THERMAL RESPONSE TEST, A ROUTINE METHOD TO DETERMINE THERMAL GROUND PROPERTIES FOR GSHP DESIGN

B. Sanner, E. Mands, M. K. Sauer, E. Grundmann
UBeG GbR, Zum Boden 6, D-35580 Wetzlar, Germany

Abstract: To design borehole heat exchangers (BHE) for Ground Source Heat Pumps (GSHP) or Underground Thermal Energy Storage (UTES), the knowledge of underground thermal properties is paramount. In particular for larger plants (commercial GSHP or UTES), the thermal conductivity should be measured on site. A useful tool to do so is a thermal response test, carried out on a borehole heat exchanger in a pilot borehole (later to be part of the borehole field). For a thermal response test, basically a defined heat load is injected into the BHE, and the resulting temperature changes of the circulating fluid are measured. The paper includes a short description of the basic concept and the theory behind the thermal response test, reviews shortly the world-wide uptake and experience of this technology, and gives the main emphasis on the experience in routine operation of the test, and on the economic reasons for testing.

Key Words: ***ground source heat pumps, underground thermal properties***

1 INTRODUCTION

The knowledge of underground thermal properties is a prerequisite for correct design of borehole heat exchangers (BHE). The most important parameter is the thermal conductivity of the ground. Since the mid 90s a method has been developed and refined to measure the underground thermal properties on site, and mobile equipment for these measurements has been built in several countries.

The Thermal Response Test (TRT, also called “Geothermal Response Test”, GeRT) is a suitable method to determine the effective thermal conductivity of the underground and the borehole thermal resistance (or the thermal conductivity of the borehole filling, respectively). A temperature curve is obtained which can be evaluated by different methods. The thermal conductivity obtained by this method is a value for the total heat transport in the underground, in the notation of thermal conductivity. Other effects like convective heat transport (in permeable layers with groundwater) and further disturbances are automatically included, so it may be more correct to speak of an “effective” thermal conductivity λ_{eff}.

There are many possible sources of error when performing a TRT. They can be grouped in two categories:
- Underground influence (high regional groundwater flow, confined or artesian groundwater in combination with not or poorly grouted BHE, karst, etc.)
- Technical influence (fluctuations of thermal power, sensor errors/failures, system leakage, etc.; also poor thermal insulation in combination with solar irradiation or ambient temperature changes)

Some external influence by groundwater flow or by power fluctuations can be accounted for when using numerical simulation for test evaluation. However, there are practical cases where a meaningful test result can not be obtained at all, due to this external influence. The

TRT is nevertheless a very helpful tool in most BHE projects, allowing for design based upon reliable, measured values instead of estimated data.

2 DEVELOPMENT OF THE THERMAL RESPONSE TEST

The theoretical basis for the TRT was laid over several decades (e.g. by Mogensen, 1983), its use for determining ground parameters first suggested by Claesson & Eskilson (1988, p. 525). In the 90s the first practical applications were made, e.g. for the investigation of borehole heat storage (BTES) in Linköping (Hellström, 1997). Heat was injected into the total BTES with 100 single-U-pipes of 10 m depth each; the resulting temperature curves are, beside the much longer duration, very similar to those of current mobile TRT (fig. 1).

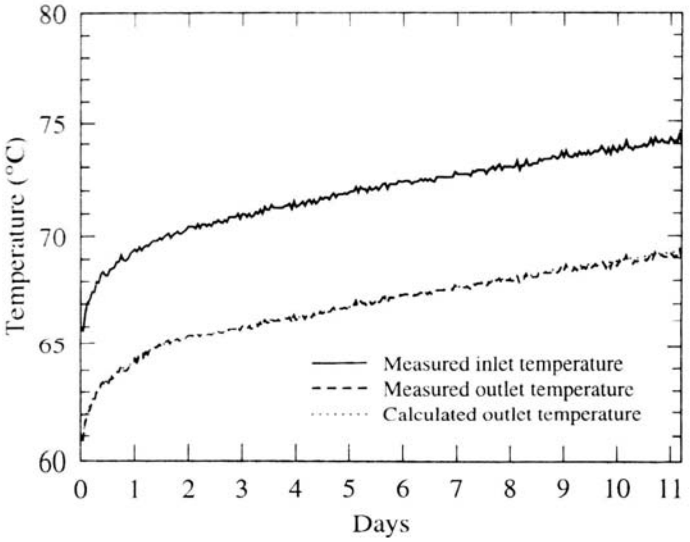

Figure 1: Thermal Response Test at Linköping BTES (original graph from Hellström, 1997)

In 1995 a mobile test equipment (fig. 2) was developed at Luleå Technical University to measure the ground thermal properties for BHE between some 10 m to over 100 m depth (Eklöf & Gehlin, 1996; Gehlin & Nordell, 1997). A similar development was going on independently since 1996 at Oklahoma State University in the USA (Austin, 1998). Annex 8 of the IEA Energy Storage Implementing Agreement (Nordell, 2000) became the platform for discussion and further development of TRT from summer 1996 on.

