Proceedings European Geothermal Congress 2007
Unterhaching, Germany, 30 May-1 June 2007

Technology, development status, and routine application of Thermal Response Test

Burkhard Sanner, Erich Mands, Marc Sauer & Edgar Grundmann

UBeG Dr. E. Mands & M. Sauer GbR, Zum Boden 6, D-35880 Wetzlar, Germany

ubeg@ubeg.de

Keywords: Ground source heat pump, thermal conductivity, borehole heat exchanger, thermal response test

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 small plants (residential houses), these parameters usually are estimated. However, 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 BHE in a pilot borehole (later to be part of the borehole field). For a thermal response test, basically a defined heat load is put into the hole and the resulting temperature changes of the circulating fluid are measured. Since late 1990s, this technology became more and more popular, and today is used routinely in many countries for the design of larger plants with BHEs, allowing sizing of the boreholes based upon reliable underground data.

The paper includes a short description of the basic concept and the theory behind the thermal response test, looks at the history of its development, and then refers the commercial experience of UBeG GbR with this technology.

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. This parameter 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”.

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 resulting is a value for the total heat transport in the underground, noted as a 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}. The test equipment can be made in such a way that it can be transported to the site easily, e.g. on a light trailer (fig. 1).

Figure 1: The first UBeG response test rig, as used on the DFS site in Langen in 1999

DEVELOPMENT OF THE THERMAL RESPONSE TEST

The theoretical basis for the TRT was laid over several decades (e.g. by Choudary, 1976; Mogensen, 1983; Claesson et al., 1985; Claesson & Eskilson, 1988; Hellström, 1991). In the 90s the first practical applications were made, e.g. for the investigation of borehole heat storage in Linköping (Hellström, 1977).

In 1995 a mobile test equipment 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). The first TRT in Germany were performed in summer 1999, with UBeG doing a test for the design of a large BHE field for the German Air Traffic Control (DFS) in Langen (fig. 1, Sanner et al., 1999). An overview of the world-wide status is given in Sanner et al. (2005).

OPERATION OF THE TEST

The general layout of a TRT is shown in fig. 2. For good results, it is crucial to set up the system correctly and to minimize external influences. This is done easier with heating the ground (electric resistance heaters) than with cooling (heat pumps). However, even 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 is required to protect the connecting pipes (fig. 3). 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 more trustworthy evaluation. A typical test curve with low external influence (weather, power, nearby drilling) is shown in fig. 4.

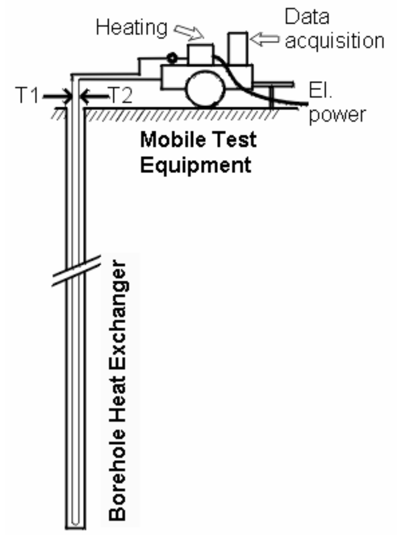

Figure 2: Test setup for a Thermal Response Test

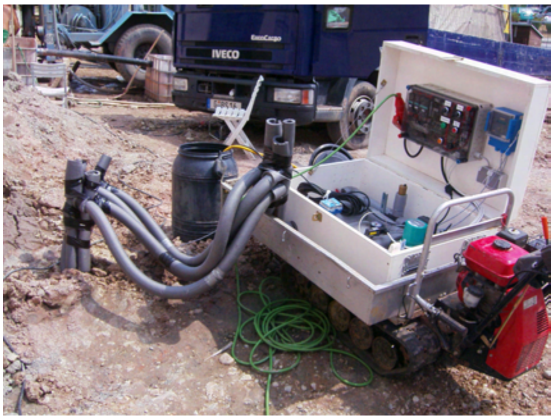

Figure 3: Modern Thermal Response Test rig from UBeG in rough site conditions

TEST 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:

