Experiences from use of TRT (Thermal Response Test) in the design praxis for BHE (Borehole Heat Exchanger): lessons learned, enhanced information, new developments

Marc Sauer, Erich Mands, Edgar Grundmann, Burkhard Sanner

UBeG GbR, Reinbergstr. 2, 35580 Wetzlar, Germany

m.sauer@ubeg.de , b.sanner@ubeg.de

Keywords: borehole heat exchangers, design, Thermal Response Test, test equipment, evaluation, improvements.

ABSTRACT

Mobile TRT (Thermal Response Test) equipment was developed 20 years ago in USA and Sweden. Through cooperation within IEA-projects the idea soon spread to other countries, and today is applied in every region where a certain market for ground source heat pumps exists. Over the years a wealth of experience could be collected, and development lead to substantial improvements, however, some experience also helped to understand what not to do. The data collection during TRT, and the information derived from TRT data, improved considerably with better equipment and increasing experience.

Proper data collection is only one part of TRT, the other, and equally important, is data evaluation. Evaluation today has little in common with that of the 1990, beside some basic mathematical rules. Parameter estimation techniques are widely used today, allowing for evaluation of tests with additional influences (variable load over time, groundwater, etc.). Temperature logs help to understand the lithological and hydrogeological setting and yield valuable additional information. The usefulness of TRT meanwhile is not only proven for determination of underground thermal conductivity, but also for other parameters like determining length of borehole heat exchangers, existence of grouting in the annulus, presence of moving groundwater, etc. The paper, however, limits the scope to the type of TRT used commercially for design of borehole heat exchangers, and does not cover variations in test operation and evaluation used in R&D, mainly to understand the basic operation of ground heat exchangers.

1. INTRODUCTION

A crucial moment for the wide deployment of TRT we see today was a meeting within Annex 8 of the Energy Storage Implementing Agreement of the IEA, held in June 1996 in Dartmouth NS, Canada. Here the Swedish students working on the mobile TRT rig they called "TED" could present their work to the international experts – and the experts listened with keen interest and had intensive discussion on the subject. The authors thought it justified to show the students here in figure 1, when relaxing from their presentations, as their joint work (Eklöf and Gehlin, 1996) is so famous among TRT circles.

Figure 1: The two "mothers" of the Swedish mobile TRT "TED", Signhild Gehin (left) and Catarina Eklöf (right), during a sail cruise in Halifax harbour, after the IEA meeting in June 1996 (photo Sanner)

When the word of mobile TRT spread within the IEA cooperation on underground thermal energy storage (UTES) and ground source heat pumps (GSHP) in the late 1990s, two different groups in Germany were involved (one at Justus-Liebig-University, Giessen, in co-operation with UBeG, Wezlar, the other at Landtechnik Weihenstephan, Freising,). Both did the first TRTs in Germany, almost simultaneously, in 1999. The authors were part of the Giessen-Wetzlar group, and today look back at the largest number of commercial TRT made by a German company. The test rigs changed substantially in appearance, in order to bring it more easily to the BHE which could not change position. Development went from heavy equipment mounted in trailers, over large boxes transported on crawlers (cf. fig. 5), to even small boxes that can be carried by one, and sent by air (fig. 2).

Figure 2: Very mobile TRT on site in Northern Germany in 2016 (devised and built by UBeG; photo Kahl)

2. 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 and Eskilson, 1988; Hellström, 1991). The first practical applications were made in the 1980s, by Mogensen (1985) in a residential house, and by Eskilson et al. (1986) and Hellström (1989) for borehole heat storages. These tests were made as a-posteriori verification of completed systems, and to understand the thermal interaction of heat exchangers and underground.

Also in Germany similar experiments were carried out at a GSHP research installation near Wetzlar since 1985; here one borehole heat exchanger (BHE) was surrounded by a number of boreholes with temperature sensor cables to the same depth (50 m), and a shack with heat pump and two fan-coil units towards the ambient air allowed for extracting heat from the ground, independent of any building heating requirement (Sanner, 1986) – a kind of 'immobile TRT rig'. The early tests in Sweden and Germany did not only consider the operation phase, but also the thermal regeneration after stop of heat extraction (fig. 3). In the German test site, also long-term extraction with relatively constant, low temperature in the BHE over several weeks was performed and the resulting temperatures in the nearby boreholes (2.5, 5 and 10 m distance) measured (fig. 4).

The possibilities of using the TRT as a part of site investigation preceding the design began to take shape some years later. In 1995 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 and Gehlin, 1996; Gehlin, 1998). A similar development was going on independently since 1996 in the USA, in collaboration of an Oklahoma-based private company and Oklahoma State University (Spitler & Smith 1996, Austin 1998). Both test rigs imposed a step heat pulse on the ground, using an electric resistance heater. A somewhat different test rig had been developed and tested in the Netherlands from 1997 on (van Gelder et al., 1999); this rig used a heat pump instead of electric resistance heaters, in order to be able to also decrease the temperature inside the BHE. In Germany, the first TRT were performed in summer 1999 (Sanner et al., 2000), and a test in the same year is reported also from Switzerland (Pahud, 2002).

