

BOWMAN GEOTHERMAL

Formation Thermal Conductivity Test

Formation Thermal Conductivity Test And Borehole Thermal Performance

Site:

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PROJECT SPECIFICS AND SUMMARY

A formation thermal conductivity (**FTC**) and borehole thermal performance test was performed at the Patuxent Naval Air Station from March 18 to March 20, 2011 in Patuxent River, MD. The test well, designated TC-1, was drilled by Aqua Well Drilling, LLC on March 14, 2011. The 4-inch well was completed with a 1" HDPE U-tube and grouted with bentonite-based thermal grout having a conductivity of approximately 0.93 BTU/hr-ft-°F. The Formation Conductivity testing was conducted by Bowman Geothermal, LC (**BG**). The results of the test were then analyzed using the "line source" method by BG 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 effective borehole resistivity (**EBR**) were determined from the test data:

Average Formation Thermal Conductivity = 1.10 BTU/hr-ft-°F
Effective Borehole Resistivity = -0.014 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 ≈ 0.70 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 ≈ 59.3°F

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

DRILLING & LITHOLOGY

Well Drilling Record	
Project Name:	Patuxent Naval Air Station
Well Designation and Location:	TC-1
Drilling Contractor:	Aqua Well Drilling, LLC
Drilling Method(s):	Mud Rotary
Boring Depth and Diameter:	300 feet / 4 "
Depth to Rock:	>300 feet
Casing Depth and type:	No Casing Installed
Completion Date:	March 14, 2011
Water Occurrences or Observations	None reported
Grout Description and Conductivity:	Thermal Bentonite, $K \approx 0.93$ BTU/hr-°F-ft
Loop Description:	300' 1" HDPE
Well Lithology – Driller's Log	
0-3 feet	Tan Clay and Sand
3-15 feet	White and Tan Sand
15-25 feet	Blue Clay
25-40 feet	White and Brown Sand
40-60 feet	Blue Clay
60-80 feet	White Sand
80-150 feet	Green Clay and Shell
150 -265 feet	Green Clay
265-270 feet	Gray Sand
270-300 feet	Gray and Black Cemented Sand



The well is located in the Coastal Plain of Maryland, an eastward thickening wedge of mostly sands and clays. The well was drilled by mud rotary to 300 feet and no bedrock was encountered. A heat capacity for the boring was calculated from a weighted average of specific heat and density values 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. Based on our interpretation of the driller's log and estimated depth to ground water, the average volumetric heat capacity of the formation is estimated to be:

$$C_v = 37.5 \frac{BTU}{^{\circ}F \text{ ft}^3}$$

TEST PROCEDURE

The American Society of heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) has published a set of recommended guidelines for performing formation thermal conductivity tests for geothermal applications. Recommended procedures and are 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 – five 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

Bowman Geothermal 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 into 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 into 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:

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

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

The bore wall temperature cannot be measured, but an “Effective BTR” can be derived using the equation above and the line-source model temperature at the borehole radius. The



Effective BTR reflects the real-world deviations between the actual wellbore and near-wellbore conditions and the ideal line-source model. The Effective BTR and the Formation Thermal Conductivity are computed together from the test data, and together they describe the borehole performance under those test conditions, which by design approximate full-load cooling.

TEST RESULTS

The rate of heat input, standard deviation, and variance during the test is summarized in the table below:

Test Power Supply Data			
	BTU/Hr/ft	Std Dev	Max variation
Design	51 - 85	<1.5%	<±10%
Actual	65.5	±0.3%	±1.3%

Heating rates and variations are well within the design standards.

The test results are shown in Figure 1, below. The undisturbed formation temperature, determined from the returning water temperature prior to heating, was 59.3°F. Return temperatures increased to 89°F at the end of the test. The average heating rate during the test was 19,662 BTU/hour, or 65.5 BTU/hr-foot.