Figure 2: Swedish TRT rig similar to the original one ("TED") from 1995, on site and coupled to a BHE (left, photo: Hellström); the first UBeG "GeRT" of 1999 on site at DFS Langen (centre) and its interior with the heating unit in the background and the control box to the right (right)

The first TRTs in Germany were performed in summer 1999, with UBeG GbR doing a test (fig. 2) for the design of a large BHE field for the German Air Traffic Control (DFS) in Langen

(Sanner et al., 1999). In the meantime the GeRT tests done by UBeG GbR count in hundreds, throughout Germany and in the neighbour countries (Austria, Belgium, France, Italy). UBeG GbR did also help to create thermal response test services in other European countries, by exporting equipment, software and knowledge to Greece, the United Kingdom, and Spain. In 2003, design help for a thermal response test rig was given in the frame of a South Korean BHE test plant (Sanner & Choi, 2005), and in 2004 a rig was exported to China and in 2005 one to South Korea. The hardware was accompanied in all cases by the necessary evaluation software and training for the operation personnel (fig. 3).

Figure 3: Training for GeRT in Beijing, China (2004) and in Athens, Greece (2007); in both cases Marc Sauer of UBeG GbR acts as instructor

A more detailed history and an overview of the world-wide status is given in Sanner et al. (2005). By the end of 2007, test rigs where available in many European countries, and in some countries like Germany a market with an increasing number of actors and growing competition has developed.

3 PERFORMING AND EVALUATING A THERMAL RESPONSE TEST

3.1 Test equipment and site measurements

The general layout of a TRT is shown in fig. 3. For good results, it is crucial to set up the system correctly and to minimize external influences. With resistance heating, the fluctuations of voltage in the grid may result in fluctuations of the thermal power injected into the ground. Another source of deviation are climatic influences, affecting mainly the connecting pipes between test rig and BHE, the interior temperatures of the test rig, and sometimes the upper part of the BHE in the ground. Insulation and sometimes shading is required to protect the connecting pipes. With open or poorly grouted BHE, also rainwater intrusion may cause temperature changes. A longer test duration allows for statistical correction of power fluctuations and climatic influence, and results in a more trustworthy evaluation. A typical test curve with low external influence (weather, power, nearby drilling) is shown in fig. 3.

The test rigs have been reduced in size considerably since the first experiments. Fig. 4 shows the current generation of UbeG GbR test rigs, built in a small series and housed in a special water-proof box. All facilities for heating, control and data acquisition are integrated. Mattson et al. (2007) report on similar efforts for size reductions in Switzerland.

The UBeG GbR unit can be mounted onto a motor crawler, which allows one single person to unload the equipment from a smaller van, to bring it to the BHE even in rough site conditions, to connect it, to start the test, and later to retrieve test equipment and data. The test duration is >48 h, so ideally the unit arrives on site before noon, is set up and started, and is retrieved in the afternoon of the second day after. When choosing a weekend, even 3 days test duration can be achieved easily, by starting the test on Friday and retrieving the unit on Monday. Another advantage of weekends is given by the fact that typically there is a break in work on sites with drilling or construction, minimising external disturbances.

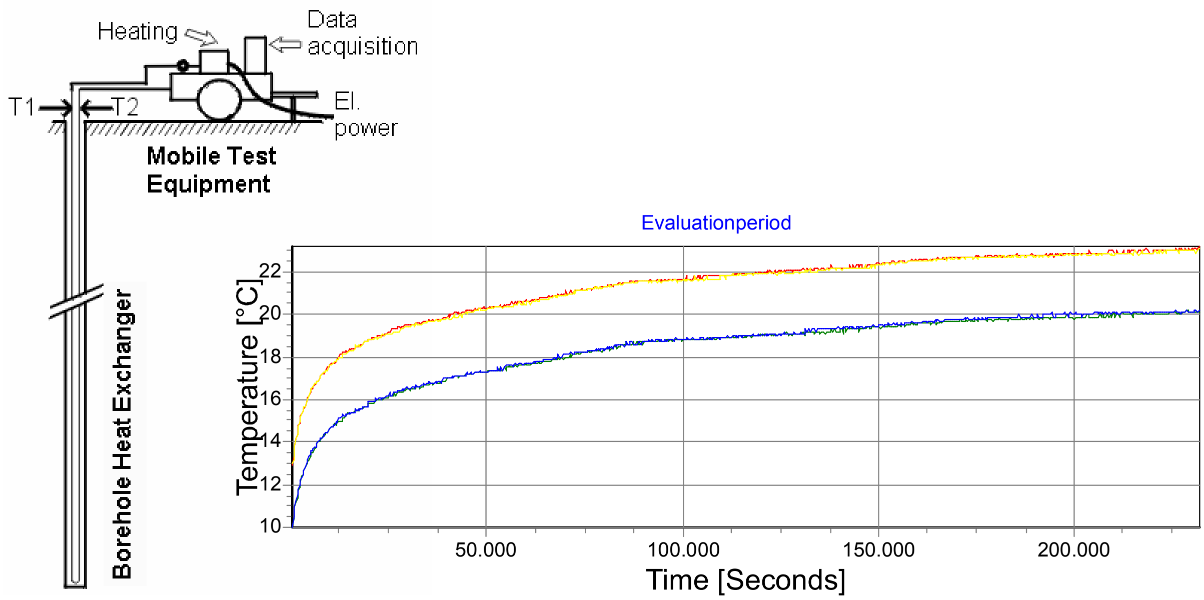

Figure 3: Schematic of TRT installation (left) and example of temperature curve with low external influence from climate or power fluctuation (right; cf. fig 1)