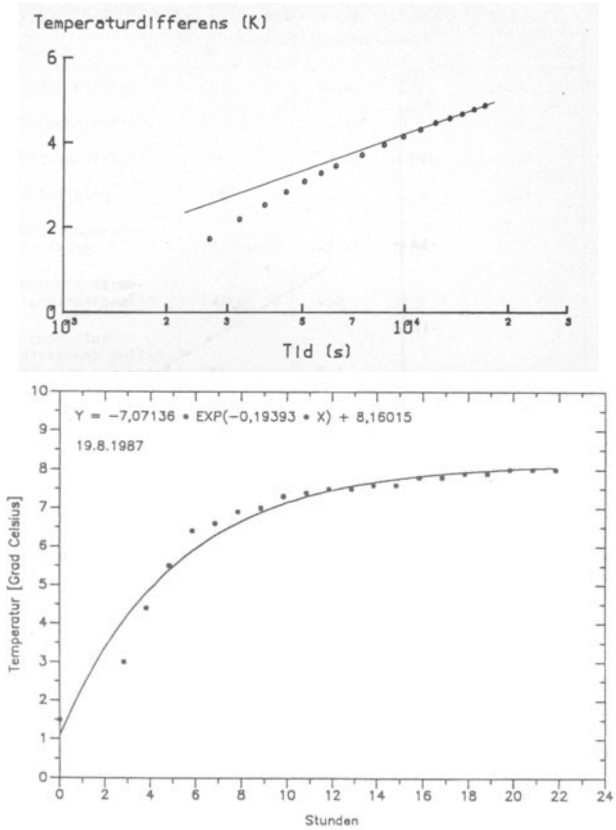

Figure 3: Original graphs from temperature measurements for characterisation of BHE systems, development after stop of heat extraction; points measured and line calculated, on a logarithmic time axis (Mogensen 1985, top) and on a normal time axis (Knoblich et al. 1993, bottom)

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, with TRT activity covered also in Annex 13 (1998-2003), and later on resumed in Annex 21 (2006-2010). A first practical comparison of test results was performed already in October 2000, with three rigs (2 German, 1 Dutch) on one site in Belgium, and the reproducibility of TRT results could be shown (Sanner et al., 2005).

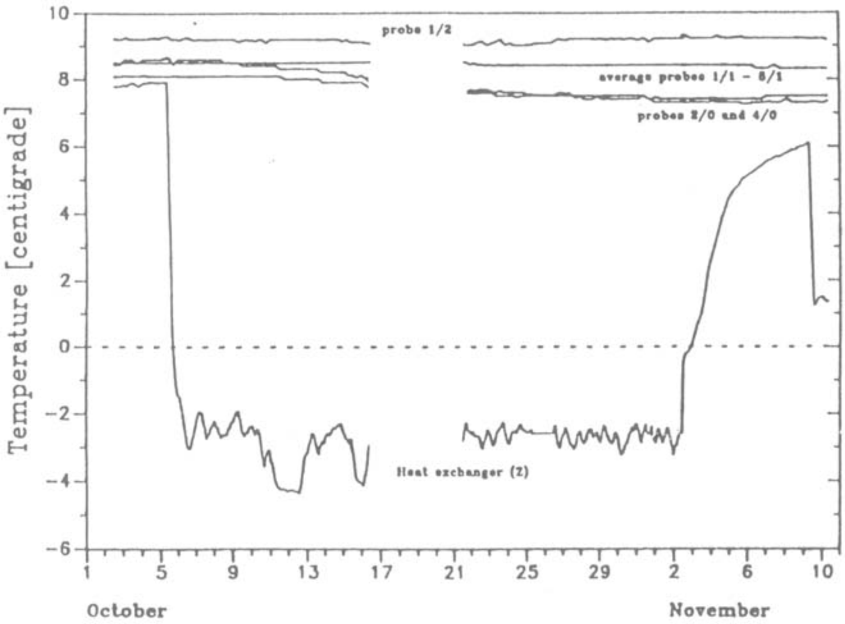

Figure 4: Temperature development in the BHE (Z) and in surrounding boreholes with temperature sensors (2/0 and 4/0 in 2.5 m, 1/1-5/1 in 5.0 m, and 1/2 in 10 m distance) during a long-term test with -2 °C mean temperature in the BHE, in fall 1987 (from Knoblich et al. 1993)

On the European level, a first workshop on TRT was organised in October 2001; the results are summarised in Eugster and Laloui (2002). Since then, TRT was a regular topic in national conferences and also in the international events in the series of the energy storage conferences of the IEA (Stock-conferences), the IEA heat pump conferences, and the EGCs.

In the beginning, TRT-development was closely coupled to practical work for BTES installation and larger GSHP-plants. Developments of more academic interest like “enhanced TRT” (using a glass-fibre cable for heating and sensoring), distributed TRT, and other followed; they are however not covered in this paper, focussed on the design praxis. An excellent and very comprehensive account on the history of TRT, dealing in particular with the theoretical concepts and evaluation methods, is given in Spitler and Gehlin (2015).

UBeG did a first test for the design of a large BHE field (154 boreholes) for the German Air Traffic Control (DFS) in Langen in 1999. In the meantime the TRTs done by UBeG count in many hundreds, throughout Germany and in neighbour countries (e.g. Belgium, France, Italy, Luxembourg, Switzerland). UBeG did also help to create thermal response test services in other European countries, by exporting equipment, software and knowledge to the Czech Republic, Denmark, Greece, Ireland, Hungary, Poland, Spain and the United Kingdom. In 2003, design help for a thermal response test rig was given in the frame of a South Korean BHE test plant, and rigs were also exported to China and South Korea. The hardware was accompanied in all cases by the necessary evaluation software and training for the operation personnel. Today in any design for a project of more than about 30-50 kW, often also in smaller projects, a TRT is performed to secure the input data.

