REHAU in-situ Borehole Thermal Performance Testing

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Purpose:

Thermal conductivity tests are commonly performed to determine the formation thermal conductivity (**FTC**) for a well field site. However, thermal conductivity is only one half of the information needed to characterize the thermal performance of a geothermal well. The other half is the borehole thermal resistance (**BTR**). The BTR describes how easily heat is transferred from the fluid to the formation. A higher BTR reflects a greater resistance to the flow of heat from the ground loop into the formation. The FTC and the related thermal diffusivity, in contrast, describe how easily heat is dissipated into the formation once it passes from the borehole. Together, these two parameters characterize the thermal performance of a geothermal well.

The BTR is typically computed based on the borehole geometry, grout conductivity, and pipe spacing. The purpose of this investigation is to derive both the FTC and BTR from the *in-situ* thermal conductivity test data for a variety of geothermal well configurations and to investigate the impact of geothermal well configuration on the overall borehole thermal performance.

Borehole Thermal Performance Testing:

REHAU NA commissioned an *in-situ* borehole test to evaluate and compare the thermal responses from four different borehole configurations. Four six-inch diameter borings were drilled at their North American headquarters in Leesburg, Virginia. The borings were drilled to three hundred feet depth and were completed with 1" U-bends and thermal grout with a conductivity of 1.0 BTU/hr-°F-ft. The loops installed were 1" DRISCOPLEX™ 5300 Climate Guard® HDPE pipe, and 1" RAUPEX® PEXa pipe.

Forty-eight hour thermal conductivity tests were conducted on each well following ASHRAE procedures. The results are summarized in the table below:

Well No.	Configuration	FTC (BTU/hr-°F-ft)	Diffusivity (ft2/day)
Well 1	Double PEXa with no spacers	1.73	1.32
Well 2	Single HDPE loop	1.78	1.36
Well 3	Double PEXa with 3" spacers	1.86	1.39
Well 4	Single PEXa loop	1.72	1.31

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Formation thermal conductivities for the four borings clustered between 1.72 and 1.86 BTU/hr-°F-ft. Insofar as the FTC is a property of the formation and not of the bore configuration, the variation in FTC is attributed to natural variations in geology or in ground water flow.

Effective BTRs were also derived from the thermal conductivity test data. The in and out water temperatures measured during the conductivity test were averaged. This temperature was compared with the temperatures calculated at the borehole radius using the same line source method for determining the FTC. This difference was then divided by the constant rate of heating to yield the Effective BTR for each test well. The results are as follows:

Well No.	Configuration	Effective BTR
Well 1	Double PEXa with no spacers	0.043
Well 2	Single HDPE loop	0.095
Well 3	Double PEXa with 3" spacers	0.002
Well 4	Single PEXa loop	0.148

