Formation Thermal Conductivity
Test & Data Analysis

Test location | **Locke Residence**
Harmony, PA

Test Date | August 16-18, 2016

Analysis For | Western Pennsylvania Geothermal Heating and Cooling
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Test Performed By | Western Pennsylvania Geothermal Heating and Cooling

Executive Summary

A formation thermal conductivity test was performed at the Locke Residence at 143 Whitestown Road in Harmony, Pennsylvania. The vertical bore was completed on April 6, 2016 by Meinert Drilling. Geothermal Resource Technologies' (GRTI) test unit was attached to the vertical bore on the afternoon of August 16, 2016.

This report provides an overview of the test procedures and analysis process, along with plots of the loop temperature and input heat rate data. The collected data was analyzed using the "line source" method and the following average formation thermal conductivity was determined.

Formation Thermal Conductivity = 2.02 Btu/hr-ft-°F

Due to the necessity of a thermal diffusivity value in the design calculation process, an estimate of the average thermal diffusivity was made for the encountered formation.

Formation Thermal Diffusivity ≈ 1.41 ft^2/day

The undisturbed formation temperature for the tested bore was established from the initial loop temperature data collected at startup.

Undisturbed Formation Temperature ≈ 52.7°F

In addition to the formation thermal properties, a thermal resistance for the bore was also calculated. Since the average value listed below was empirically determined from the test data it may not correlate with values found in loopfield design programs.

Bore Thermal Resistance = 0.118 hr-ft-°F/Btu

The formation thermal properties determined by this test do not directly translate into a loop length requirement (i.e. feet of bore per ton). These parameters, along with many others, are inputs to commercially available loop-field design software to determine the required loop length. Additional questions concerning the use of these results are discussed in the frequently asked question (FAQ) section at www.grti.com.

Test Equipment & Procedures

The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) has published recommended procedures for performing formation thermal conductivity tests in the ASHRAE HVAC Applications Handbook, Geothermal Energy Chapter. The International Ground Source Heat Pump Association (IGSHPA) also lists test procedures in their Design and Installation Standards. GRTI's test procedures meet or exceed those recommended by ASHRAE and IGSHPA, with the specific procedures described below for this project:

Grouting Procedure for Test Loops – To ensure against bridging and voids, it is recommended that the bore annulus is uniformly grouted from the bottom to the top via tremie pipe.

Time Between Loop Installation and Testing – A minimum delay of five days between loop installation and test startup is recommended for bores that are air drilled, and a minimum waiting period of two days for mud rotary drilling.

Undisturbed Formation Temperature Measurement – The undisturbed formation temperature should be determined by recording the loop temperature as the water returns from the u-bend at test startup.

Required Test Duration – A minimum test duration of 36 hours is recommended, with a preference toward 48 hours**.**

Data Acquisition Frequency - Test data is recorded at five minute intervals.

Equipment Calibration/Accuracy – Transducers and datalogger are calibrated per manufacturer recommendations. Manufacturer stated accuracy of power transducers is less than ±2%. Temperature sensor accuracy is periodically checked via ice water bath.

Power Quality – The standard deviation of the power should be less than or equal to 1.5% of the average power, with maximum power variation of less than or equal to 10% of the average power.

Input Heat Rate – The heat flux rate should be 51 Btu/hr (15 W) to 85 Btu/hr (25 W) per foot of installed bore depth to best simulate the expected peak loads on the u-bend.

Insulation – GRTI's equipment has 1 inch of foam insulation on the FTC unit and 1/2 inch of insulation on the hose kit connection. An additional 2 inches of insulation is provided for both the FTC unit and loop connections by insulating blankets.

Retesting in the Event of Failure – In the event that a test fails prematurely, a retest may not be performed until the bore temperature is within 0.5°F of the original undisturbed formation temperature or until a period of 14 days has elapsed.

DATA ANALYSIS

Geothermal Resource Technologies, Inc. (GRTI) uses the "line source" method of data analysis to determine the thermal conductivity of the formation. The line source method assumes an infinitely thin line source of heat in a continuous medium. A plot of the late-time temperature rise of the line source temperature versus the natural log of elapsed time will follow a linear trend. The linear slope is inversely proportional to the thermal conductivity of the medium. When a u-bend grouted in a borehole is used to inject heat into the ground at a constant rate in order to determine the average formation thermal conductivity, the test must be run long enough to allow the finite dimensions of the u-bend pipes and the grout to become insignificant. Experience has shown that approximately ten hours is required to allow the error of early test times and the effects of finite borehole dimensions to become insignificant.