3. RECOMMENDATIONS FOR TRT

3.1 Test equipment

A typical TRT setup of 2016 is shown in figure 5. The test box, cables, pipes and tools are carried in a light van, and the rig can be manoeuvred as close to the BHE top as possible even under adverse terrain conditions. Electric power usually is available somewhere on construction sites or sites under development; if not, a generator with sufficient electric power output (and tank volume for long enough operating time!) is required. Thus a single person is sufficient to set up and start the test, and to collect the equipment after the test. Data can be transmitted online to a PC in the office for interim evaluation, a feature that comes in handy when a decision is required to keep a test running longer e.g. in cases of external influence.

Electric heaters are used in most of the TRT equipment in use in Europe today; heat pumps are in minority. The pros and cons of the two options are discussed in Sauer et al. (2012). Outside of academic application, there are few cases only where heat extraction (lowering the temperature in the BHE) actually is required.

3.2 Test set-up and operation

Based upon many years of experience, UBeG exercises some mandatory routine procedures to be performed before the start of the response test. In order to help others in avoiding unpleasant incidents, the main items are reported here:

- Power supply check. The test can of course not be performed without electric power, be it from the grid or from a generator. Considering the required power levels, typically 3-phase AC is the source. Wrong phasing of this power supply can result in shunt fault, controller failure, overheating and even smouldering of the device. Power breakdown or instable power supply may lead to inconsistent development of the temperatures, and thus makes it difficult or impossible to evaluate the test.

- Sufficient de-aeration. Without proper de-aeration, gas cushions can develop and, in the worst case, the flow inside the borehole can collapse after an unknown amount of time, bringing the test to an unexpected early end. Air bubbles also can disturb flow meter readings.
- Insulation of the test rig and connections. The ambient influence (heat or cold, solar irradiation) should be kept as low as possible, as it cannot be controlled or measured, and heavily affects the test in a similar way as fluctuating power supply.
- Make sure that there is no drilling work ongoing near the BHE used for testing. Preferably there is no drilling during the test at all. The drilling in near surroundings may induce a groundwater flow that disturbs the TRT

Figure 5: Typical TRT-setup at BHE on a site under development, in summer 2016 (photo Kahl)

Some experience and geological knowledge is required for selecting a suitable heat load. The temperature increase during a TRT should be in the same order of magnitude as the expected temperatures during operation of the finished plant; furthermore, a minimum increase of more than about 10 K is required to obtain a signal that allows sufficient accuracy in evaluation. Too high temperatures are not desirable either, as thermal properties might be influenced, and of course overheating of the equipment has to be prevented. Figure 6 shows the thermal loads used for TRT at boreholes of different depth; the respective specific injection rate varies from 31 to 94 W/m, with an average of 55 W/m..

Also the flowrate has to be set to a suitable value to secure a temperature difference between inlet and outlet high enough for good accuracy in measuring the thermal load, but still allowing for turbulent flow, if possible; about 5 K are a good compromise.

Before starting the actual test, it is important to determine the undisturbed ground temperature. There are several options with different degree of accuracy:

- running the circulation pump without heating
- measuring temperatures of the first circulation cycle with short time intervals, without heating
- running a temperature log down the BHE before connecting the TRT device

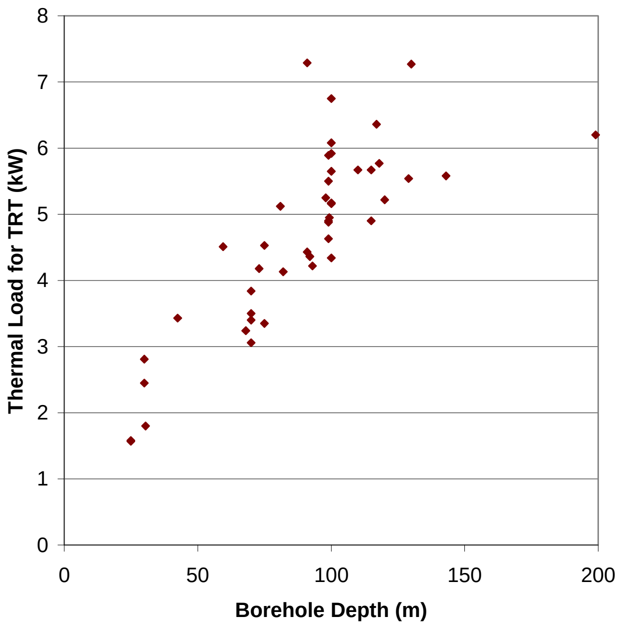

Figure 6: Thermal load for TRT versus borehole depth for a number of tests performed in 1999-2006

The first one, circulation without heating, is the easiest and classic method. It yields an average undisturbed ground temperature over the length of the BHE. Drawback is the limited accuracy, as the value is influenced by heat input from the circulation pump, heat capacity of test device, and possible movement of groundwater. The second method reduces these influences, but is more complicated and provides a useful vertical temperature profile only when very high time resolution can be achieved.

The preferred method with UBeG is the temperature log; a typical example in undisturbed ground is given in figure 7.