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

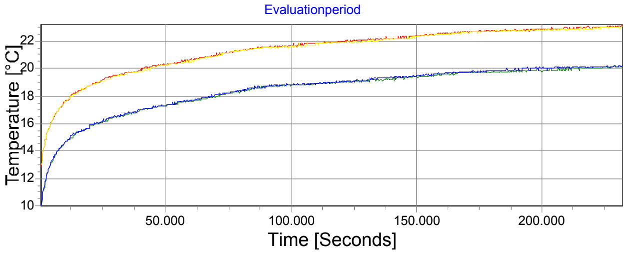

Figure 4: Measured temperature curve with low climatic influence

A more complicated method to evaluate a thermal response test is parameter estimation using numerical modelling, as done for instance at a duct store in Linköping (Hellström, 1997). Further work on parameter estimation was done, among others, at Oklahoma State University by Spitler et al. (1999), Spitler et al. (2000), and at Oak Ridge National Laboratory (Shonder & Beck, 1999). In consequence, more advanced evaluation methods (parameter estimation through numerical simulation) can enhance accuracy and give additional information, but can reduce test time only slightly.

EXPERIENCES FROM THERMAL RESPONSE TESTING

The first test in Germany was made for a large office building in 1999 in Langen (south of Frankfurt, see fig. 1) In the meantime the tests done by UBeG count in hundreds, throughout Germany and in the neighbour countries (Belgium, France, Italy). UBeG did also help to create thermal response test services in other European countries, by exporting equipment, software and knowledge e.g. to Greece, the United Kingdom, and soon 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 (fig. 5) 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.

Figure 5: UBeG thermal response test rig exported to China, during training course in Beijing 2004

Limitations of Thermal Response Test

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. Using a step-wise evaluation in real time allows to determine if the test can be stopped earlier (after several hours of constant thermal conductivity), or if more time is needed to achieve a trustworthy result.

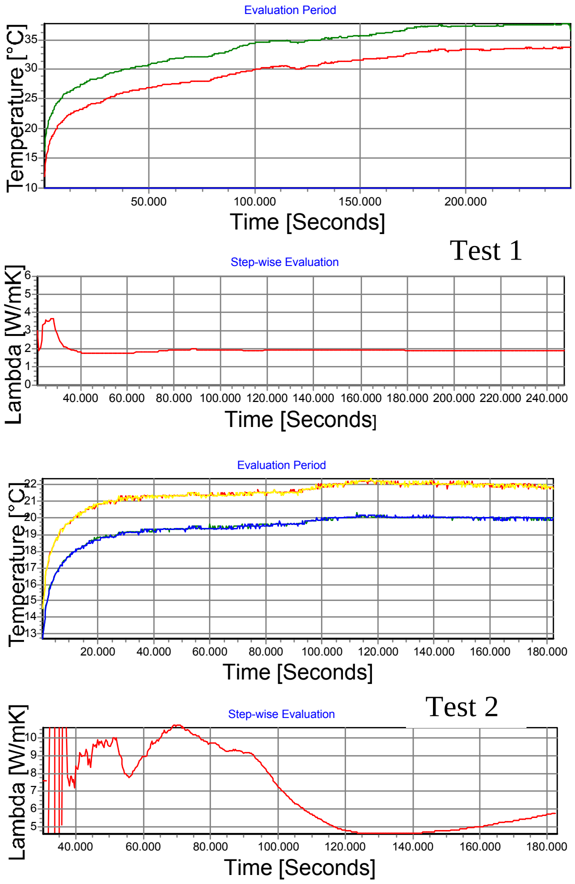

Figure 6: Raw data graph and step-wise evaluation showing perfect convergence (above, Test 1), and the same from a test with high groundwater flow and unreasonably high thermal conductivity value (below, Test 2); for test 1 the result kept stable from 22 hours on, so the full duration of 70 h was not required

An even more problematic kind of groundwater influence is groundwater flow upwards or downwards in the borehole annulus. This occurs in open boreholes (Sweden, see above), 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.

