Determining Undisturbed Ground Temperature for Thermal Response Test

Signhild E.A. Gehlin
Associate Member ASHRAE

Bo Nordell, Ph.D., P.E.

ABSTRACT

This study treats the determination of undisturbed ground temperature in a borehole for ground heating/cooling and its effect on the accuracy of a thermal response test analysis. Three different ways of estimating temperatures were used in one groundwater-filled borehole in crystalline rock. The first method, temperature logging along the borehole, is assumed to give the correct temperature profile and results in the best estimate of the mean temperature of the ground. A good estimate is also obtained by circulating a heat carrier through the borehole heat exchanger pipes while measuring the flow temperature at a short time interval (10 seconds). The calculated temperature profile is used for deriving a mean temperature of the borehole. Heat is added to the fluid by friction heat caused by the pump work, which results in an overestimation of the borehole temperature. This influence becomes significant after 20 minutes of pumping.

INTRODUCTION

Thermal response test is a method for determining ground thermal properties for ground heat exchangers. Since its introduction in 1995-1996, this in situ method for ground-source heat pump systems has spread to most countries where borehole thermal energy storage (BTES) is used on a larger scale. The method is described in several papers, e.g., Gehlin (1998), Witte et al. (2002), Sanner et al. (2000) in Europe and Austin (1998) and Austin et al. (2000), Shonder and Beck (2000), Kavanaugh and Rafferty (1997), Kavanaugh et al. (2000), Smith and Perry (1999), Cruickshanks (2000) in North America. Most analysis procedures for estimating the ground thermal conductivity from the response test require good estimates of the undisturbed ground temperature at the site. This temperature should be determined before the response test has started. The error in the estimated thermal conductivity is then directly proportional to the error in the undisturbed ground temperature. In some line source evaluation methods the undisturbed ground temperature is eliminated in the analysis procedure. However, a good estimate of the undisturbed ground temperature is necessary for a correct design of the ground heat exchanger.

The undisturbed ground temperature increases with depth due to the geothermal gradient, an effect that cannot be neglected. The geothermal gradient varies over the world and is normally in the range 0.5-3 K per 100 m (0.3°F to 1.6°F per 100 ft). Eskilson (1987) shows that for BTES applications, it is not necessary to consider the temperature variation along the borehole. The mean temperature along the borehole is a good approximation of a homogeneous undisturbed ground temperature around the borehole.

There are mainly two ways used to determine the undisturbed ground temperature before a thermal response test. Both methods require that the borehole be at thermal equilibrium with the surrounding ground. One commonly used method is circulating the heat carrier fluid of the borehole heat exchanger through the borehole for about half an hour before the heater is switched on for the test. The collected temperature data are used to estimate the average borehole temperature. However, even though no heat is injected by the heater during this period, there will always be some heat gain to the system from the pump work.

Another method is lowering a thermocouple down the water-filled U-tube before the measurement has started. The temperature is measured every few meters along the U-pipe and the readings are used to calculate an arithmetic mean borehole temperature.

Signhild E.A. Gehlin is a graduate student and **Bo Nordell** is a professor at Luleå University of Technology, Luleå, Sweden.

TABLE 1
Data for the Test Borehole at Luleå University of Technology

Drilled depth	60 m (197 ft)
Groundwater level during test	2 m (6.5 ft)
Active borehole length	58 m (190 ft)
Borehole diameter	152 mm (6 in.)
Ground type	Hard rock (gneiss/granite)
Borehole filling	Groundwater
Collector type	Single U-tube PE DN 32 PN6
Heat carrier fluid	Water/glycol mixture

The importance of determining the undisturbed ground temperature, and various ways of doing it, has previously been discussed by, e.g., Kavanaugh et al. (2000), who also presents measurements. Kavanaugh recommends activating the pump and recording the minimum temperature as a good estimate of the initial ground temperature.

The Borehole

The experiments were conducted in a well-documented borehole (Nordell 1985, 1986, 1994) at Luleå University of Technology. The borehole is drilled in hard crystalline rock to a depth of 60 m (197 ft) and fitted with a single water/glycol mixture filled U-tube. The borehole is groundwater filled and not grouted, which is the normal case in Sweden. A summary of borehole data is found in Table 1.

