Formation Thermal Conductivity Test

And Borehole Thermal Performance

Site:

Loudoun County
Juvenile Detention Center
Claudia Drive
Leesburg, VA 20176

Prepared for:

Northern Virginia Drilling

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PROJECT SPECIFICS AND SUMMARY

A formation thermal conductivity (**FTC**) and borehole thermal performance test was performed at the planned Loudoun County Juvenile Detention Center in Leesburg, Virginia from October 10 – 12, 2017. The test well, designated Well # 1 was completed by Northern Virginia Drilling on September 29, 2017. The 6-inch well was completed with double one-inch RAUGEO PEXa U-tubes, and grouted with bentonite-based thermal grout having a conductivity of approximately 1.2 BTU/hr-ft-°F. The Formation Conductivity testing was conducted by GeoEx Analytics (**GXA**). The results of the test were then analyzed using the "line source" method by GXA to determine the Formation Thermal Conductivity thermal diffusivity, and other parameters needed for closed loop field design.

The following report outlines the testing procedures and presents the data and analysis of the results. These results provide important design values needed to size the geothermal ground loop. The following average formation thermal conductivity (**FTC**) and borehole thermal resistivity (**BTR**) were determined from the test data:

Average Formation Thermal Conductivity = 1.25 BTU/hr.-ft.-°F
Borehole Thermal Resistivity = 0.138 ft. °F hr./BTU

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 ≈ 0.93 ft²/day

The undisturbed formation temperature was determined from the returning water temperatures during the first half hour of circulation but prior to start of the heating.

Undisturbed Formation Temperature ≈ 58.1°F

A copy of the collected data in electronic or hard copy format is available upon request.

DRILLING & LITHOLOGY

Well Drilling Record	
Project Name:	**Loudoun County Juvenile Detention Center**
Well Designation and Location:	Well # 1
Drilling Contractor:	Northern Virginia Drilling
Drilling Method(s):	Air Rotary
Boring Depth and Diameter:	360 feet, 6" diameter
Depth to Rock:	40 feet
Casing Depth and type:	40 feet steel casing grouted in place
Completion Date:	9/29/17
Water Occurrences or Observations	no water
Grout Description and Conductivity:	Thermal Bentonite, K$\approx$ 1.2 BTU/hr-°F-ft
Loop Description:	360 feet of 1" double PEXa with spacers
Well Lithology – Driller's Log	
0–40 feet	Overburden, Concrete, Trash
40–360 feet	Diabase

A heat capacity for the boring was calculated from a weighted average of specific heat and density values for rocks and soils listed by Kavanaugh and Rafferty (Ground-Source heat Pumps – Design of Geothermal Systems for Commercial and Institutional Buildings, ASHRAE, 1997) and Soil and Rock Classification for the Design of Ground-Coupled Heat Pump Systems Field Manual (Table 3, distributed by IGSHPA) for additional soil data. No data is given for diabase, so a value for gabbro, an intrusive rock of similar composition, was used instead. Based on this value, the average volumetric heat capacity of the formation is estimated to be:

$$C_v = \mathbf{32.4}\,\frac{\text{BTU}}{°\text{F ft}^3}$$

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TEST PROCEDURE

The American Society of heating, Refrigeration, and Air-conditioning Engineers (2011 ASHRAE Handbook HVAC Applications, Chapter 34) has published a set of recommended guidelines for performing formation thermal conductivity tests for geothermal applications. A partial list of recommended procedures is as follows:

1. Required Test Duration – A minimum test duration of 36 hours is recommended, with a preference of 48 hours.
2. 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. To best simulate the expected peak loads on the U-bends, the heat flux rate per foot of borehole depth should be 51 BTU/hr to 85 BTU/hr or 15 Watts to 25 Watts respectively.
3. Undisturbed Formation Temperature Measurement – The undisturbed formation temperature should be determined by circulating water through the loop for approximately one half hour before the heating elements are turned on, and recording the stabilized loop-return temperatures.
4. Installation Procedures for Test Loops – The target borehole diameter is 4.5” with a not to exceed borehole of 6”. The bore annulus is to be uniformly grouted from the bottom to the top utilizing a tremie pipe to avoid bridging and voids.
5. Time Between Loop Installation and Testing – three days between loop installation and test start-up is recommended.