Figure 4: Latest generation of UbeG test units (GeRT); transported to the site in a small van (left) and moved on site to the BHE on a crawler, even in rough terrain (right)

3.2 Evaluation

The easiest way to evaluate thermal response test data makes use of the line source theory. This theory already was used in the 40s to calculate the temperature development in the ground over time for ground source heat pump plants (Ingersoll & Plass, 1948). An approximation is possible with the following formula, given in Eklöf & Gehlin (1996):

$$k = \frac{Q}{4\pi H \lambda_{eff}} \qquad [1]$$

with		
	k	Inclination of the curve of temperature versus logarithmic time
	Q	heat injection/extraction
	H	length of borehole heat exchanger

λ_{eff}	effective thermal conductivity (incl. influence of groundwater flow, borehole grouting, etc.)

To calculate thermal conductivity, the formula has to be transformed:

$$\lambda_{eff} = \frac{Q}{4\pi H k} \qquad [2]$$

A more time-consuming method to evaluate a thermal response test is parameter estimation using numerical modelling. Original work on parameter estimation was done by, among others, Spitler et al. (1999, 2000), and Shonder & Beck (1999). These methods can enhance accuracy, in particular in cases where fluctuating heat load and convective influence from groundwater has to be accounted for, and they may yield additional information. A reduction of the necessary test duration by applying parameter estimation is possible only in few cases, as the physical impact of heat injection has to reach out from the borehole into the surrounding ground before a meaningful result can be obtained. However, parameter estimation allows for getting results already in a transient thermal regime, while line-source approximation requires quasi steady-state for good results.

UBeG GbR typically uses the line-source method for routine evaluation. The software program GeRT-CAL, developed in-house, enables quick and accurate performance of this task, including a step-wise evaluation to check the validity of the result (see following chapter). Only for cases with incomplete temperature curves, external influences, or specific requirements parameter estimation is applied. The FE-Software FEFLOW® (Diersch, 2006) has proven suitable for the related numerical simulations.

4 BOREHOLE THERMAL RESISTANCE

The thermal conductivity of the underground is site-specific and cannot be influenced by engineering. The thermal contact from the borehole wall to the fluid inside the pipes, however, is controlled by borehole diameter, pipe size and configuration, pipe material, and the filling inside the annulus. These items are subject to efforts in order to reduce the thermal resistance between borehole wall and fluid, usually summarised in the parameter “borehole thermal resistance” (first introduced by Claesson & Eskilson, 1988, p. 520).

In a TRT, the borehole thermal resistance (r_b) can be determined using the following formula:

$$r_b = \frac{H}{Q} \cdot \left(T_f - T_0\right) - \frac{1}{4\pi\lambda} \cdot \left(\ln(t) + \ln\left(\frac{4\alpha}{R_0^{\,2}}\right) - 0{,}5772 \right) \qquad [3]$$

with	Q	heat injection (W)
	H	borehole depth (m)
	T_0	initial ground temperature (°C)
	λ	thermal conductivity (W/m/K)
	α	thermal diffusivity, $\lambda/\rho c_p$ (m^2/s)
	R_0	borehole radius (m)

When using parameter estimation techniques, typically the individual constituents of r_b are found (e.g. thermal conductivity of the grout), and r_b can be calculated.

The determination of r_b with TRT was used to verify the impact of thermally enhanced grout on the heat transfer properties of BHE (e.g. Sanner, 2003). With increasing the thermal conductivity of the borehole filling (grout), the borehole thermal resistance r_b is decreased. In fig. 5 r_b is plotted against the borehole diameter. As should be expected, r_b increases with increasing borehole diameter; however, two fields of data can be seen, for standard grouting (values typically >0.1 K/(W/m)) and for thermally enhanced grout (typically <0.1 K/(W/m)).