The borehole is one of 120 boreholes in an old high-temperature borehole storage. The 10 × 12 borehole heat storage was shut down in 1990, after six years of operation, and the ground is still thermally disturbed by the heat storage. The normal annual mean ground surface temperature in the area is 3.5°C (38.3°F), but even ten years after the closing down of the heat storage, the peripheral boreholes are still measuring around 13°C (55.4°F).

The test borehole is number 4 out of 12 in the outermost borehole row on one side of the store, and this and other holes have been used for several thermal response tests since 1996 (Gehlin 1998).

The Response Test Equipment

The response test device used in this experiment was constructed at Luleå University of Technology in 1995-1996 (Eklöf and Gehlin 1996; Gehlin and Nordell 1997). It is set up on a small covered trailer and consists of an in-line electric resistance heater, instrumentation, and an 85-liter (22.5-gallon) tank used for purging and as an expansion tank. The tank also contains fluid for the initial filling of the pipe system.

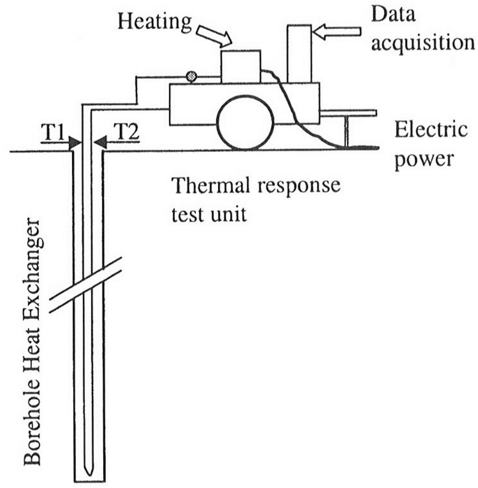

Figure 1 *Thermal response test setup.*

A 1.75 kW (5970 Btu/h) pump circulates the heat carrier fluid through the borehole. The heater has step-wise adjustable power rates in the range of 3-12 kW (10,200-40,950 Btu/h). Fluid temperatures are measured by thermocouples at the inlet and outlet of the borehole. The fluid temperatures, ambient air temperature, air temperature inside trailer, and power rate are recorded at an optional preset time interval. A more thorough description of the response test apparatus is given in Gehlin (1998).

When running the test, the response test facility is placed as close as possible to the test borehole and is connected to the fluid-filled borehole pipes. The connection pipes are filled with fluid from the purge tank (air separator) and the test loop (i.e., the collector pipes and the response test device) is purged. Exposed parts between the borehole and the response test apparatus are well insulated. The purge tank (air separator) is connected to the pipe system to collect air bubbles but the fluid is not flowing through the tank. Once the pipe system is full, no fluid is added to the pipe system from the tank; in fact, a small inflow into the tank is caused by the volume expansion of heated fluid. The test procedure is fully automated as soon as the test has started. The principle of a thermal response test setup is seen in Figure 1.

MEASUREMENTS

Method 1—Temperature Logging Along the Borehole

A temperature sensor (PT104) at the end of a 70 m (230 ft) cable (about 5 mm [0.2 in.] diameter) was lowered down the groundwater-filled borehole. The cable was connected to a universal instrument, set for PT104, on which the temperature logging was read manually. Lead weights were attached to the end of the cable to pull the sensor and cable down the borehole. Meter values were marked along the cable, starting with 0 m (0 ft) at the sensor and ending with 70 m (230 ft) near the connection to the universal instrument. The borehole was in thermal equilibrium with its surroundings when the logging started.

Temperatures were read every meter for the uppermost 10 meters (33 ft) of the borehole and every second meter below that level all the way down to the bottom of the borehole. The resulting temperature profile along the borehole is shown in Figure 2. An arithmetic mean temperature of 11.8°C (53.2°F) was calculated from the groundwater table and down to the bottom of the borehole. The water table was, at this time of the year (October 2001), 2 m (6 ft) below ground surface (see Table 1) and the ambient air temperature was 0°C (32°F). Only the active part of the borehole, i.e., below the groundwater table (standing column) or below the top of the grout, is included in the mean temperature estimation. This active part of the ground heat exchanger accounts for the essential part of the heat transfer. The upper part of the borehole does not reflect the ground temperature but is disturbed by ambient conditions (air temperature, wind, and rain).