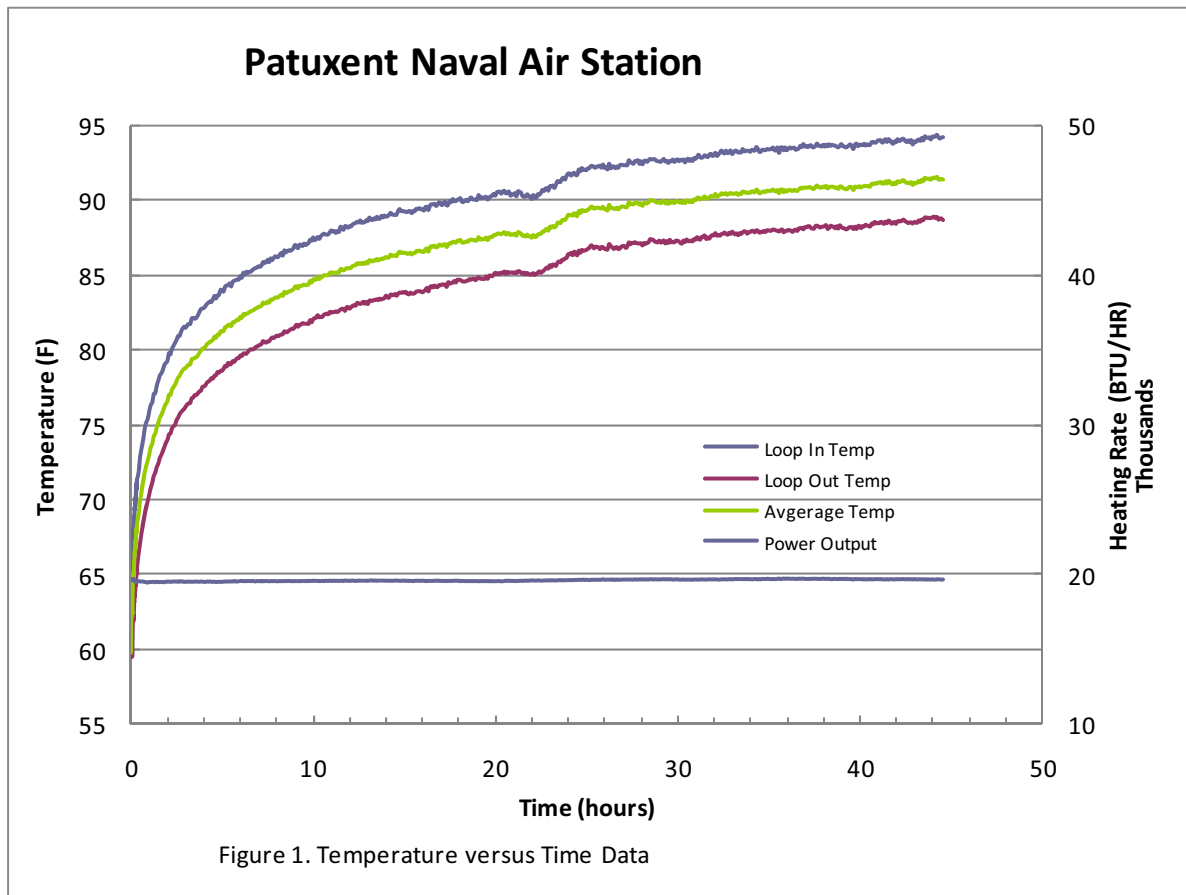
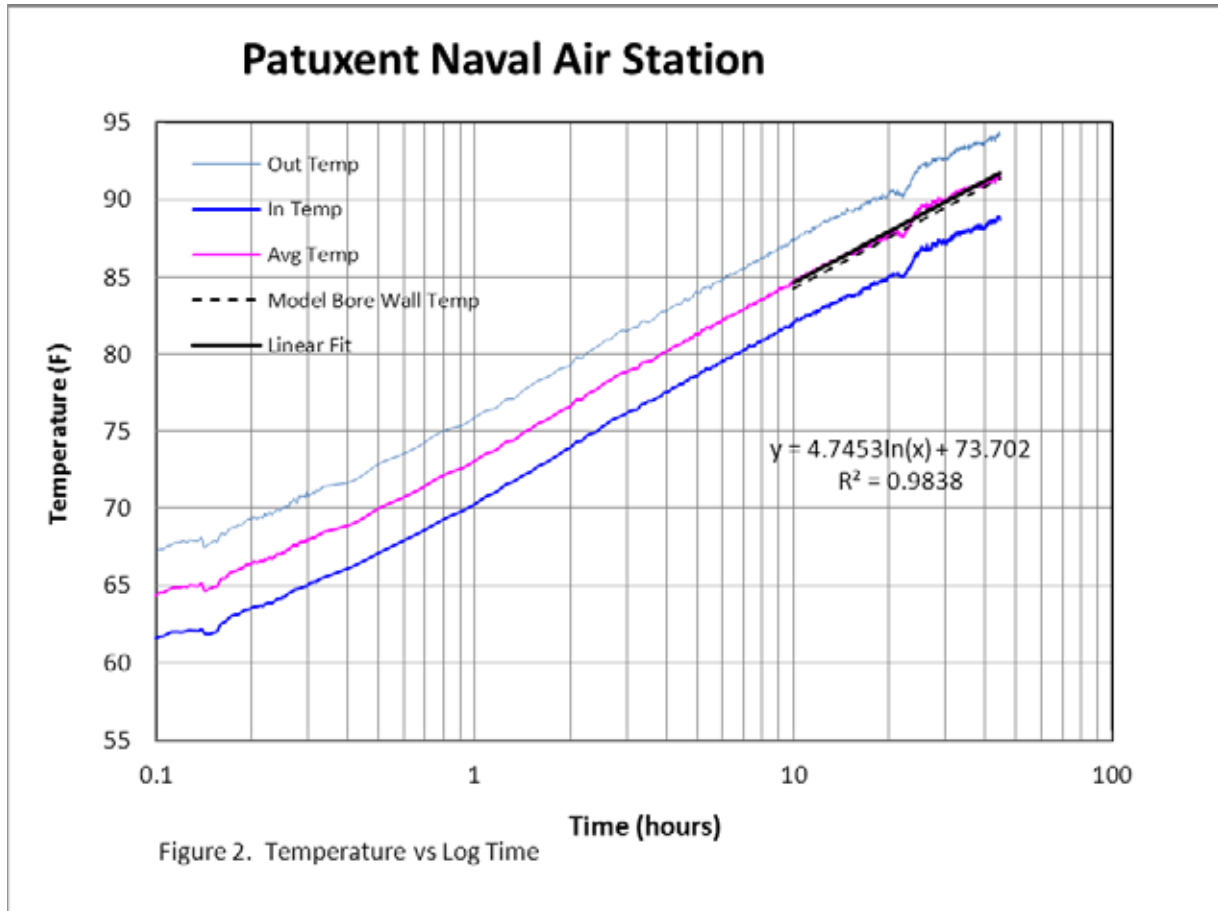