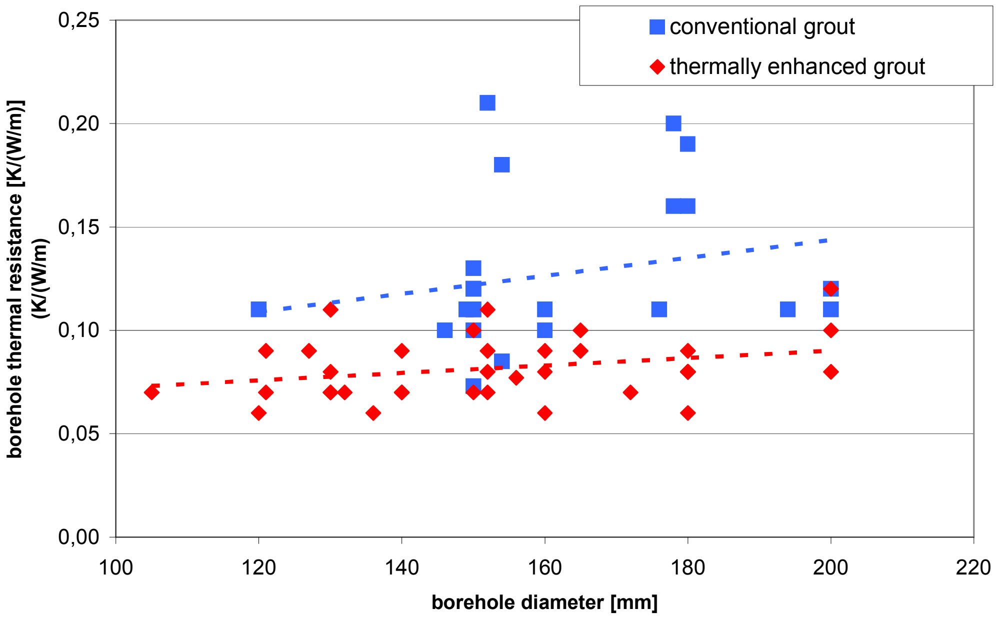

Figure 5: Borehole thermal resistance vs. borehole diameter of 21 BHE with standard grouting and 30 BHE grouted with thermally enhanced material, determined by TRT

5. VALIDITY OF THERMAL RESPONSE TEST

5.1 Reproducing test results

Results from TRT can be reproduced, and different rigs on the same site did yield similar results with good accuracy. A comparison of three different TRT-rigs from Germany and the Netherlands took place in October 2000 at the site for a new BTES system in Mol, Belgium, in the context of a workshop within Annex 12 and 13 of the IEA Energy Storage Implementing Agreement (Mands & Sanner, 2001). 3 BHE with different grout were available for the test. The Dutch test in bentonite-grouted BHE had some problems during the test period, and the values should not be considered. The other tests resulted all in a thermal conductivity of the ground between 2,40 and 2,51 W/m/K, while the r_b was different according to the various backfill materials (table 1). In the saturated underground situation in Mol, simple sand provided the lowest value for r_b, while the standard bentonite grout did not perform as good.

Table 1: Results of the tests at Mol TRT workshop in 2000 (unit 1 from NL, unit 2 is the one from UBeG GbR; only the Dutch one tested all BHE, for the bentonite-grouted BHE see text)

Grouting \ TRT-unit	1	2	3
Mol-sand	λ = 2.47 W/m/K r_b = 0.06 K/(W/m)	-	λ = 2.47 W/m/K r_b = 0.05 K/(W/m)
Graded sand	λ = 2.40 W/m/K r_b = 0.1 K/(W/m)	-	λ = 2.51 W/m/K r_b = ?
Bentonite	*λ = 1.86 W/m/K* *r_b = 0.08 K/(W/m)*	λ = 2.49 W/m/K r_b = 0.13 K/(W/m)	-

In Langen (cf. fig. 2) a total of 4 tests was made in the same BHE-field, the first for design in 1999, the others during the construction of the BHE-field in 2000. One of the tests was performed with equipment from Eastern Germany in order to compare the results, but due to external acts no trustworthy data could be obtained with this particular test. The results of the other three tests, all performed by UBeG GbR, are listed in table 2. While tests 2 and 3 show very similar results, test 1 is somewhat different. The reason is that the BHE for test 1 was 99 m deep (exploration borehole), the depth for the rest of the BHE was decreased to 70 m during the design optimisation for cooling, and thermally enhanced grout was used in 2 and 3. So in the later tests the geological layers with higher thermal conductivity below 70 m are not reached, and the new grout resulted in lower r_b.

On another site in Germany, in Mainz, two tests were made in virtually the same lithological underground conditions. The results (table 2) show a very close match of the ground thermal conductivity; the r_b-values vary somewhat and are generally on the high side, which was caused by the use of an inadequate grouting material.

Table 2: Results of multiple GeRT on the same site

	thermal conductivity λ	borehole thermal resistance r_b
Location in Langen, Germany, tests in 1999 (Langen 1, BHE 99 m) and 2000 (Langen 2 and 3, BHE 70 m)		
Langen 1	2.8 W/m/K	0.11 K/(W/m)
Langen 2	2.3 W/m/K	0.08 K/(W/m)
Langen 3	2.2 W/m/K	0.07 K/(W/m)
Location in Mainz, Germany, test in summer 2003		
Mainz 1	1.43 W/m/K	0.16 K/(W/m)
Mainz 2	1.41 W/m/K	0.20 K/(W/m)

5.2 Limitations for TRT and external influences

A limitation to TRT is the amount of groundwater flow. Because the thermal conductivity obtained includes convection effects, with high groundwater flow the thermal conductivity *sensu strictu* becomes masked, and the values cannot be used for design of BHE plants. The groundwater flow considered here is not the simple velocity (the time a water particle travels from one point to another, e.g. in m/s), but the Darcy-velocity, which is a measure for the amount of water flowing through a given cross-section in a certain time ($m^3/m^2/s$, resulting also in m/s). The Darcy-velocity thus depends on the porosity and the velocity.