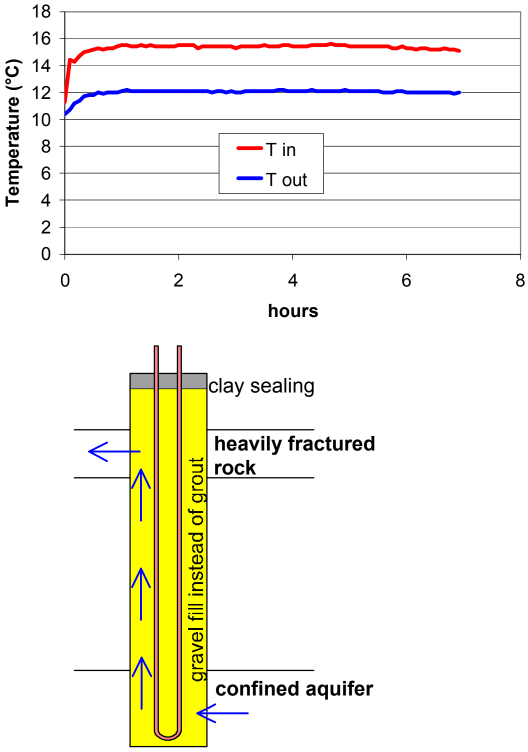

Figure 7: TRT with vertical groundwater flow along the borehole axis, temperature development (above) and explanation

Reliability of Thermal Response Test

Results from TRT can be reproduced, and different rigs on the same site did yield similar results. On a site in Mainz, Germany, two tests were made in virtually the same underground conditions. The results (table 1) show a very close match of the ground thermal conductivity; the borehole thermal resistance varies somewhat and is generally on the high side, which was caused by the use of an inadequate grouting material.

	thermal conductivity	borehole thermal resistance
Mainz 1	1.43 W/m/K	0,16 K/(W/m)
Mainz 2	1,41 W/m/K	0,20 K/(W/m)

Table 1: Results of two test on the same site in summer 2003

In Langen (cf. fig. 1) a total of 4 tests was made in the same BHE-field, the first for design in 1999, and the other 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 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 test 1 different geological layers are affected, and a different grout is used.

	thermal conductivity	borehole thermal resistance
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)

Table 2: Results of 3 tests on the Langen site

Also in the famous comparison of three different TRT-rigs in October 2000 at the site for a new borehole storage system in Mol, Belgium, UBeG was involved (Mands & Sanner, 2001). A workshop within IEA ECES Annex 12 and 13 allowed to bring one Dutch and two German rigs together. 3 BHE with different grout were available for the test. One of the Dutch tests had some problems during the test period and 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 borehole thermal resistance was different according to the various backfill materials. In the saturated underground situation in Mol simple sand had the lowest thermal resistance, while the standard bentonite grout did not perform well.

Temperature logs

With small sensors temperature logs can be recorded inside the BHE (this is also possible with optical glass-fibre technology, but this is much too expensive for routine application). UBeG runs the following logs (fig. 8):