The Effective BTRs range from a low of 0.002 (ft°Fhr)/BTU in the well completed with double PEXa loops and spacers (Well#3) to a high of 0.148 in the single PEXa loop (Well#4).
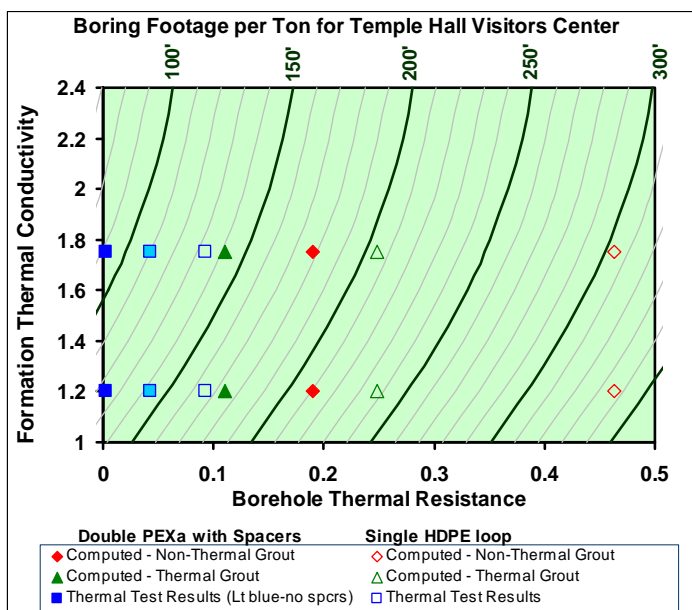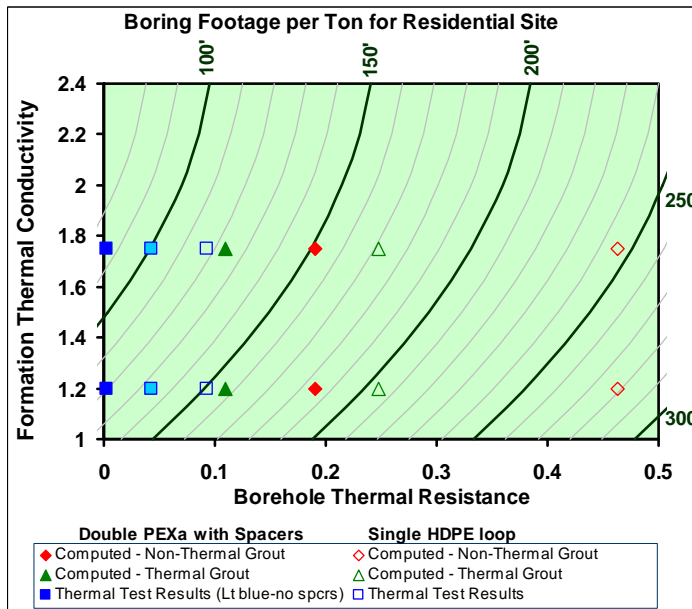
The ordering of the BTRs determined from the test data is exactly as would be expected. The BTR for the single PEXa loop is higher than the HDPE loop at least in part because the PEXa loop is thicker walled (DR9) compared to standard geothermal HDPE pipe (DR11), and the pipe sizes for PEXa run smaller than the equivalent pipe sizes for HDPE. The lowest BTR was for the double PEXa loop with spacers.

Taken together, the FTC and the BTR characterize the flow of heat from the ground loop and dispersal into the formation, and together they characterize the thermal performance of the wellbore under the test conditions and under typical peak cooling load.

Impact of Borehole Performance on loop Design:

The figures below illustrate how the FTC and BTR interrelate to determine the required loop size for two buildings in the Washington DC area. One is a typical five-ton residence, and the other is the Temple Hall Visitors Center in Leesburg, Virginia. The first is modestly heating dominated and the latter is cooling dominated. The contours of feet per ton were calculated using Gaia Geothermal Ground Loop Design program based on the building and loop design details specific to each structure. The attached reports summarize this information.

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Boring Footage per Ton for Residential Site

Double PEXa with Spacers — Single HDPE loop
- ◆ Computed - Non-Thermal Grout
- ◇ Computed - Non-Thermal Grout
- ▲ Computed - Thermal Grout
- △ Computed - Thermal Grout
- ■ Thermal Test Results (Lt blue-no spcrs)
- ☐ Thermal Test Results

Boring Footage per Ton for Temple Hall Visitors Center

Double PEXa with Spacers — Single HDPE loop
- ◆ Computed - Non-Thermal Grout
- ◇ Computed - Non-Thermal Grout
- ▲ Computed - Thermal Grout
- △ Computed - Thermal Grout
- ■ Thermal Test Results (Lt blue-no spcrs)
- ☐ Thermal Test Results

The square data points correspond to the Effective BTRs derived from the thermal test data for the HDPE loop (open symbols) and for the double PEXa loop with spacers (filled symbols). The triangles represent computed BTRs for the same two loop types with a borehole grout conductivity of 1.0, and the diamonds represent computed BTRs for a grout conductivity of 0.4 (non-thermal grout). BTRs for the double PEXa loop were explicitly computed using the known pipe separations. The BTRs for the HDPE pipe were computed by Ground Loop Design program using "average" pipe separation. The points are plotted for FTC of 1.75 and a lower value of 1.2 to evaluate the relative influence that FTC and BTR have on required loop length.