A useful method to check for excessive groundwater flow in the standard line-source evaluation is the step-wise evaluation with a common starting point and increasing length of data-series. The resulting thermal conductivity for each time-span can be calculated and plotted over time. Usually in the first part of such a curve the thermal conductivity swings up and down, converging to a steady value and a horizontal curve in the case of a prefect test. If this curve continues to rise (i.e. the more heat is carried away the longer the test lasts), a high groundwater flow exists and the test results may be useless (fig. 6). This method also shows if other external factors (weather, unstable power for heating, etc.) are disturbing the measurement.

An even more problematic kind of groundwater influence is groundwater flowing upwards or downwards in the borehole annulus. This may occure in open boreholes (standard in Scandinavia), but also in poorly grouted BHE or in those backfilled with sand. In combination with confined aquifers or other vertical pressure differences this leads to tests which cannot be evaluated at all. Fig. 7 shows an example.

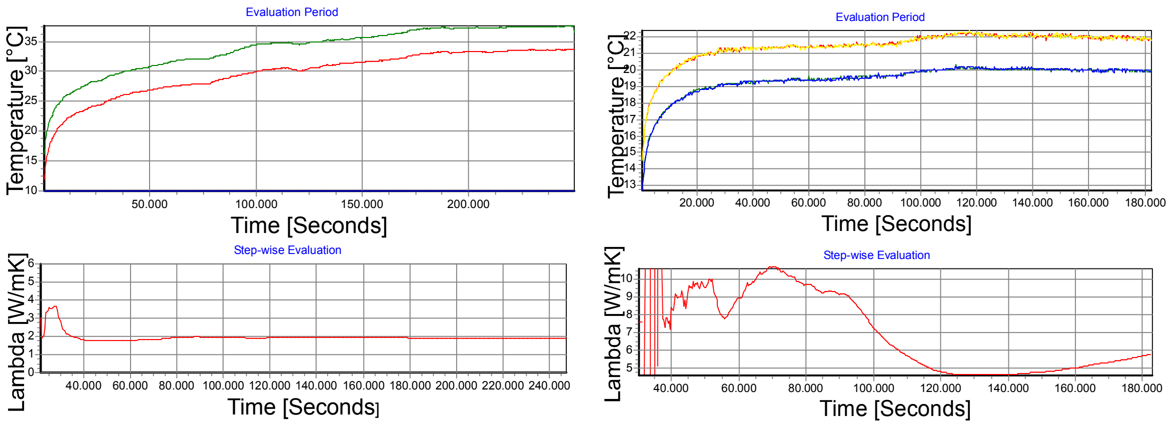

Figure 6: Raw data graph and step-wise evaluation showing perfect convergence (left), and the same from a test with high groundwater flow and unreasonably high thermal conductivity value (right); evaluation using GeRT-CAL

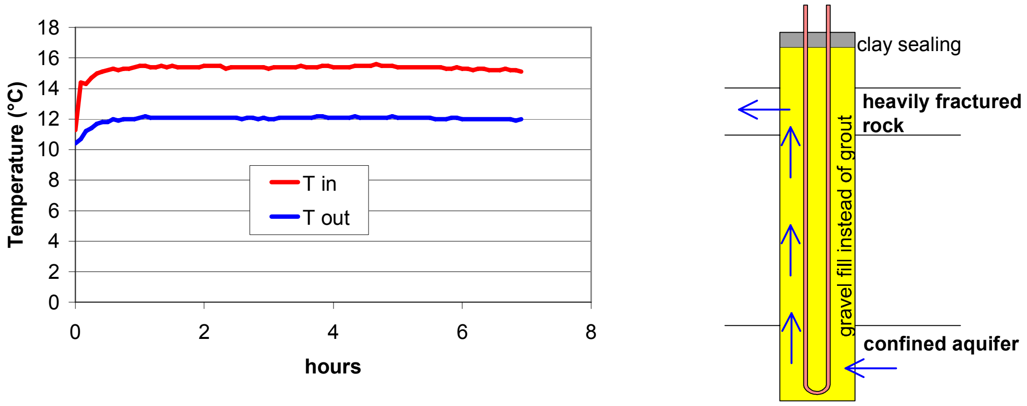

Figure 7: TRT with vertical groundwater flow along the borehole axis, temperature is stable after short time (left), and explanation (right)

5.3 Supporting temperature logs

With small sensors temperature logs can be recorded inside the BHE. UBeG GbR routinely runs the following logs:

- one log before starting the test, in order to see the undisturbed ground conditions,
- two logs after the test has been stopped (one log <1 hour after stop, the other about 1 hour later).

Measuring during operation of the test is not possible.