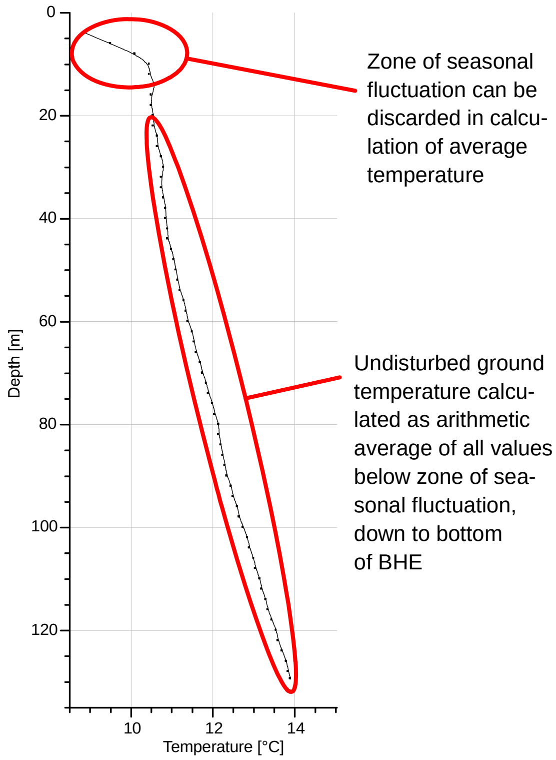

Figure 7: Example of temperature log in BHE to determine undisturbed ground temperature (taken towards the end of winter)

The exclusion of the zone of seasonal variation when determining the average undisturbed temperature is an important aspect, as that value, giving the "back-ground temperature" against which design calculations are made, has considerable influence on the predicted temperature development of a BHE plant.

Sensors to fit inside a BHE pipe are available today. Glass-fibre cables for temperature measurement can yield a wealth of information for R&D on BHE; how-ever, they are not necessary for commercial TRT, and hinder test operation.

The temperature log yields some further information, and can be used for additional purposes (cf. 4.3). Quite often not the perfect geothermal gradient as in figure 7 is found, as groundwater layers, convection in highly permeable ground or in not properly grouted boreholes, surface influences (mainly in cities), recent drilling activity, etc. disturb the temperatures. The log can give indications of such problems and is one part of the toolbox for identifying them in detail.

During heating the BHE, not only recording of the temperature development is crucial, but also of the development of the heat load. Load control is a chal-lenge under rough conditions on construction sites, and while the control within the rig might be achieved well, the heat actually injected into the BHE might vary nevertheless, due to external influences, and despite thorough insulation. Hence a good point for measuring the heat load injected is by using the tem-peratures taken directly at the top of the BHE (and the flow rate, of course).

Figure 8 gives an example of thermal output and the resulting temperature development at the BHE. As long as the fluctuations are small and do not show an upward or downward trend, and the test time is suffi-ciently long, the evaluation can be done by using the average heat load. A sequential evaluation (cf. 3.3) can confirm the validity. In cases were a trend is visi-ble, or larger fluctuations, parameter estimation with the actual heat load curve is required (Sauer, 2013).

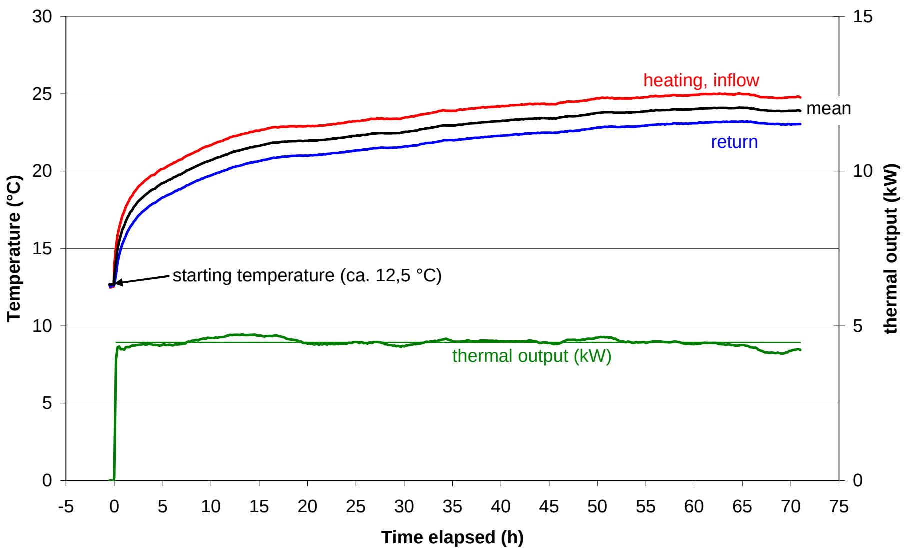

Figure 8: Example of temperature and load curve for TRT, from real data over >70 hours; small fluctuations in thermal load can be seen, but no upward or downward trend

Also systems just using the temperature difference between inlet and outlet for load control are not recommended, as they can result in small, but constant increase of the heat injected. The reason is the decreasing viscosity of the water, leading to increasing flow volume at constant pumping power; with temperature difference kept constant this means an increase in heat injected. When evaluating such test using the average heat load, the actual load will be lower in the beginning and higher towards the end of the test, and the values for thermal conductivity will be slightly over-estimated. UBeG never used this principle; however, the authors could see signs of the effect sometimes in data from other TRT, both from Germany and abroad.

3.3 Test evaluation practice

The classical evaluation method as described for instance in Eklöf and Gehlin (1996) is an approximation of the line-source theory. This method has the advantage of limited requirements for calculation and can be performed with simple statistical formulas e.g. in MS Excel. Hence it was well suited for the computing power available outside research institutions in the 1990s.