In each case, the required loop length was significantly lower for the double PEXa loop with spacers compared to the single HDPE loop. For the residential site, the Effective BTRs and computed BTRs for the thermal grout show similar loop length reductions of 20% to 26%. The higher reductions are computed sites with higher FTC. For the cooling-dominated Temple Hall Visitors Center, the loop length reductions for the double PEXa loops are higher, in the range of 24% to 32%. For non-thermally grouted holes, the reductions are even more dramatic, with loop reductions of up to 40%.

The double loop without spacers (square symbols with light blue fill) also showed significant, but less dramatic loop length reductions. Only the BTRs derived from the test data are shown because of the inherent uncertainty in computing BTRs with unknown pipe spacings. The results of the analysis for the two sites are summarized in the table below.

Loop Type	Basis	BTR	Residence		Visitors Center	
			Heating Dominated		Strongly Cooling Dominated	
			FTC=1.2	FTC=1.75	FTC=1.2	FTC=1.75
SDR11 HDPE	REHAU Test Results	.095	150	115	165	135
Double PEXa SDR9-No Spacers		.043	135 (-10%)	100 (-13%)	140 (-15%)	110 (-18%)
Double PEXa SDR9-Spacers		.001	120 (-20%)	85 (-24%)	125 (-24%)	95 (-30%)
SDR11 HDPE	Computed Grout TC=1.0	0.24	205	170	235	205
Double PEXa SDR9-Spacers		0.11	155 (-24%)	125 (-26%)	175 (-26%)	140 (-32%)
SDR11 HDPE	Computed Grout TC=0.4	0.46	280	245	335	305
Double PEXa SDR9-Spacers		0.19	185 (-34%)	150 (-39%)	210 (-33%)	180 (-41%)

Effective vs. Computed BTRs:

From the figures above, it is apparent that the effective BTRs are substantially lower than the computed BTR values. In the case of the double PEXa loop with spacers, the "actual" BTR can be rigorously computed. A finite-difference grid with 0.1" spacing was used to compute the borehole using the pipe dimensions and resistivity for PEXa and a grout conductivity of 1.0. The pipe spacing is 3" OC on each side, and the pipes were assumed to be centered within the 6" borehole. The results of the computation yielded a computed BTR of 0.110. This is substantially higher then the Effective BTR of 0.002.
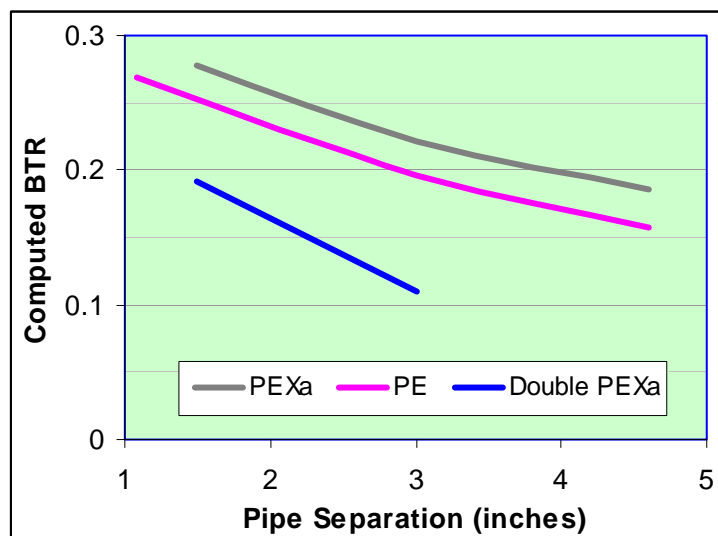

