values. Traditional methods suggest longer tests (~48 hours) are necessary. Data sets were placed into three groups: low conductivity [1.0 Btu/hr-ft-°F (1.7 W/m-°C)], mid-range [1.0 and 1.5 Btu/hr-ft-°F (1.7 to 2.6 W/m-°C)] and high conductivity [1.5 Btu/hr-ft-°F (2.6 W/m-°C)].

The data were analyzed using the line source method applied to three time intervals for each data set. They are 1-12 hours, 1-24 hours, and 1-48 hours. The conductivity values were plotted against the test duration as shown in Figure 5.4c and a. For the high conductivity soils the effect of test duration is apparent. As the test duration increases, so do the values for conductivity. The trend for lower conductivity soils is less pronounced and frequent. Two noteworthy exceptions to these trends are the data sets for Sisseton, South Dakota, and Brookings, South Dakota. As the test duration increases, the value of thermal conductivity decreases. This could be an indicator of moisture migration from the U-tubes, effectively lowering the conductivity of the soil, which is primarily silt and clay at this site.





Test Time vs. Conductivity for High and Low Conductivity Formations

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