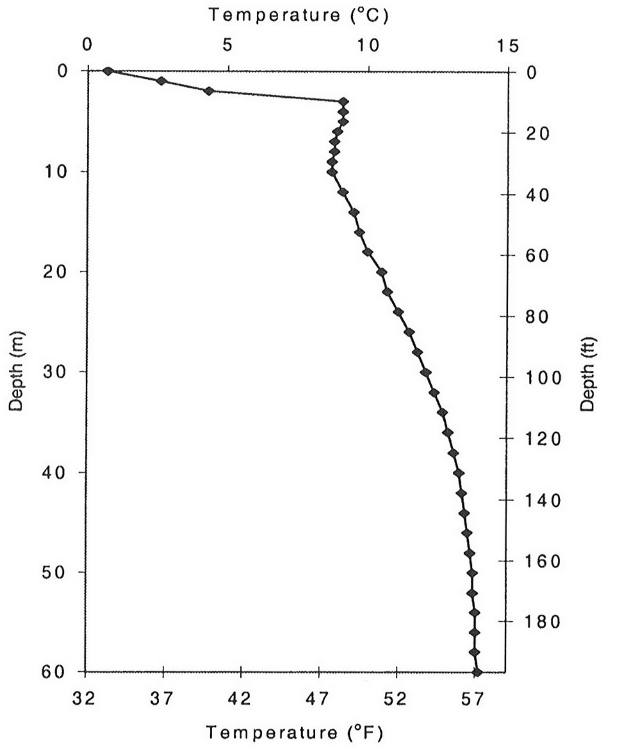

Figure 2 *Temperature profile along the test borehole.*

Method 2—Flow Temperature Measurements at 10-second Interval

After the manual temperature logging was completed, the borehole collector pipes were connected to the thermal response test device. The data logger was set to record the inlet and outlet temperatures every 10 seconds during the experiment. The electric resistance heater was off during the test. The heat carrier in the collector U-tube was allowed to circulate for 77 minutes, and the initial 10 minutes of circulation gave a temperature profile of the fluid flow in the collector pipes, as seen in Figure 3. The temperature measurements were analyzed assuming plug flow and no delay in temperature recording, which means that measurements taken at certain times correspond to certain depths. The plug flow assumption is reasonable in small diameter pipes and the temperature recordings are reliable, as small temperature sensors immersed in the fluid were used.

The recorded temperatures show the influence of the fluid in the above ground piping, which had come to equilibrium with the environment. It is seen as initial temperature downward spikes in Figure 6. At the time when the experiment was

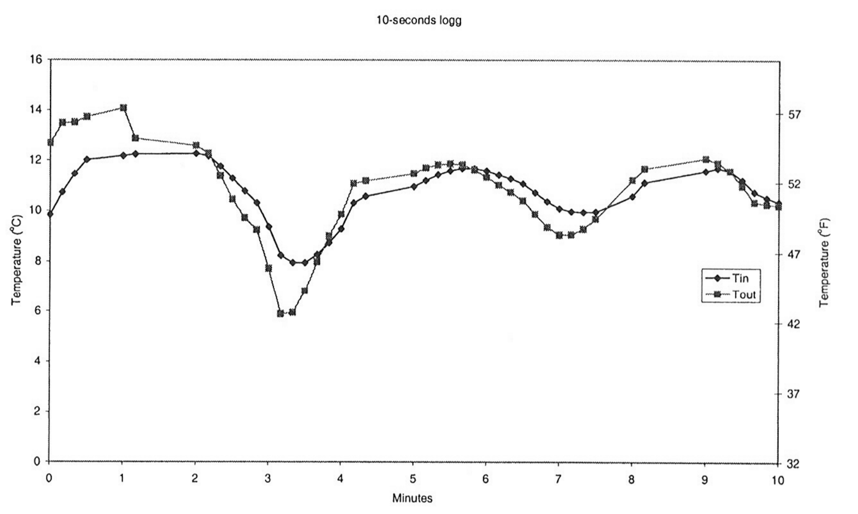

Figure 3 *Collector pipe plug-flow temperatures logged at 10-second time interval.*