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

Measuring during operation of the test is not possible

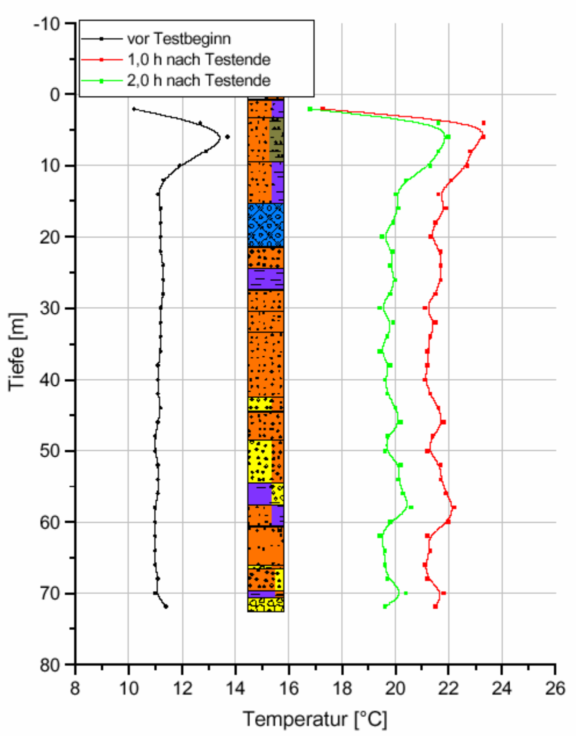

Figure 8: Geological cross-section and temperature log before test (black), immediately after the test (red), and 1 hour later (green), TRT in Berlin 2006

In the test in Berlin in fig. 8 the underground is very homogeneous, with the temperature decrease after the end of the test distributed virtually equally over the depth of the borehole. Together with very low external influence a perfect temperature curve and early convergence in the step-wise evaluation are the result (fig. 9).

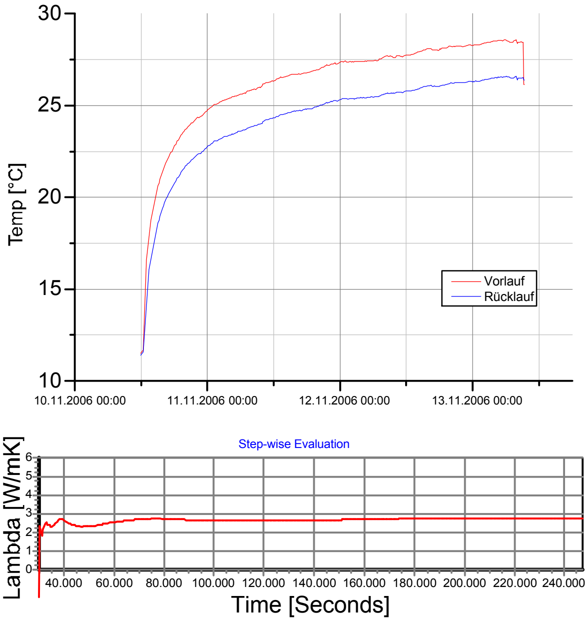

Figure 9: Temperature curve and stepwise evaluation of test from Berlin 2006

In fig.10 another test from Eastern Germany 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.

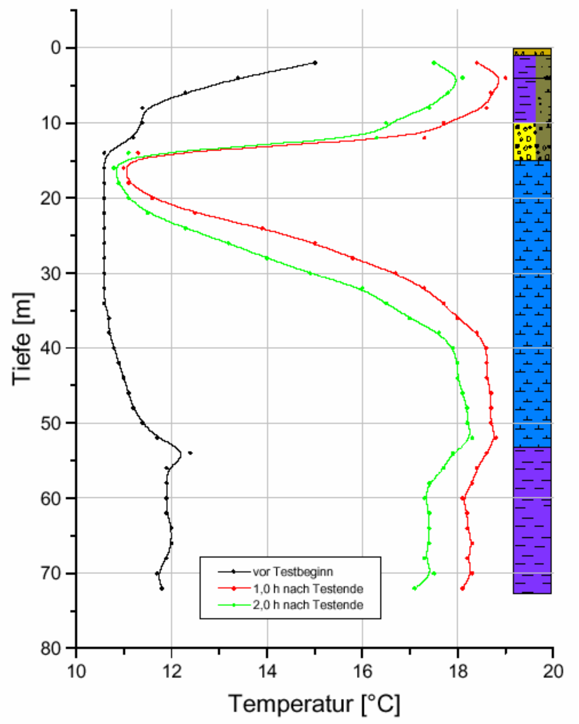

Figure 10: Geological cross-section and temperature log before test (black), immediately after the test (red), and 1 hour later (green), TRT in Camburg 2006

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.