The temperature logs help to identify zones of higher or lower heat transport along the borehole axis. As the TRT results give an average value for thermal conductivity over the whole BHE length, the temperature logs allow some vertical differentiation. In fig. 8 a test is shown, where a strong groundwater influence can be seen in a very narrow zone (sand on top of silt). After 1 hour almost all temperature increase has vanished in the high permeable zone. Nevertheless, in this case the value for thermal conductivity is not much affected, because the permeable layer is not thick and the actual amount of water relatively low

6 ECONOMIC REASONS FOR THERMAL RESPONSE TEST

Fig.9 shows a comparison of 86 thermal conductivity data, where those hade been estimated from expected lithology in pre-feasibility studies, and later been measured with TRT. In 25%

of the cases the estimated values have been higher, which means that the TRT was required to adjust the design to a sound level. In 65% the TRT allowed for cost savings, where the underground conditions were better than expected. Only in 8% the measurement did yield the estimated value with some accuracy. The deviation was higher than ±0,5 W/m/K in 45%.

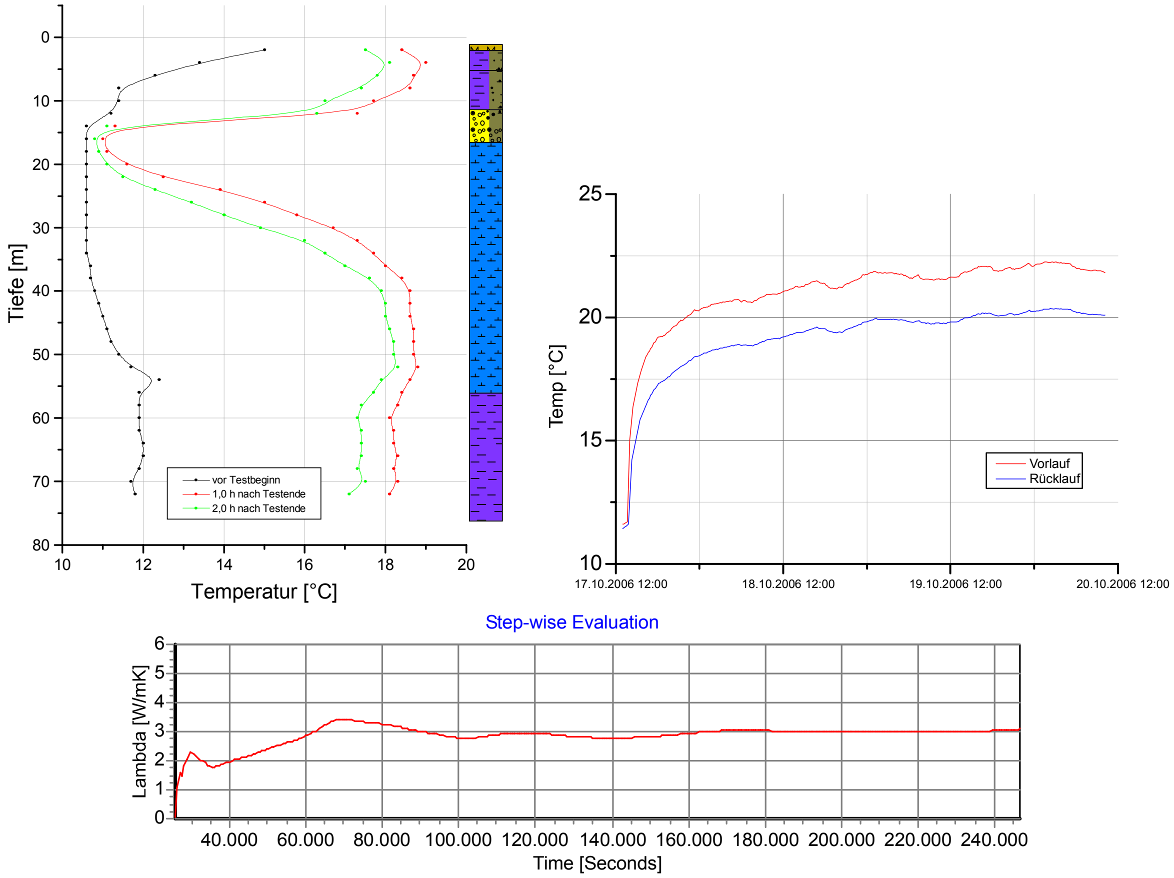

Figure 8: TRT with groundwater flow in a narrow zone at ca. 15 m depth; temperature logs inside BHE (upper left), temperature development during test (upper right), and step-wise evaluation of thermal conductivity using GeRT-CAL (lower centre)

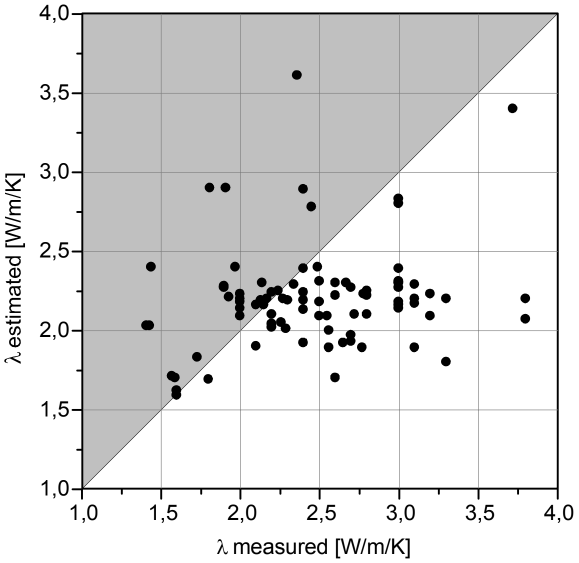

Figure 9: Comparison of estimated and measured values for ground thermal conductivity