Without knowing the actual pipe spacings in the other configurations it is not possible to compute accurate BTRs. The figure above shows how the computed BTRs vary with pipe separations within a six-inch borehole with 1.0 TC grout. Increased separation significantly reduces the BTR. The figure illustrates that without knowledge of the downhole spacing and position of the pipes, any computation of BTR is poorly constrained. Even more important is the question of whether we should even use computed BTRs. Should we instead be using the Effective BTRs, since they represent the borehole thermal performance under the conditions that by design simulate actual conditions? What does the Effective BTR represent and why are they systematically lower than computed BTRs?

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The low Effective BTRs derived from test data appears to be a very common phenomenon. The discrepancy clearly results from a deviation by the real world geothermal bore from the idealized line source heat conduction model.

A clue to the cause for low Effective BTRs is revealed in the conductivity test data itself. FTC calculations are based on the measured temperature increase of heated water as it circulates through the ground loop. It is widely observed that it requires about ten hours for the rate of temperature increase to stabilize and become linear, a necessary condition to apply the line-source heat conduction model, and to calculate the FTC.

We deduce from this timing that the deviation from the idealized line source model extends on the order of three feet out from the wellbore. The figure to the right shows temperature-time curves for a line-source heat conduction model at various distances from the source, under conditions typical for full cooling-load geothermal wells and for conductivity tests. For the idealized homogeneous solid, the temperature rise at three inches (the edge of a wellbore) becomes linear after only about five minutes. The temperature at all points within this radius, including the temperature of water in the U-bends would also increase linearly from that time forward. The fact that it requires ten hours to reach linear temperature increase means that real-world deviations must extend well beyond the edge of the wellbore. After ten hours, the line source model shows that the region of linearly increasing temperature extends out three feet from the line source. The observation that temperature increases in real-world tests become linear after ten hours indicates that no significant deviations from the ideal heat conduction model are encountered beyond about three feet.
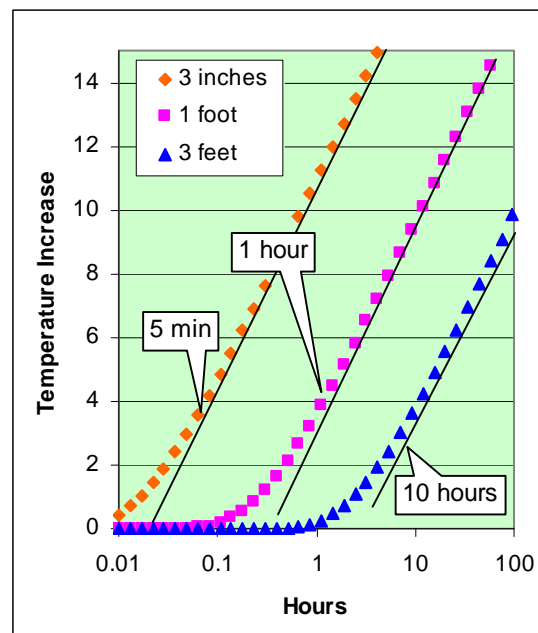
We suggest that the source of deviation from the line source model is convection of ground water within three feet around the line heat source. At the wellbore edge, a strong temperature gradient of about 20°F/ft is quickly established and maintained. This gradient imposes a strong horizontal density gradient and a drive for free convection around the wellbore. The gradient drops quickly with distance. At three feet, the gradient reaches a maximum only of about 2°F/ft, and convection would be expected to cease.