An improvement was the sequential analysis (also called step-wise analysis in the beginning); it allows for cross-checking if external effects like high groundwater flow or excessive load fluctuations have an influence on the test results. An evaluation of the recorded data is performed here with a fixed start time and increasing length of the data set, until the full duration to the end time. 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 perfect test (figure 9, top). This procedure is a useful tool to check the quality of the data collected and the validity of the results.

With substantial influence of flowing groundwater, the curve rises upwards steadily after some time (figure 9, middle). In this case the test result value (λ) is determined by the duration of the test, and the longer the testing time is, the higher λ will be. There is no reliable result for such a test. In case of influence of fluctuating power supply or environmental influences (e.g. solar radiation), the test result is not stable, and testing time must be extended (figure 9, bottom).

To overcome the limitations of the line-source approximation by taking into account variable heat loads and external factors, parameter estimation technique is used. The temperature curve is calculated (e.g. by using numerical simulation) with the thermal load file as input, and the relevant parameters like thermal conductivity, specific heat capacity, etc. are varied until the best fit with the measured curve is found. This approach was already reported by Shonder & Beck (1998), and meanwhile is a standard method for test evaluation in cases where simple line-source approximation cannot be used.

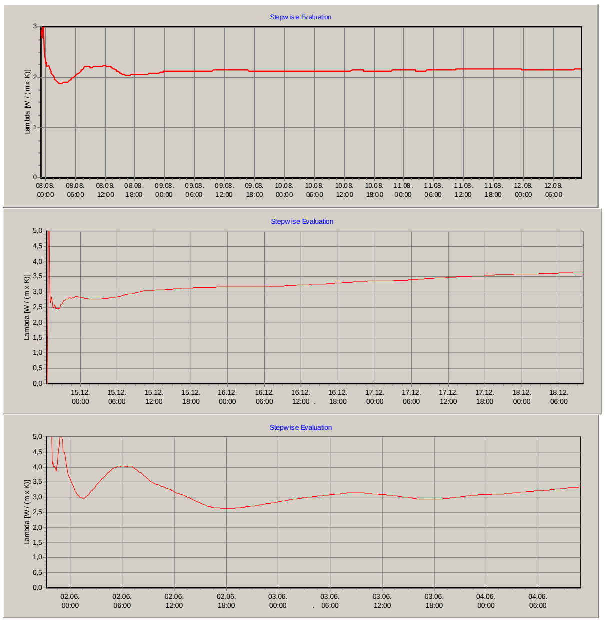

Figure 9: Examples of sequential line-source evaluation of TRT: dominated by conductivity (good reliability, top), dominated by advection (not usable, middle), and high fluctuations (low reliability, prolonged test time required, bottom), from Sauer and Sanner (2011)

While modern computing technology makes numerical simulation more feasible as a tool to use with parameter estimation, there is still a certain amount of work necessary to set up the proper model for each case, and some time for execution of the simulation. The finite element (FEM) software FEFLOW has proven suitable, but requires certain experience to handle it. Hence simpler methods have been developed and tested recently for calculating the temperature curve in those cases where the external factors are limited and mainly the thermal load variation needs to be considered.

A good compromise for practical application is to use superposition of the line source approximation, following the approach of Eskilson (1987). With this method, the temperature development is calculated using the different heating loads for each time step. The thermal conductivity and borehole resistance are varied within predetermined limits and the resulting temperature curve is compared with the measured temperatures. The parameters of the best fit curve are regarded as the result. All kind of power fluctuations and variations can be handled this way.

Sauer (2013) compared the evaluation of test data from 5 TRT with instable thermal load by parameter estimation using line-source superposition and FEM. The average deviation between the methods was 3.1 %, with a maximum of 4.8 %. Another comparison of 21 TRT with stable thermal loads resulted in a deviation of 2.7 % on average between standard line-source approximation and superposition (fig. 10). Hence the superposition method can be considered adequate for evaluating proper as well as improper

TRT data in commercial application, while avoiding the complicated and long numerical simulation.

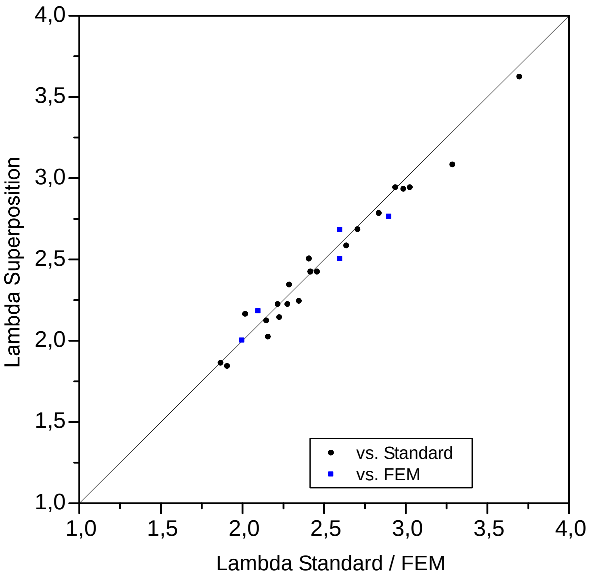

Figure 10: λ/λ diagram Superposition against Standard/FEM (from Sauer, 2013)

4. EXPERIENCES IN THE DESIGN PRAXIS

4.1 Use of TRT results

In the routine case, and with heat transport dominated by conduction, the values for thermal conductivity can directly be used as input to software like EED or for numerical simulation of BHE, energy piles or similar. Also recent guidelines use thermal conductivity as an input value for BHE sizing tables, like MIS 3005 in UK (with MCS 022, "Ground Heat Exchanger look-up tables"), or the new draft of VDI 4640-2 in Germany, published in May 2015.