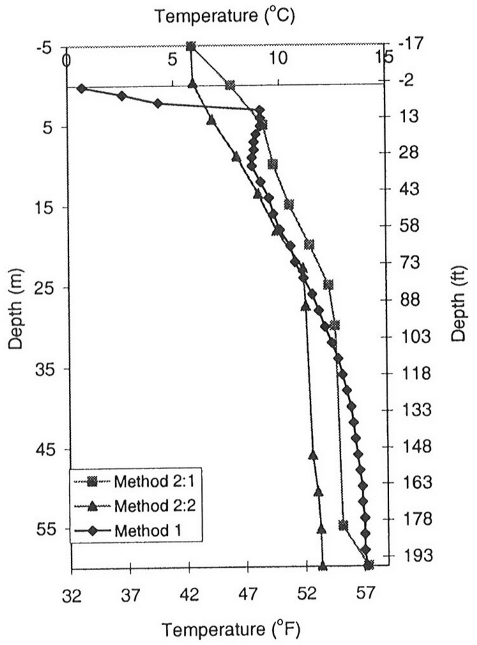

Figure 4 *Borehole temperature profiles determined by method 1 and method 2.*

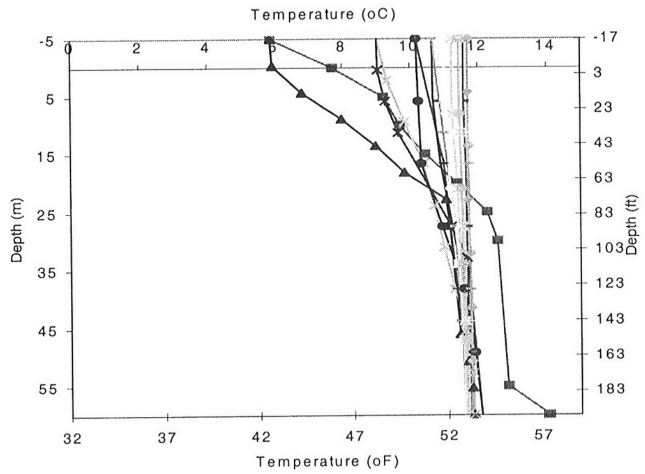

Figure 5 *Fluid temperatures during the initial 15 minutes.*

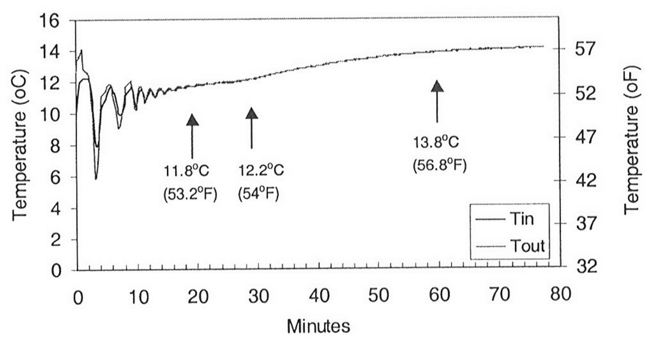

Figure 6 *Ten-second interval temperature loggings in the borehole.*

conducted, the ambient air temperature was about 0°C (32°F) and there was a slight snowfall. Thus, the ambient air was cooling the heat carrier. A comparison of the manual temperature log and the temperature profiles from the first cycle (up and down) is shown in Figure 4. Arithmetic mean temperatures were calculated for the first cycle—one for the up-flow and one for the down-flow. The first profile gives a mean temperature of 11.7°C (53.1°F), and the second profile gives 10.3°C (50.5°F). Thus, the cooling effect of the ambient conditions is clearly seen in the latter.