Optimisation of test equipment

Experience with the first test has shown that a remote controlling of the test equipment is desirable. Today it is easy to establish a modem connection via mobile phone, and to download the data wherever the test equipment is located. Thus the operation can be checked regularly without a specialist going on site each time. A remote switch-off is also helpful if a temperature recovery curve shall be measured after the test itself.

The test rigs no longer occupy a larger trailer, as was the case in the first years (fig. 11). With the speed of such trailers limited on motorways, the transport of the test rig to the site could take relatively long. Meanwhile UBeG has developed a series of smaller, compact test rigs that can be mounted onto a motor crawler (fig. 12). The crawler allows one single person to unload the rig from a smaller van (without trailer, so no speed limit on German highways), to bring it to the BHE even in rough site conditions (cf. fig. 3), to connect it, to start the test, and later to retrieve test rug and data.

Figure 10: Original UBeG TRT-equipment of UBeG on site for design of a BHE field in Aachen, Germany

Figure 11: Modern UBeG TRT-equipment, optimized for operation without supervision, and for installation and retrieval by one single person.

THERMAL RESPONSE TEST IN SUPPORT OF BHE OPTIMISATION

A parameter where engineering can help to increase the efficiency of a BHE is the borehole thermal resistance. With increasing the thermal conductivity of the borehole filling (grout), the borehole thermal resistance is decreased (e.g. with Stuewatherm, see Sanner et al., 2005). The TRT now allows to measure this in practice. In fig. 12 the borehole thermal resistance is plotted against the borehole diameter. As should be expected, borehole thermal resistance increases with increasing borehole diameter; however, to well distinct fields of data can be seen, for standard and for thermally enhanced grout.

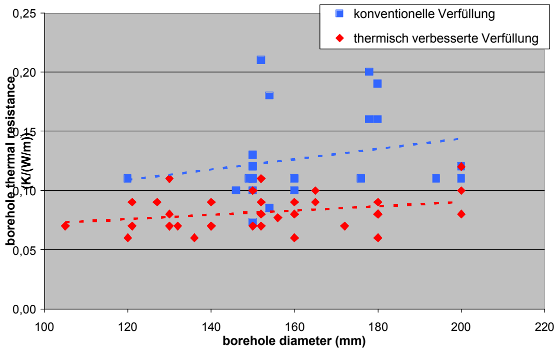

Fig. 12: Borehole thermal resistance versus borehole diameter for standard grout (blue) and thermally enhanced grout (red)

CONCLUSIONS AND OUTLOOK

The TRT meanwhile is used routinely for commercial design of BHE systems. The exact knowledge of ground thermal properties allows to reduce safety margins necessary when estimating the parameters, and thus the TRT becomes economic for systems comprising ca. 10 BHE and more. Fig.13 shows a comparison of thermal conductivity data estimated in pre-feasibility studies, and measured with TRT. In most cases the estimated values have been higher, which means that the TRT was required to adjust the design to a sound level. In other instances the TRT allowed for cost savings, where the underground conditions were better than expected.

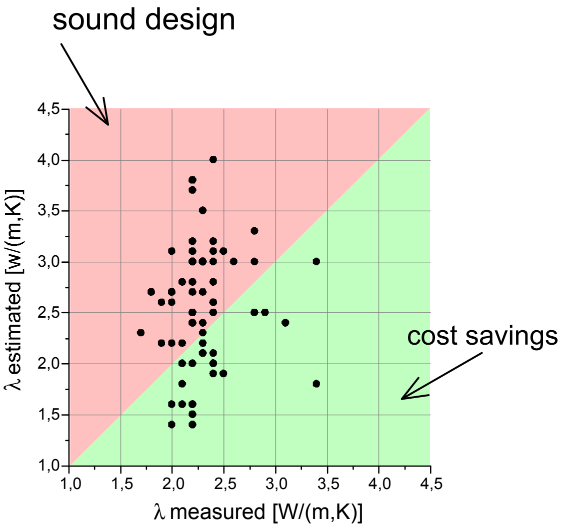

Figure 13: Comparison of estimated and measured values for ground thermal conductivity

TRT has developed into a routine 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 can yield additional accuracy and information it required.