In any case, caution is advised towards the validity of test results, mainly in two areas, and the designer should check the reports from TRT:

- With line-source approximation, the validity has to be confirmed by sequential evaluation (figure 9):
- If parameter estimation was used, all estimated values (not only the target value of thermal conductivity, but also accessory values like specific heat capacity) have to be checked for plausibility, and for being inside empirical ranges.

As long as evaluation was done mainly by line-source approximation, test results with a high groundwater influence (heat transport by advection) simply had to be rejected. In that case, the apparent value for thermal conductivity resulting from line-source evaluation increases steadily with test time (figure 9, middle), and thus a definite value cannot be given. As a rough assumption, the value at the start of the increasing part of the curve might be taken as an indication for the thermal conductivity; this would allow for a conservative design of a GSHP plant.

If data from TRT on sites with groundwater influence are evaluated by use of numerical simulation, including advective heat transport, values for both the thermal conductivity and the remaining part of heat transfer can be obtained. If the advective part should be considered in the design, the hydraulic situation in the underground has to be investigated (wells, pumping test, tracers, etc.), and a coupled thermo-hydraulic model must be used for the design calculations.

4.2 Representativity of TRT results

The value for thermal conductivity obtained from TRT is valid for the direct vicinity of the respective BHE. For larger projects, distances between the test BHE and other BHE in the field might be considerable, up to 100 m and more. Geological knowledge is required to decide for which area a TRT might be representative, and if more BHE need to be tested to adjust the conductivity values.

Already Pahud (2002) reported deviations of TRT-values from tests in 1999 near Lucerne, Switzerland. The estimation of the ground thermal conductivity differed by 10 % between two boreholes 160 m deep and about 30 m apart, with 3.0 in one and 3.3 W(m·K) at the other. He calculated that measurement and parameter uncertainties, heat injection rate etc. can produce an error of 5 %, but cannot explain the difference of 10 %.

The local geology however could explain the differences, as the ground layers (Molasse, Tertiary sandstone and siltstone) have different thermal parameters and are dipping (figure 11), and thus the average ground thermal conductivity, estimated along a given depth, could actually differ.

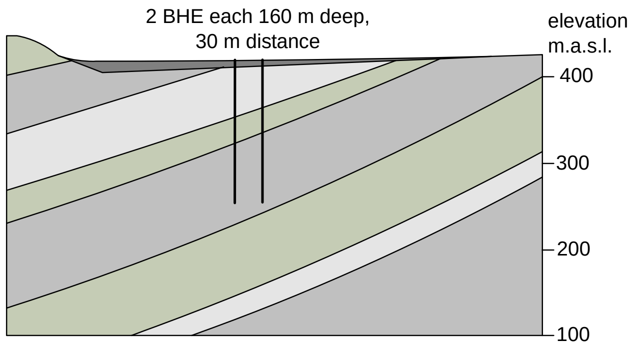

Figure 11: Geological situation at the site of the TRTs in Lucerne in 1999, re-drawn after Pahud (2002)

In multiple tests for larger projects we could find similar situations as reported from Lucerne. This is frequent in sediments dipping or faulted, but could also be seen in igneous rock. At a site in the crystalline part of the Odenwald mountains, Hesse, Germany, close to the Eastern main fault of the Upper Rhine Graben, BHE were drilled in a zone of granite and granodiorite. A TRT at the first BHE had given a quite high thermal conductivity, as to be expected from granite. When a second BHE at the other end of the field was tested, the value was much lower, close to 2 W(m·K) only. A fault which had been expected to be outside the field divided the granite from diorites; the drillers had observed a change in colour of the cuttings already. The fault line could be identified and the design adapted to the fact that a part of the field was in rocks of much lower conductivity than the rest.

On the other hand, multiple TRT on sites with horizontal, homogeneous layers usually show rather constant values. This was already confirmed in the early days of mobile TRT; in table 1, the relevant results both from the joint test in Mol, Belgium, in 2000, and from two multiple tests by UBeG in Germany are listed.

Table 1: Results of multiple TRT on the same site (Mol TRT workshop in 2000 and two projects in Germany)

Borehole / TRT-unit		1 (NL)	2 (DE, UBeG)	3 (DE)
1, backfilled with Mol-sand		$\lambda = 2.47$ W/(m·K)	-	$\lambda = 2.47$ W/(m·K)
2, backfilled with graded sand		$\lambda = 2.40$ W/(m·K)	-	$\lambda = 2.51$ W/(m·K)
3, backfilled with bentonite		*test disturbed*	$\lambda = 2.49$ W/(m·K)	-
Location in Langen, Germany, tests by UBeG in 1999 (Langen 1) and 2000 (Langen 2 and 3)				
Borehole	Depth	Grout	thermal conductivity	borehole therm. res.
Langen 1	99 m	standard bentonite	$\lambda = 2.8$ W/(m·K)	$r_b = 0.11$ K/(W·m)
Langen 2	70 m	therm. enhanced	$\lambda = 2.3$ W/(m·K)	$r_b = 0.08$ K/(W·m)
Langen 3	70 m	therm. enhanced	$\lambda = 2.2$ W/(m·K)	$r_b = 0.07$ K/(W·m)
Location in Mainz, Germany, tests by UBeG in summer 2003				
Mainz 1	30 m	standard	$\lambda = 1.43$ W/(m·K)	$r_b = 0.16$ K/(W·m)
Mainz 2	30 m	standard	$\lambda = 1.41$ W/(m·K)	$r_b = 0.20$ K/(W·m)

Table 1 also shows that the TRT results are only valid for the actual depth of the test BHE. In the Langen project, the original BHE for testing before the design started was almost 100 m deep, while the final design limited borehole depth to 70 m. The site is in a region of horizontal Quaternary and Tertiary layers with different thermal properties, and the sediments with higher thermal conductivity are apparently found at depth below 70 m. Also the influence of the grout on borehole thermal resistance can be seen in table 1.