Conclusions:

We conclude that the Formation Thermal Conductivity and the Effective Borehole Thermal Resistance together describe the borehole performance under the test conditions from which these parameters are derived. Insofar as these test conditions simulate actual full cooling load operation, it should be entirely appropriate to use the Effective BTR when designing a geothermal well field performance during peak cooling mode. The Effective BTRs in the Rehau tests are significantly lower than the computed BTRs. We attribute this decrease to the actual enhancement to heat transfer from the loop into the formation due to ground water convection within one to three feet of the wellbore. It must be cautioned, however, that the Effective BTR cannot be extrapolated to the heating cycle, which operates under very different conditions from the test. Ground water reaches a maximum density of 39°F, and a temperature gradient near this temperature will induce a much smaller density gradient and smaller drive for convection. During heating mode operations, therefore, it may be more appropriate to use the computed BTR based on borehole geometry and grout conductivity.

Regardless of which set of BTR values is used to design the wellbore field, the use of double PEXa loops with spacers reduces the required loop length by 20% or more compared to single HDPE loops for the two sites modeled in this study.

About the Authors:

Justin G. Mahlmann, PE – Mr. Mahlmann has over 15 years of experience in engineering and all aspects of land development. As Managing Director of **Bowman Geothermal**, Mr. Mahlmann is responsible for oversight and growth of this division within Bowman Consulting. Additionally Mr. Mahlmann serves on the **Bowman Consulting** Board of Directors. Mr. Mahlmann has a Bachelor of Science in Civil Engineering from the University of Virginia (1994). He is registered as a Professional Engineer in Virginia, the District of Columbia, Maryland, New York, and Nevada.

Harrison Crecraft, PhD, CPG – Mr. Crecraft has over 15 years of geothermal experience. His experience includes geothermal energy resources and design and installation of over 100 geothermal ground loop systems. Mr. Crecraft has a Bachelor of Science in Geology from Brown University (1975), a Doctor of Science in Geology from the University of Utah (1983) and a Masters of Science in Computational Sciences from George Washington University (2002). He is a Certified Professional Geologist in Virginia and an IGSHPA certified installer.

Bowman Geothermal combines expertise in soils and geology with a thorough understanding of geothermal technology to deliver efficient and cost effective geoexchange systems. We provide conductivity testing, design, drilling, loop installation, and construction management to deliver turnkey systems to our residential, commercial, and institutional clients.

For additional information please contact either Mr. Mahlmann or Mr. Crecraft at:

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Borehole Design Project Report - 10/9/2009

Project Name: **Attachment 1. Typical Residence Model Information**

Loads File: *Rehau Residence.zon*   **Project Start Date:** 10/2/2009

Calculation Results

	COOLING	HEATING
Total Length (ft):	504.3	592.2
Borehole Number:	3	3
Borehole Length (ft):	168.1	197.4
Ground Temperature Change (°F):	-0.3	-0.3
Unit Inlet (°F):	90.0	35.0
Unit Outlet (°F):	100.7	28.6
Peak Load (kBtu/Hr):	54.0	60.0
Total Unit Capacity (kBtu/Hr):	79.2	60.0
Peak Demand (kW):	0.7	4.6
Heat Pump EER/COP:	14.3	3.9
System EER/COP:	14.3	3.9
System Flow Rate (gpm):	13.5	15.0

Input Parameters

Fluid		Soil	
Flow Rate	3.0 gpm/ton	Ground Temperature:	57.5 °F
Fluid:	10% Methanol	Thermal Conductivity:	1.20 Btu/(h*ft*°F)
Specific Heat (Cp):	1.02 Btu/(°F*lbm)	Thermal Diffusivity:	0.90 ft^2/day
Density (rho):	56.4 lb/ft^3		

Piping			
Pipe Type:	1 in. (25 mm)	Radial Pipe Placement:	Average
Flow Type:	Turbulent - SDR11	Borehole Diameter:	6.00 in
Pipe Resistance:	0.071 h*ft*°F/Btu	Grout Thermal Conductivity:	1.00 Btu/(h*ft*°F)
U-Tube Configuration:	Double	Borehole Thermal Resistance:	0.187 h*ft*°F/Btu