Further development of TRT points in two directions:

- “Quick and dirty” tests with 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 (Heidinger et al., 2004; Rohner et al., 2004)

Guidelines for TRT are required to prevent inadequate testing and ensure the necessary accuracy for a given task.

REFERENCES

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

Choudary, A.: An approach to determine the thermal conductivity and diffusivity of a rock in situ. - PhD-thesis, OSU, 1976

Claesson, J., Eftring, B., Eskilson, P. & Hellström, G.: Markvärme, en handbok om termiska analyser. 3 vol., SCBR T16-18:1985, Stockholm 1985

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

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

Eugster, W.J., Sanner, B. & Mands, E.: Stand der Entwicklung und Anwendung des Thermal-Response-Test. – *Proc. 7. Geothermische Fachtagung*, 304-314, 2002

Eugster, W.J. & Laloui, L. (eds.): Proc. Workshop Geothermische Response Tests Lausanne, GtV, 124 p., 2001

Gehlin, S. & Nordell, B.: Thermal Response Test - a Mobile Equipment for Determining Thermal Resistance of Borehole. - *Proc. Megastock ’97*, 103-108, 1997

Gehlin, S. Thermal Response Test - In-situ measurements of thermal properties in hard rock. Lic.-thesis 1998:37, LuTH, 1998

Gehlin, S. & Hellström, G.: Recent Status of In-Situ Thermal Response Tests for BTES Applications in Sweden. - *Proc. Terrastock 2000*, 159-164, 2000

Gehlin, S.: Thermal response test – Method development and evaluation. Doctoral Thesis 2002:39, LuTH, 2002

Gehlin, S. & Hellström, G.:. Comparison of four models for thermal response test evaluation. *ASHRAE transactions*, 109, 1 –12, 2003

Heidinger, G., Dornstädter, J., Fabritius, A., Welter, M., Wahl, G. & Zurek: EGRT – Enhanced Geothermal Response Test. *Proc. 8. Geothermische Fachtagung*, 316-323, 2004

Hellström, G. : Ground Heat Storage, Thermal Analysis of Duct Storage Systems, I. Theory. 262 p., LTH, 1991

Hellström, G.: Fluid-to-ground thermal resistance in duct ground heat storage. *Proc. Calorstock ’94*, 373-380, 1994

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

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

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

Mands, E. & Sanner, B.: Erfahrungen mit kommerziell durchgeführten Thermal Response Tests in Deutschland. *Geothermische Energie* 32-33/01, 15-18, 2001

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

Rohner, E., Rybach, L. & Schärli, U.: Neue Methode zur in-situ-Bestimmung der Wärmeleitfähigkeit für die Dimensionierung von Erdwärmesonden-Feldern. *Proc. 8. Geothermische Fachtagung*, 324-328, 2004

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

Sanner, B., Reuss, M., Mands, E. & Müller, J.: Thermal Response Test - Experiences in Germany. *Proc. Terrastock 2000*, 177-182, 2000

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

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

Sanner, B., Mands, E. & Giess, C.: Erfahrungen mit thermisch verbessertem Verpressmaterial für Erdwärmesonden. ***bbr 56, 9/05,*** 30-35, 2005

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

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

Spitler, J.D., Yavuzturk, C. & Rees, S.J.: In Situ Measurement of Ground Thermal Properties. *Proc. Terrastock 2000*, 165-170, 2000