During the test, water is heated at a uniform rate and circulated through the ground loop. Heat is rejected to the ground to simulate full cooling load operations. The water temperatures to and from the loop, water flow rate, and electrical power consumption (equal to heating rate) are measured and recorded prior to heating and throughout the test duration.

DATA ANALYSIS METHODOLOGY

GeoEx Analytics uses the “line source” method of data analysis recommended by ASHRAE. The line source method is based on an infinitely thin constant heat source in a homogeneous medium. For a uniformly heated line source, a plot of the line source temperature vs the logarithm of time is linear. The formation thermal conductivity of the medium is derived from the slope of this line, and is given by:

$$FTC = \frac{Q/L}{4\pi \times slope}$$

where Q/L is the heating rate per length of borehole and “slope” is the slope of temperature vs natural log (time).

Real-world deviations from the line source model can result in non-linear temperature- log time plots, particularly during the early times of heating. It commonly takes about ten hours for the effects of the actual heat source and the wellbore and near-wellbore heterogeneities to be dampened. After about ten hours, the heating curve becomes approximately linear with log(time). The slope in the FTC equation is determined by a Least-Squares best-fit to the data from this linear range. This slope is then used to derive the conductivity of the formation beyond the effects of the near-wellbore deviations from the idealized line-source model.

The thermal conductivity and thermal diffusivity describe how quickly and how far heat is transported away from the wellbore once it gets to the formation. This is only one half of the information needed to characterize the thermal performance of a geothermal well. The other piece of information needed is a measure of the ease or difficulty of transferring heat from the ground loop to the formation. This is described by the borehole thermal resistivity (**BTR**).

BTR is defined by the temperature difference between the average loop temperature and the temperature at the margin of the borehole, divided by the heat flux per foot:

$$\text{BTR} = \frac{T_{loop} - T_{bore-edge}}{Q/L}$$

It has units of °F-hr-ft/BTU. A higher BTR reflects a greater resistance to the flow of heat from the ground loop to the borehole wall. Together, these two parameters characterize the thermal performance of a geothermal well.

The bore wall temperature cannot be measured, but the BTR can be derived using the equation above and the line-source model temperature at the borehole radius. The BTR reflects the real-world deviations between the actual wellbore and the ideal line-source model. The BTR and the Formation Thermal Conductivity are computed together from the test data, and together they describe the borehole performance under those test conditions. By design, the test conditions approximate full-load cooling.

TEST RESULTS

The test results are shown in Figures 1 to 3, below. Startup temperatures are shown in Figure 1. After 30 minutes, the temperatures stabilized at 58.1° prior to turning on the heating elements. This is the undisturbed formation temperature.

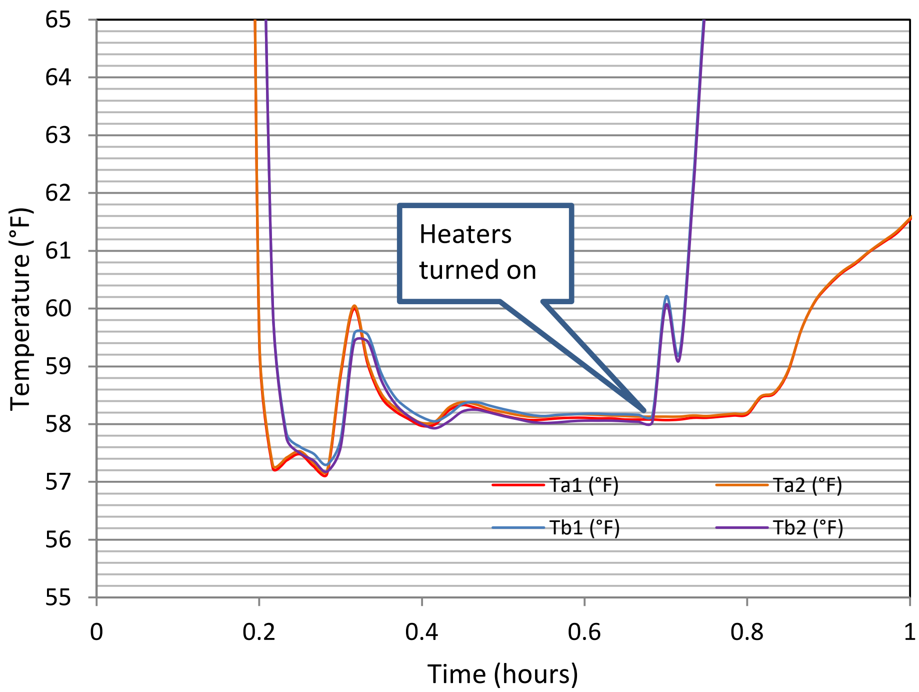

Figure 1. Startup Temperatures

Figure 2 shows the temperatures and electrical power (in btu/hr) for the test starting with startup of heating. The rate of heat input, standard deviation, and variance during the test are summarized in the table below:

Test Power Supply Data			
	BTU/Hr/ft	Std Dev	Max variation
Design	51 - 85	<1.5%	<±10%
Actual	79.6	±0.2%	±0.6%

The heating rate was within the recommended range, and power stability was excellent. The average heating rate during the test was 28,644 BTU/hour, or 79.6 BTU/hr-foot. The heating rate corresponds to approximately 2.4 Tons and 151 feet boring per ton. The water circulation rate was 6.7 gpm.

Return temperatures from the ground increased from 58.1 to 86°F after 45 hours of heating.

The temperature data are shown versus log time in Figure 3. The linear range extends from about 10 to hours to 45 hours. The slope of the linear range is 5.0496. This slope and the heat rate per foot of wellbore are used to compute the formation conductivity.

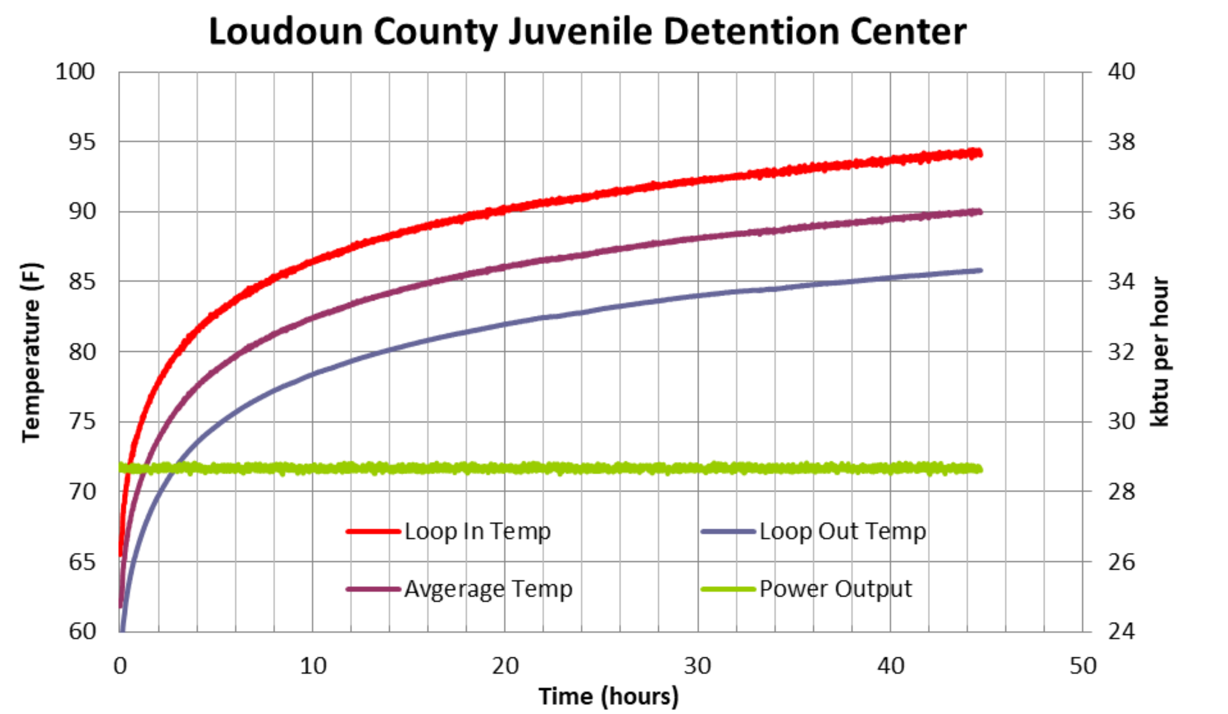

Figure 2. Temperature and Power versus Time

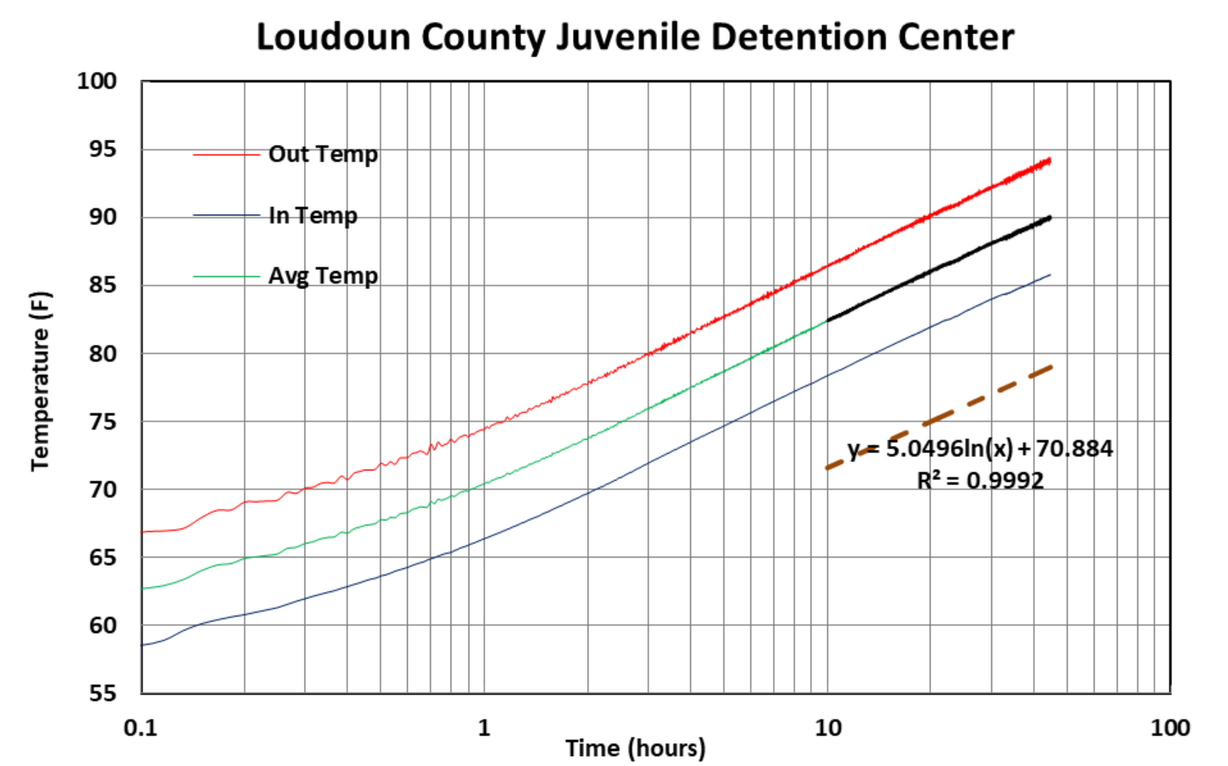

Figure 3. Temperature vs Log Time

The calculated line-source model temperature at the borehole edge is also shown by the dashed line. The difference between the model bore-wall temperature and the average loop temperature, divided by the power input per foot yields the Borehole Thermal Resistance.

FORMATION THERMAL CONDUCTIVITY & BOREHOLE THERMAL PERFORMANCE

The results of the test data are shown in the table below:

Estimated Average heat Capacity (BTU/ft³-°F)	Thermal Conductivity (BTU/hr-ft-°F)	Estimated Thermal Diffusivity (ft²/day)	Apparent Borehole Thermal Resistivity (hr-ft-°F/BTU)	Undisturbed Ground Temperature
32.4	1.25	0.93	0.138	58.1

The thermal diffusivity is calculated by the ratio of the computed formation thermal conductivity and the estimated heat capacity. Computation of the other terms was previously discussed.

The Borehole Thermal Resistivity calculated from the test data is 0.138 (hr)(ft)(°F)/btu. This compares to a BTR of 0.127 hr-°F-ft/btu, based on numerical calculation for double 1" PEXa with spaces in a 6" bore.

The formation thermal conductivity, the undisturbed formation temperature, and the BTR together describe the thermal performance of the test well for conditions approximating the test conditions. Most ground loop sizing programs allow the user to override the default BTR computed from the borehole geometry. For a well field with similar well construction, the recommended BTR for well field sizing is given below:

Recommended BTR for Field Sizing: 0.138 ft°Fhr/btu

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