Pattern		Modeling Time Period		Extra kW	
Vertical Grid Arrangement:	3 x 1	Prediction Time:	10.0 years	Pump Power	0.0 kW
Borehole Separation:	20.0 ft	Long Term Soil Temperatures:		Cooling Tower Pump:	0.0 kW
Boreholes per Parallel Circuit:	1	*Cooling:* 57.2 °F		Cooling Tower Fan:	0.0 kW
Fixed Length Mode	Off	*Heating:* 57.2 °F		Additional Power	0.0 kW

Heat Pumps			Optional Boiler/Cooling Tower		
				Tower	Boiler
Manufacturer:	WaterFurnace				
Series:	Envision NZ Dual Vertical (Full)		Load Balance	0 %	0 %
Design Heat Pump Inlet Load Temperatures:			Capacity (kBtu/Hr)	0.0	0.0
	Cooling (WB)	*Heating (DB)*	Cooling Tower Flow Rate (gpm):	0.0	
Water to Air:	67 °F	70 °F	Cooling Range (°F):	8.7	
Water to Water:	55 °F	100 °F	Annual Operating Hours (hr/yr):	0	

Borehole Design Project Report - 10/9/2009

Project Name: **Attachment 2. Temple Hall Model Information**
Loads File: *TempleHall.zon* **Project Start Date:** 8/21/2009

Calculation Results

	COOLING	HEATING
Total Length (ft):	**5016.9**	**2802.8**
Borehole Number:	**8**	**8**
Borehole Length (ft):	**627.1**	**350.3**
Ground Temperature Change (°F):	**+0.4**	**+0.7**
Unit Inlet (°F):	**85.0**	**45.0**
Unit Outlet (°F):	**96.0**	**38.8**
Peak Load (kBtu/Hr):	**186.0**	**101.0**
Total Unit Capacity (kBtu/Hr):	**191.0**	**164.6**
Peak Demand (kW):	**1.8**	**9.3**
Heat Pump EER/COP:	**12.8**	**3.5**
System EER/COP:	**12.0**	**3.2**
System Flow Rate (gpm):	**46.5**	**25.3**

Input Parameters

Fluid		Soil	
Flow Rate	3.0 gpm/ton	Ground Temperature:	57.5 °F
Fluid:	10% Methanol	Thermal Conductivity:	1.20 Btu/(h*ft*°F)
Specific Heat (Cp):	1.02 Btu/(°F*lbm)	Thermal Diffusivity:	0.90 ft^2/day
Density (rho):	56.4 lb/ft^3		

Piping			
Pipe Type:	1 in. (25 mm)	Radial Pipe Placement:	Average
Flow Type:	Turbulent - SDR11	Borehole Diameter:	6.00 in
Pipe Resistance:	0.104 h*ft*°F/Btu	Grout Thermal Conductivity:	0.40 Btu/(h*ft*°F)
U-Tube Configuration:	Single	Borehole Thermal Resistance:	0.463 h*ft*°F/Btu

Pattern		Modeling Time Period		Extra kW	
Vertical Grid Arrangement:	4 x 2	Prediction Time: 15.0 years		Pump Power	0.9 kW
Borehole Separation:	25.0 ft	Long Term Soil Temperatures:		Cooling Tower Pump:	0.0 kW
Boreholes per Parallel Circuit:	1	*Cooling:* 57.9 °F		Cooling Tower Fan:	0.0 kW
Fixed Length Mode	Off	*Heating:* 58.2 °F		Additional Power	0.0 kW

Heat Pumps			Optional Boiler/Cooling Tower		
Manufacturer:	WaterFurnace			Tower	Boiler
Series:	Envision Large Horizontal		Load Balance	0 %	0 %
Design Heat Pump Inlet Load Temperatures:			Capacity (kBtu/Hr)	0.0	0.0
	Cooling (WB)	*Heating (DB)*	Cooling Tower Flow Rate (gpm):	0.0	
Water to Air:	67.0 °F	70.0 °F	Cooling Range (°F):	10.0	
Water to Water:	55.0 °F	100.0 °F	Annual Operating Hours (hr/yr):	0	