In order to analyze real data from a formation thermal conductivity test, the average temperature of the water entering and exiting the u-bend heat exchanger is plotted versus the natural log of elapsed testing time. Using the Method of Least Squares, linear equation coefficients to produce a line that fits the data are calculated. This procedure is normally repeated for various time intervals to ensure that variations in the power or other effects are not producing inaccurate results. These coefficients are then used, along with several other parameters (undisturbed formation temperature, thermal diffusivity, and bore diameter) to calculate the bore thermal resistance. The calculated bore resistance applies only to the test conditions, and a bore in an operating loopfield could have a significantly different thermal resistance due to changes in bore construction, loop fluid temperature, flow rate, and presence of antifreeze.

The calculated results are based on test bore information submitted by the driller/testing agency. GRTI is not responsible for inaccuracies in the results due to erroneous bore information. All data analysis is performed by personnel that have an engineering degree from an accredited university with a background in heat transfer and experience with line source theory. The test results apply specifically to the tested bore. Additional bores at the site may have significantly different results depending upon variations in geology and hydrology.

Through the analysis process, the collected raw data is converted to spreadsheet format (Microsoft Excel®) for final analysis. If desired, please contact GRTI and a copy of the data will be made available in either a hard copy or electronic format.

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[1] Richard A. Beier and Marvin D. Smith. "Borehole Thermal Resistance from Line-Source Model of In-Situ Tests," ASHRAE Transactions 111, part 1 (2005): 702-713.

Test Bore Details
(As Provided by Adam Locke)

Site Name	Locke Residence
Location	Harmony, PA
Driller	Meinert Drilling
Installed Date	April 6, 2016
Borehole Diameter	10 inches from 0-15 ft 7 7/8 inches from 15-263 ft
Casing	Temporary 6 inch PVC casing to 15 ft
Heat Exchanger Size	GeoKOAX concentric, 5 1/2 inches OD
Heat Exchanger Depth Below Grade	252 ft
Grout Type	Limestone/dolomite chips w/bentonite
Grout Mixture	70% limestone/dolomite, 30% bentonite
Grouted Portion	Entire bore

Note: A grout sample taken during installation had a reported thermal conductivity of 0.87 Btu/hr-ft-°F.

Drill Log

Formation Description	Depth (ft)
BGS CL dry (lean clay)	0'-8'
CL moist mottled, kaolinite predominate (perched unconfined water table)	8'-12'
Sandstone saprolite with shale dry, iron nodules throughout	12'-15'
Gray shale, argillaceous. Water encountered at 40ft (intermediate confined aquifer)	15'-60'
Sandstone, fine grained (making 7-8 gpm)	60'-81'
Fracture, 2 ft drop (open basal fracture, camera verified) shale, gray with minor silica	81'-83'
Shale, gray with minor silica	83'-161'
SS (deep aquifer to depth)	161'-195'
SS, hard; dolomitic (minor)	195'-205'
SS, as above	205'-232'
Shale, as above	232'-263'

Note: Bore produced approximately 40 gpm water total.