4.3 Other uses of TRT, additional in formation

A temperature log before the test, combined with several temperature logs after the end of the TRT, will show the gradual cooling of the fluid inside the pipes and allows for various conclusions (Sanner et al., 2007). Among the features visible are groundwater flow, layers with different conductivity, or missing grout. The latter is either visible as a zone of very quick cooling in cases where groundwater can move vertically in the non-grouted borehole annulus, or by zones of slow cooling if there is no groundwater movement and contact between ground and pipe hampered over short stretches.

Sometimes it is not clear if the temperature sensor actually went all the way to the bottom, or if the BHE is just blocked (e.g. by a pinch). A short stretch of faster cooling at the lower end of the BHE, the ‘bottom heat dissipation’, gives a prove for having reached the bottom, as at this point the heat is also transported in vertical direction downwards and thus temperature decreases quicker.

TRT can be used for Determination of BHE length, by using the Thermo-Impulse Method, was first published in Sauer et al. (2010), where also the validation is given. Sometimes disputes arise on the question if the BHE actually has the full length as contracted. The TRT rig can offer a convenient method of determining the actual BHE-depth within a narrow margin of error. It comprises the following steps:

- A strong thermal signal (impulse) is injected into the BHE circuit
- The time the impulse needs to return is measured.
- With the (measured) flow rate and pulse-time-delay the volume of the BHE can be calculated.
- With the known diameter of the BHE tube and the volume the length can be calculated.

It should be reiterated here that the geothermal heat flux can be determined from temperature logs before TRT, combined with thermal conductivity as a result of the TRT. Estimates on the expected lithology under the site allow for extrapolation of these values down to the depth required for deep geothermal installations. Naturally, such extrapolation will not sufficiently reflect deep groundwater movements and other factors contributing to geothermal anomalies, but it can be a first hint to the geothermal character of an area where no deep boreholes yet exist. In this way the TRT can also be of service for the deep geothermal sector.

5. STANDARDS AND GUIDELINES FOR TRT

The first attempt to give some definition and rules for TRT was made in Annex 13 of the IEA Energy Storage Implementing Agreement. A draft guideline has been developed by an expert group in that Annex, and was published as an appendix to the proceedings of the first TRT workshop (Eugster and Laloui, 2002). The draft was reprinted in Sanner et al. (2005).

This draft was taken up by the Technical Committee TC 341 of CEN on "Geotechnical investigation and testing" and combined with rules for construction of the BHE for testing, and on the documentation of construction and test. The standard was published in 2015 as EN ISO 17628. The description of the TRT contained therein thus is basically identical with a document about 15 years old and already outdated in several aspects. The standard also sets only the framework of rules, and no practical help how to perform and evaluate the test.

The actual state of the art is much better described in VDI 4640-5, the draft of which was eventually published in July 2016. Alas, this draft is only available in German language. Two of the authors of this paper are members of the small committee drafting VDI 4640-5, and thus it is not by chance that experiences reported in this paper are in a similar way formulated as rules in the guideline. VDI 4640-5 has two main parts, the TRT as such, and extended methods and ancillary measurements. The contents of VDI 4640-5 are:

Thermal Response Test

- Theoretical Background (line source, cylinder source, numerical simulation)
- TRT equipment and connections
- Performing a TRT (site requirements, identification of test parameters, connecting the TRT-rig to the BHE, determination of undisturbed ground temperature, performing the measurement
- Requirements for sensors and data recording
- Evaluation of measured data (convergence of result, sequential evaluation forward and backward, groundwater, correct use of the results)
- Documentation of results

Extended methods and ancillary measurements

- Temperature logs
- TRT with individual values for depth layers
- Test to determine vertical permeability inside the annulus
- Test to determine the actual BHE length
- Multi-Pulse Test

To summarise, at this moment the terms 'standard' and 'guideline' have to be used in singular each, with EN ISO 17628 in the first and VDI 4640-5 in the second category. Both are intended to secure accuracy and comparability of TRT results for practical application, at the current state-of-the-art, and in no way should hinder further development or other, more sophisticated approaches in R&D. More such technical documents are expected in near future from other countries.

6. CONCLUSIONS

Three years ago, Sanner et al. (2013) estimated the number of TRT rigs in use in Europe to about 70, about half of which (34 rigs) in Germany. At least 43 entities having own TRT could be identified. With the market development for shallow geothermal stable on a low level in most of Europe (Antics et al., 2016), no big changes can be assumed.

Improvement of TRT did proceed continuously, and it meanwhile is not only widely accepted, but even more a standard feature in the design of BHE systems. 20 years after the pivotal IEA workshop in Canada, TRT is becoming regulated by standards and guidelines from the relevant organisations. TRT are a fixture for shallow geothermal development and also used in R&D.