Figure 1. Temperature versus Time Data



The temperature data are shown versus log time in Figure 2, below. The linear range extends from about ten hours to test termination at 45 hours. The slope of the linear range is 4.745. This slope and the heat rate per foot of wellbore are used to compute the formation conductivity.



The calculated line-source model temperature at the borehole edge is also shown as 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 Effective Borehole Resistivity.

FORMATION THERMAL CONDUCTIVITY & BOREHOLE THERMAL PERFORMANCE

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


Estimated Average heat Capacity (BTU/ft ³ -°F)	Thermal Conductivity (BTU/hr-ft-°F)	Estimated Thermal Diffusivity (ft ² /day)	"Effective" Borehole Thermal Resistivity (hr-ft-°F/BTU)	Undisturbed Ground Temperature
37.5	1.10	0.70	-0.014	59.3

The thermal diffusivity is calculated by the ratio of the computed formation thermal conductivity and the estimated heat capacity (multiplied by 24 hours/day). Computation of the other terms was previously discussed.

The Effective Borehole Resistivity calculated from the test data is -0.014. The "actual" borehole resistivity calculated for the loop and a grout conductivity of 0.93. btu/hr-°F-ft is 0.225 hr-°F-ft/btu. A possible explanation for the low Effective BTR values which are commonly calculated from the test data is the effect of thermal convection immediately adjacent to the wellbore. Such convection could be induced by heating of the wellbore and adjacent formation. While an actual negative BTR is physically impossible, convection can significantly enhance heat flow from the bore out into the formation, and the low calculated Effective BTR accounts for this enhancement in the near-bore formation. A regional ground water flow would also enhance heat exchange. However, its effect would extend uniformly from the wellbore, and this enhancement would be reflected by an increased value for calculated formation conductivity.

The formation thermal conductivity, the undisturbed formation temperature, and the Effective BTR together describe the thermal performance of the test well for conditions approximating the test conditions. The effective BTR may therefore be appropriate for describing the thermal performance during full-load cooling, which the test conditions simulate. It must be cautioned, however, that the Effective BTR cannot be extrapolated. In particular, during heating mode, circulation of cold water through the loop would not be expected to cause significant thermal convection adjacent to the wellbore, and the actual BTR is probably more appropriate to describe the wellbore's thermal performance.




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