Thermal Conductivity Test Data

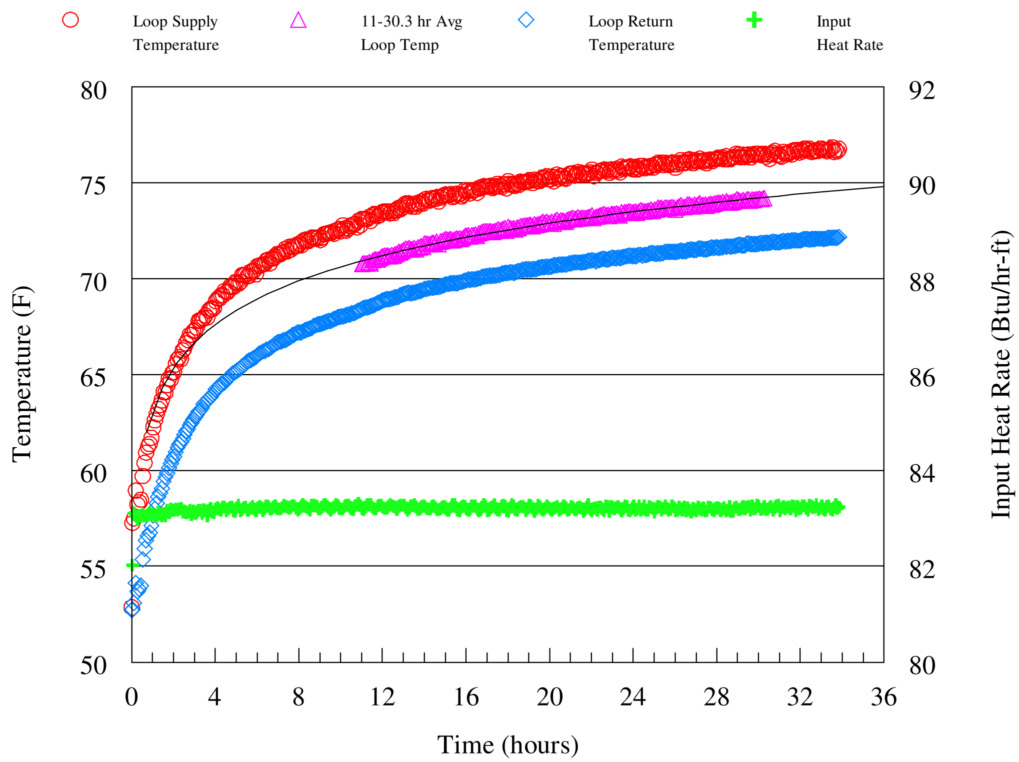

Fig. 1: Temperature & Heat Rate Data Vs Time

Figure 1 above shows the loop temperature and heat input rate data versus the elapsed time of the test. The temperature of the fluid supplied to and returning from the U-bend are plotted on the left axis, while the amount of heat supplied to the fluid is plotted on the right axis on a per foot of bore basis. In the test statistics below, calculations on the power data were performed over the analysis time period listed in the Line Source Data Analysis section.

Summary Test Statistics

Test Date	August 16-18, 2016
Undisturbed Formation Temperature	Approx. 52.7°F
Duration	33.9 hr
Average Voltage	238.8 V
Average Heat Input Rate	20,970 Btu/hr (6,144 W)
Avg Heat Input Rate per Foot of Bore	83.2 Btu/hr-ft (24.4 W/ft)
Measured Circulator Flow Rate	8.9 gpm
Standard Deviation of Power	0.05%
Maximum Variation in Power	0.10%