REFERENCES

Antics, M., Bertani, R. and Sanner, B. (2016): Summary of EGC 2016 Country Update Reports on Geothermal Energy in Europe, *Proc. EGC 2016*, Strasbourg (2016), 1-16

Austin, W.: Development of an in-situ system for measuring ground thermal properties, *MSc-thesis, OSU*, Stillwater OK (1998)

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

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

Eklöf, C. and Gehlin, S.: TED - a mobile equipment for thermal response test, *MSc-thesis 1996:198E, LuTH*, Luleå (1996)

EN ISO 17628: Geotechnical investigation and testing – Geothermal testing – Determination of thermal conductivity of soil and rock using a borehole heat exchanger, *CEN*, Brussels (2015)

Eskilson, P., Hellström, G. and Wånggren, B.: Response Test for a Heat Store with 25 Boreholes. *Dept. Math. Phys., Lund Univ*., Lund (1986)

Esklison, P.: Thermal Analysis of Heat Extraction Boreholes. *PhD-thesis, Lund Univ*., Lund (1987)

Eugster, W.J. and Laloui, L. (eds.): Proc. Workshop Geothermische Response Tests Lausanne 2001, *GtV,* Geeste (2002), 1-124

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

Hellström, G.: Thermal response test at bedrock heat store in Luleå. Lund, LTH, Lund (1989)

Hellström, G.: Ground Heat Storage, Thermal Analysis of Duct Storage Systems, I. Theory, *Doctoral Thesis, LTH*, Lund (1991)

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

Knoblich, K., Sanner, B. and Klugescheid, M.: Energetische, hydrologische und geologische Untersuchungen zum Entzug von Wärme aus dem Erdreich (Energetical hydrological and geological investigations on the extraction of heat from the ground), *Giessener Geologische Schriften* **49** (1993), 1-192

MIS 3005: Requirements for Contractors Undertaking Design, Installation, Set to work commissioning and Handover of Microgeneration Heat Pump Systems, version 3.0, *DECC*, London (2008)

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

Mogensen, P.: Fullskaleförsök med berg som värmekälla för värmepump i Järfälla, mätning och utvärdering (Full-scale experiment with rock as heat source for a heat pump in Järfälla, measurement and evaluation). *Byggforskningsrådet R123:1985*, Stockholm (1985), 1-22

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

Pahud, D.: Two response tests of two 'identical' boreholes drilled to a depth of 160 m near Luzern, in: Workshop Geothermische Response Tests Lausanne, Eugster, W.J. and Laloui, L. (eds.), *GtV,* Geeste (2002)

Sanner, B.: Schwalbach Ground Coupled Heat Pump Research Station, *Newsletter IEA Heat Pump Center* **4/4**, Karlsruhe (1986), 8-10,

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

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

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

Sanner, B., Hellström, G., Spitler, J.D. and Gehlin, S.: More than 15 years of mobile Thermal Response Test – a summary of experiences and prospects. *Proc. EGC 2013*, Pisa (2013), paper SG3-01, 1-9

Sauer, M., Mands, E., Grundmann, E. and Sanner. B.: Erweiterte Anwendungsmöglichkeiten des Geothermal Response Test: Bestimmung der Erdwärmesondenlänge mittels Thermoimpuls (extended application of TRT: determination of BHE length using thermal impulse), *Proc. Geothermiekongress Karlsruhe 2010*, Berlin (2010), paper F11.4, 1-7

Sauer, M. and Sanner, B.: Thermal Response Test (TRT): Practical recommendations for drillers, in: Geotrainet Training Manual for Driller, Andersson, O. and Sanner B. (eds.), *EGEC/Geotrainet*, Brussels (2011), 60-75

Sauer, M.: Evaluating improper response test data by using superposition of line source approximation. *Proc. EGC 2013*, Pisa (2013), paper SG3-14, 1-6

Sauer, M., Sanner, B., Mands, E., Grundmann, E. and Fernández, A.: Thermal Response Test: Practical experience and extended range of application, *Proc. Innostock 2012*, Lleida (2012), paper INNO-U-27, 1-9

Shonder, J.A. and Beck, J.V.: Determining Effective Soil Formation Thermal Properties from Field Data Using a Parameter Estimation Technique, *ASHRAE Transactions*. **105(1)** (1998), 458-466

Spitler, J.D. and Smith, M.D.: Development of an In Situ System for Measuring Ground Thermal Properties. *Oklahoma State University*, Stillwater OK (1996)

Spitler, J.D. and Gehlin, S.: Thermal response testing for ground source heat pump systems - An historical review, *Renewable and Sustainable Energy Reviews* **50** (2015), 1125–1137

Van Gelder, G., Witte, H.J.L., Kalma, S., Snijders, A. and Wennekes, R.G.A: In-situ-Messung der thermischen Eigenschaften des Untergrunds durch Wärmeentzug (In-situ determination of thermal properties of the underground by heat extraction), *Proc. OPET-Seminar Erdgekoppelte Wärmepumpen*, Cottbus (1999), 56-58

VDI 4640-2: Thermische Nutzung des Untergrunds, Erdgekoppelte Wärmepumpen (Thermal Use of the Underground, Ground Source Heat Pumps), draft guideline, *VDI*, Düsseldorf (2015)

VDI 4640-5: Thermische Nutzung des Untergrunds , Thermal Response Test (Thermal Use of the Underground, Thermal Response Test), draft guideline, *VDI*, Düsseldorf (2016)