Method 3—Flow Temperature After Period of Circulation

The heat carrier fluid was circulated for 77 minutes. After approximately 15 minutes, the temperature fluctuations along the borehole even out. A plot of all temperature profiles from the first 15 minutes of circulation is seen in Figure 5. Each line represents a temperature profile along the borehole at different times of the test. The profiles converge at the mean borehole temperature of 11.8°C (53.2°F). The fluid velocity was estimated from the time between peak temperatures (see Figure 6) and the known flow distance through the pipe system.

As seen in Figure 6, the fluid temperature increases with time. Plug flow is assumed through the pipe system though some mixing of colder and warmer water occurs. This effect does not influence the estimation of undisturbed ground temperature. After 30 minutes, the fluid temperature is 12.2°C (54°F) and after 60 minutes, it reads 13.8°C (56.8°F). The increase of the mean fluid temperature is caused by the heat gain from the 1.75 kW (5970 Btu/h) circulation pump.

RESULTS AND DISCUSSION

The resulting estimations of the undisturbed ground temperature around the test borehole with the three different methods are summarized in Table 2.

The undisturbed ground temperature calculated from the manual log and the temperature calculated from the recordings from the first few minutes of circulation in the pipes show an agreement within 0.1°C (0.2°F). After about 15 minutes (velocity 1 m/s [3.3 ft/s]), the temperature fluctuations in the pipe ceased. The temperature readings of the fluid after 20, 30, and 60 minutes showed that the value at 20 minutes of circulation agreed well with the manual log, whereas the heat gain from the circulation pump to the fluid overestimates the undisturbed temperature by 0.4°C (0.7°F) after 30 minutes. After 60 minutes, the overestimation is 2°C (3.6°F).

In this test, a 60 m (197 ft) borehole and a 1.75 kW (5970 Btu/h) circulation pump were used. The temperature disturbance occurring from the circulation pump is proportional to the specific power load on the measured borehole; thus, a

TABLE 2
Summary of Mean Borehole Temperatures Estimated with the Different Methods in the Study

Method	Resulting Temperature Estimation
Method 1—Temperature logging along the borehole	11.8°C (53.2°F)
Method 2—Flow temperature measurements at 10-second interval (1st pulse)	11.7°C (53.1°F)
Method 2—Flow temperature measurements at 10-second interval (2nd pulse)	10.3°C (50.5°F)
Method 3—Flow temperature after 20 minutes of circulation	11.8°C (53.2°F)
Method 3—Flow temperature after 30 minutes of circulation	12.2°C (54°F)
Method 3—Flow temperature after 60 minutes of circulation	13.8°C (56.8°F)

smaller pump or deeper borehole would result in a less disturbed temperature.

At the time of the measurement, the temperature of ambient air was considerably lower than the ground temperature, and although the connection pipes and coupling of the test device were insulated, some cooling of the circulation circuit occurred. In the case of warmer weather or solar radiation during the response test, the circuit will be warmed. The disturbance from the ambient conditions will be smaller for deeper boreholes and with better insulation of exposed parts of the test device.

The undisturbed ground temperature profile from the test borehole is, in this specific case, slightly rounded. Normally the ground temperature will increase more or less linearly with depth below a few meters depth, above which the seasonal variation of the ground surface temperature will characterize the temperature profile. The reason for the rounded shape of the test borehole temperature profile is the heat (or temperature) distribution in the old heat store. The law of diffusion gives that the warmest temperatures in the heat storage volume will be found in the center. This nonlinear temperature distribution along the borehole does not interfere with Eskilson's (1987) approximation of a homogenous ground temperature.

The temperature estimation recommended by Kavanaugh et al. (2000), to use the recorded minimum flow temperature, is not supported by measurements performed. This recommendation would give a strongly underestimated temperature in this case (see Figure 6).

CONCLUSION

Temperature logging of the borehole is assumed to give the correct undisturbed ground temperature profile. Short interval fluid temperature logging gives an estimation that is close to the undisturbed temperature. In this case, with a relatively large circulation pump and a shallow borehole, it cannot be recommended to use the temperature reading after 30 minutes of fluid circulation as an estimation of the undisturbed ground temperature. A maximum of 20 minutes of circulation is the limit for a reasonable estimation of the ground temperature from one reading, in this case. In a deeper borehole, the disturbance from the circulation pump would be smaller, and it would take a longer time for the temperature fluctuations in the pipe to cease.