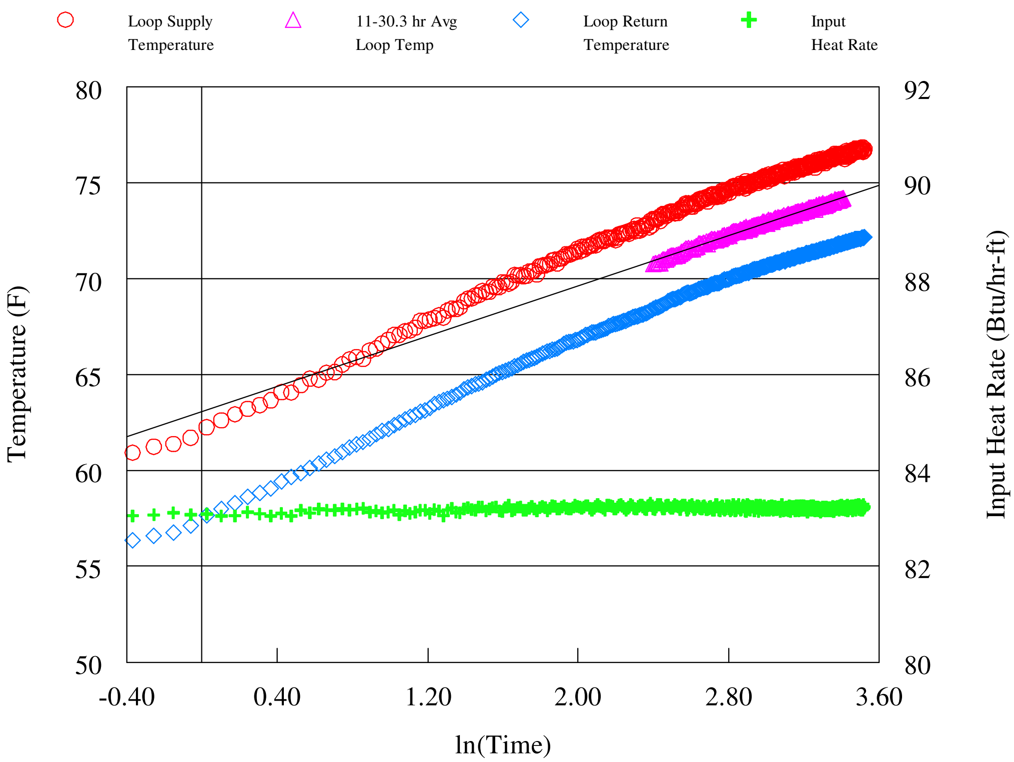

Fig. 2: Temperature & Heat Rate Vs Natural Log of Time

The loop temperature and input heat rate data versus the natural log of elapsed time are shown above in Figure 2. Due to a loss of flow at 33.9 hours, a limited amount of data was applicable for analysis. The results of a shorter test are more sensitive to fluctuations in ambient temperature and supplied power, potentially biasing the results. However, the supplied power for this test was very stable for the analysis time interval, with a standard deviation of 0.05% and a maximum variation in power of 0.10%. The temperature versus time data was analyzed using the line source method (see page 3) in conformity with ASHRAE and IGSHPA guidelines. A linear curve fit was applied to the average of the supply and return loop temperature data between 11 and 30.3 hr. The slope of the curve fit was found to be 3.27. The resulting thermal conductivity was found to be **2.02 Btu/hr-ft-°F**.

The thermal conductivity is fairly high compared to other tests in the area. The bore produced approximately 40 gpm water while drilling, and water flow through the formation may be having some influence on the test results. Comparing results and drill logs from other tests in the area, an expected conductivity range for the formation would be 1.7-1.8 Btu/hr-ft-°F.

Thermal Diffusivity

The reported drilling log for this test borehole indicated that the formation consisted primarily of clay, saprolite, shale, and sandstone. Heat capacity values for shale and sandstone were calculated from specific heat and density values listed by Kavanaugh and Rafferty[3]. A weighted average of heat capacity values based on the indicated formation was used to determine an average heat capacity of 34.5 Btu/ft^3-°F for the formation. A diffusivity value was then found using the calculated formation thermal conductivity and the estimated heat capacity. The thermal diffusivity for this formation was estimated to be **1.41 ft^2/day**.

[3]Stephen P. Kavanaugh and Kevin Rafferty, Ground-Source Heat Pumps - Design of Geothermal Systems for Commercial and Institutional Buildings (Atlanta: ASHRAE, 1997), 27.

Bore Thermal Resistance

Bore thermal resistance calculations were made on the test data using the modified line source method[3]. Factors that affect bore thermal resistance include the resistance of the pipe material, the diameter and spacing of the pipes in the bore, the bore diameter, casing length and type, and the thermal conductivity of the grout/backfill in the bore annulus.

Required inputs for the bore resistance calculation include the calculated formation thermal conductivity and thermal diffusivity along with the curve fit coefficients that were determined from the test data. Additional inputs for the resistance calculations include the bore diameter and the average undisturbed formation temperature. Using the modified line source method the bore thermal resistance from 11-30.3 hours was found to be **0.118 hr-ft-°F/Btu**.

The calculated bore resistance applies only to this bore under these test conditions, and a bore in an operating loopfield could have a significantly different thermal resistance due to changes in the bore construction, loop fluid temperature, flow rate and presence of antifreeze. Thus, the resistance value may not directly correlate with values found in loopfield design programs, and could be expected to increase at low loop temperatures especially if antifreeze is used.

Additional information on bore resistance may be found on the IGSHPA website where the results are reported for a study by Oklahoma State University and Oklahoma Gas & Electric that tested various vertical bore heat exchanger configurations[4].

[3] Beier and Smith, 702-713.

[4] Richard A. Beier and Garen N. Ewbank. "In-Situ Test Thermal Response Tests Interpretations, OG&E Ground Source Heat Exchange Study", http://www.igshpa.okstate.edu/geothermal/research/In_situ_TRT_report.pd

Certificate of Calibration

GRTI maintains calibration of the datalogger, current transducer and voltage transducer on a biannual schedule per the manufacturers recommendations. The components are calibrated by the manufacturer using recognized national or international measurement standards such as those maintained by the National Institute of Standards and Technology (NIST).

FTC Unit 253

DA Unit 60

Primary Equipment		
Component	Last Calibration Date	Calibration Due Date
Datalogger	1/6/2016	1/6/2018
Current Transducer	1/11/2016	1/11/2018
Voltage Transducer	1/11/2016	1/11/2018

GRTI periodically verifies the combined temperature sensor/datalogger accuracy via an ice water bath. Temperature readings are simultaneously taken with a digital thermometer that has been calibrated using instruments traceable to NIST.

Date	6/30/2016	1/12/2016		
Thermocouple 1 (°F)	32.1 32.1 32.1	32.1 32.1 32.1		
Thermocouple 2 (°F)	32.0 32.0 32.1	32.0 32.0 32.0		
Thermocouple 3 (°F)	32.0 32.1 32.1	32.1 32.1 32.1		
Thermocouple 4 (°F)	32.0 32.0 32.0	32.0 32.0 32.0		
Digital Thermometer (°F)	32.2 32.1 32.1	32.0 32.0 32.0		