The consequences of under- or oversizing are listed in fig. 10. Some parameter studies have been made to evaluate the impact on operational cost (in case of undersizing) and first cost (in case of oversizing); details are given in Sauer et al. (2007). Table 3 shows that due to a reduced seasonal performance factor (SPF), the annual operational cost can increase by more than 1000 € with only 0,4 W/m/K over-estimation of thermal conductivity. In case of under-estimation of about 0,4 W/m/K, the first cost for BHE is about 10’000 € higher than necessary (table 4). In both cases the cost for TRT would be well justified.

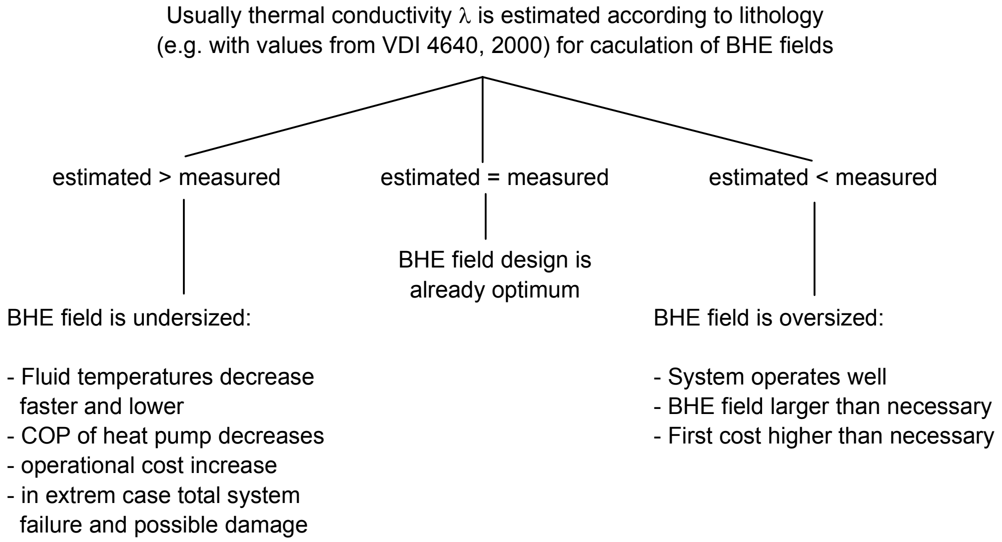

Figure 10: Possible consequence of error in estimated thermal conductivity values

Table 3: Incremental annual electricity cost due to undersizing for GSHP with 50 kW heating capacity, design 12 BHE each 102 m deep for estimated thermal conductivity λ = 2.2 W/m/K

thermal conduct-ivity [W/m/K]	SPF [-]	annual power cons. [MWh/a]	annual electricity cost [€/a]	incremental cost [€/a]
2.2	4.0	26.3	3’945	-
2.0	3.5	30.0	4’500	555
1.8	3.1	33.9	5’085	1’140
1.6	2.8	37.5	5'625	1’680

Table 4: Incremental investment cost due to oversizing for GSHP with 50 kW heating capacity, basic design 12 BHE each 102 m deep for estimated thermal conductivity λ = 2.2 W/m/K

thermal conduct-ivity [W/m/K]	necessary length for 12 BHE [m]	total BHE length [m]	first cost of BHE [€]	incremental cost [€]
2.2	102.2	1’226.4	91’980	-
2.4	96.7	1’160.4	87’030	4’950
2.6	91.5	1'098.0	82’350	9’630
2.8	86.7	1’040.4	78’030	13’950

7 CONCLUSIONS

TRT has developed into a standard tool for investigating ground thermal parameters for the design of BHE plants. The concept has proven reliable and results are reproducible. A prerequisite therefore is high accuracy in the temperature sensing, diligent test setup and operation, and sufficiently long test time. The standard line-source-based evaluation method is sufficient in most cases and can be enhanced by step-wise evaluation. Parameter estimation with numerical modelling may be required in case of external influences, it also can yield additional accuracy and information if required.

Further development of TRT points in two directions:

- "Quick and dirty" tests with lower cost, but reduced accuracy for routine checking in quality control during the construction of BHE-fields, or for design of small systems in residential houses
- More sophisticated tests with additional information, e.g. vertical thermal conductivity distribution along the BHE, and increased accuracy of the sensors, in particular for use in R&D.