A high ambient air temperature could affect the ground temperature estimation, i.e., shorten the measurement time within which reliable temperatures are obtained. A possible approach would be to use the intercept temperature as the undisturbed ground temperature. This would need further investigation.

ACKNOWLEDGMENTS

The economic support by The Swedish Council for Building Research, the Swedish Heat Pump Association, and Luleå University of Technology is gratefully acknowledged.

REFERENCES

Austin III, W.A. 1998. Development of an in-situ system for measuring ground thermal properties, Master's thesis, Oklahoma State University, Stillwater, Oklahoma.

Austin III, W.A., C. Yavuzturk, and J.D. Spitler. 2000. Development of an in-situ system for measuring ground thermal properties. *ASHRAE Transactions*. 106(1): 365-379. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Cruickshanks, F., J. Bardsley, H.R. Williams. 2000. In-situ measurement of thermal properties of cunard formation in a borehole, Halifax, Nova Scotia. *Proceedings of the 8th International Conference on Thermal Energy Storage*, Terrastock 2000, 28 August – 1 September 2000, Stuttgart, Germany.

Eklöf, C., and S. Gehlin. 1996. TED—A mobile equipment for thermal response test, Master's thesis 1996:198E, Lulea University of Technology, Sweden.

Eskilson, P. 1987. Thermal analysis of heat extraction boreholes. Lund-MPh-87/13, Dept. of Mathematical Physics, Lund Institute of Technology, Sweden.

Gehlin, S. 1998. Thermal response test, in-situ measurements of thermal properties in hard rock, Licentiate thesis. Luleå University of Technology, Department of Environmental Engineering, Division of Water Resources Engineering. 1998:37. (Available at <http://

epubl.luth.se/1402-1757/1998/37/LTU-LIC-9837-SE.pdf>.)

Gehlin, S., and B. Nordell. 1997. Thermal response test—A mobile equipment for determining thermal resistance of boreholes. *Proceedings Megastock'97*, Sapporo. Japan. June 18-21 1997, pp. 103-108.

Kavanaugh, S.P., et al. 2000. Investigation of methods for determining soil and rock formation thermal properties from short term field tests. Final Report for ASHRAE TRP-1118.

Kavanaugh, S.P., and K. Rafferty. 1997. *Ground Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Nordell, B. 1985. The borehole heat store at Luleå, Sweden, ENERSTOCK 85, Int. Conf. on Energy Storage for Building Heating and Cooling. Toronto, Canada, Sept. 1985.

Nordell, B. 1986. Large-Scale seasonal heat storage in rock. Construction and operation experiences. Int. Symp. on Engineering in Complex Rock Formations. Nov 1986. Beijing, China, p. 361-366.

Nordell, B. 1994. Borehole heat store design optimization, Doctoral thesis 1994:137D. Division of Water Resources Engineering, Luleå University of Technology, Sweden.

Sanner, B., M. Reuss, and E. Mands. 2000. Thermal response test—Experiences in Germany. *Proceedings Terrastock 2000*, 8th International Conference on Thermal Energy Storage, Stuttgart, Germany, August 28 – September 1, 2000. Vol I, pp. 177-182.

Shonder, J.A., and J.V. Beck. 2000. A new method to determine the thermal conductivity of soil formations from in situ field tests. ORNL/TM-2000/97. Oak Ridge National Laboratory, Tennessee. (Available at <http://www.ornl.gov/femp/pdfs/soilproperties.pdf>.)

Smith, M., and R. Perry. 1999. In-situ testing and thermal conductivity testing. *Proceedings of The 1999 GeoExchange Technical Conference & Expo*, Oklahoma State University, Stillwater, Oklahoma, May 16-19, 1999.

Witte, H.J.L., G.J. van Gelder, and J.D. Spitler. 2002. In situ measurements of ground thermal conductivity: The Dutch perspective. *ASHRAE Transactions* 2002, No. 1.