Guidelines for TRT are required to prevent inadequate testing and to ensure the necessary accuracy for a given task. A first proposal for a guideline had been elaborated in Annex 13 of the IEA Energy Storage Implementing Agreement; it is published (for information only) in Sanner et al (2005). The text of the relevant German guideline VDI 4640, part 2, was finalized in 2001 before TRT became an accepted method of investigation; the upcoming revision to this guideline, however, will deal with TRT in detail (based mainly upon the Annex 13 proposal). The draft of Swiss norm SIA 384/6 mentions TRT in a table, but does not give details on how to perform such a test.

The TRT meanwhile is used routinely for commercial design of BHE systems, and for UBeG GbR alone typically several test units (fig. 11) are working on sites in Germany and the neighbour countries at any given time. The exact knowledge of ground thermal properties allows for reducing the safety margins necessary when estimating the input parameters, and thus the TRT is considered economically favourable for systems comprising ca. 10 BHE or more.

Figure 11: Some GeRT test equipment developed and used by UBeG GbR (the original GeRT trailer to the right, now equipped with a generator for use independent from the grid)

8 REFERENCES

Austin, W. 1998. "Development of an in-situ system for measuring ground thermal properties." MSc-thesis, OSU, 164 p.

Claesson, J. and Eskilson, P. 1988. "Conductive Heat Extraction to a deep Borehole, Thermal Analysis and Dimensioning Rules." *Energy* 13/6, pp. 509-527

Diersch, H.-J.G. 2006. "FEFLOW® 5.3 User´s Manual". WASY GmbH, Berlin, 200 p.

Eklöf, C. and Gehlin, S. 1996. “TED - a mobile equipment for thermal response test.” MSc-thesis 1996:198E, LuTH, 62 p.

Gehlin, S. and Nordell, B. 1997. “Thermal Response Test - a Mobile Equipment for Determining Thermal Resistance of Borehole.” *Proc. Megastock ’97 Sapporo*, pp. 103-108

Hellström, G. 1997. “Thermal response test of a heat store in clay at Linköping, Sweden.” *Proc. Megastock ’97 Sapporo*, pp. 115-120

Ingersoll, L.R. and Plass, H.J. 1948. ”Theory of the ground pipe heat source for the heat pump.” *Heating, Piping & Air Conditioning* 20/7, pp. 119-122

Mands, E. and Sanner, B. 2001. “In-situ-determination of underground thermal parameters.” *Proc. IGD Germany 2001 Bad Urach*, Suppl. pp. 45-54

Mattsson, N., Steinmann, G. and Laloui, L. 2007. “In-Situ Thermal Response Testing – New Developments.” *Proc. EGC 2007 Unterhaching*, paper #193, pp. 1-5

Mogensen, P. 1983. “Fluid to Duct Wall Heat Transfer in Duct System Heat Storages.” *Proc. Int Conf Subs Heat Storage,* pp. 652-657

Nordell, B. 2000. “Implementing Underground Thermal Energy Storage, main results and findings of IEA ECES Annex 8”. *Proc. Terrastock 2000 Stuttgart*, pp. 7-12

Sanner, B., Reuss, M. and Mands, E. 1999. ”Thermal Response Test - eine Methode zur In-Situ-Bestimmung wichtiger thermischer Eigenschaften bei Erdwärmesonden.“ *Geothermische Energie* 24-25/99, pp. 29-33

Sanner, B. 2003. “Thermally enhanced grout and the reduction of borehole thermal resistance.” *Proc. Futurestock 2003 Warsaw*, pp. 705-708

Sanner, B. and Choi, B.-Y. 2005. “Ground Source Heat Pump Research in South Korea.” *Proc. WGC 2005 Antalya*, paper #1435, pp. 1-2

Sanner, B., Hellström, G., Spitler; J. and Gehlin, S. 2005. “Thermal Response Test – current status and world-wide application.” *Proc. WGC 2005 Antalya*, paper #1436, pp. 1-9

Sanner, B., Mands, E., Sauer, M. and Grundmann, E. 2007. ”Technology, development status, and routine application of Thermal Response Test.” *Proc. EGC 2007 Unterhaching*, paper #194, pp. 1-6

Sauer, M., Mands, E., Sanner, B. and Grundmann, E. 2007. ”Wirtschaftliche Aspekte beim Einsatz von Geothermal-Response-Tests.“ *Proc. Geothermiekongress 2007 Bochum*, paper #124, pp. 1-12

Shonder, J.A. and Beck, J.V. 1999: “Determining Effective Soil Formation Thermal Properties from Field Data Using a Parameter Estimation Technique.” *ASHRAE Transactions,* 105(1), pp. 458-466

SIA 2008. „Erdwärmesonden,“ SIA 384/6 draft, SIA, Zürich

Spitler, J.D., Yavuzturk, C. and Jain, N. 1999. “Refinement and Validation of In-situ Parameter Estimation Models.” short report, OSU

Spitler, J.D., Yavuzturk, C. and Rees, S.J. 2000. “In Situ Measurement of Ground Thermal Properties.” *Proc. Terrastock 2000 Stuttgart*, pp. 165-170

VDI 2000. “Thermal Use of the Underground,” VDI 4640 part 1, Beuth Verlag, Berlin

VDI 2001. “Thermal Use of the Underground,” VDI 4640 part 2, Beuth Verlag, Berlin