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Thermal Response Test – Two Decades of Experience of Mobile TRT, the Dos and Don´ts and latest developments

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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, including Germany, where two different groups did the first TRTs, almost simultaneously, in 1999. The authors were part of one of these groups, and today look back at the largest number of commercial TRTs made by a German company.

Over more than 15 years a wealth of experience could be collected. Development lead to substantial improvements, however, some experience also helped to understand what not to do. The paper will discuss successful approaches and point out caveats for practical TRT execution. 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 1999, 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 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 will give examples of these techniques, and will discuss possibilities for further improvements and applications.

Keywords:

Underground Thermal Energy Storage (UTES), Standards, Regulation

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 (Nordell, 2000), 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 (Eklöf and Gehlin, 1996) to the international experts – and the experts listened with keen interest and had intensive discussion on the subject.

As an excellent and very comprehensive account on the history of TRT, dealing in particular with the theoretical concepts and evaluation methods, has been published recently (Spitler and Gehlin, 2015), this part needs not to be covered here. It should just be mentioned that the theoretical basis for the TRT predates the 1996 meeting by about two decades, with publications like Choudary (1976) and Mogensen (1983). The possibilities of using the TRT as a part of site investigation before plant design began to take shape when 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.

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, Wetzlar, the other at Landtechnik Weihenstephan, Freising). Both did the first two TRTs in Germany, almost simultaneously, in 1999 (Sanner et al., 2000). 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. 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 (Sanner and Choi, 2005), 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 most design work for a project of more than about 30-50 kW, often also in smaller projects, a TRT is performed to secure the input data.

2. Early TRT deployment

2.1. Evaluation and optimisation in IEA ECES Annexes 8, 13 and 21

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 furthermore covered in Annex 13 (1998-2003), and later on resumed in Annex 21 (2006-2010). A first practical comparison of test results with different equipment was performed already in October 2000, where the reproducibility of TRT results could be shown (Sanner, 2001). A joint workshop within IEA ECES Annex 12 and 13 allowed to bring one Dutch and two German rigs together on the site for a new BTES in Mol, Belgium, where three BHE with different grout were available for the tests. The Dutch rig had done the tests before the workshop, the two German ones were doing tests on different BHE at the same time parallel to the workshop, and one test afterwards. The following BHE were available:

- Single-U, grouted with sand produced while drilling
- Single-U, grouted with specially graded sand
- Single-U, standard bentonite/cement grout

Table **1** lists the results from the different rigs as obtained with evaluation following the line-source approximation as used by Eklöf and Gehlin (1996). One of the tests of Groenholland had some problems during the test period and should not be considered here (values in italics). 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 so well. An evaluation of the Groenholland tests with parameter estimation using a 2-D-simulation model provided only marginally higher values for the ground thermal conductivity in the sand-filled boreholes, with the value for the bentonite-grouted BHE being closer to the rest now (Table 2). This evaluation method does not determine borehole thermal resistance, but the grout thermal conductivity instead; in the boreholes backfilled with sand this value correctly is similar to that of the surrounding soil, which is basically sandy on the Mol site

Table 1: Results of the TRT comparison in Mol, Belgium, Oct. 2000; evaluation with line-source approximation

Grout type	Groenholland	UBeG	LT Weihenstephan
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 = n/a
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)	-

Table 2: Results of the TRTs performed by Groenholland in Mol, Belgium, Oct. 2000, evaluated with parameter estimation using a 2-D-simulation

	Mol-Sand	Graded Sand	Bentonite
Soil	λ = 2.56 W/(m·K)	λ = 2.47 W/(m·K)	*λ = 2.26 W/(m·K)*
Grout	λ = 2.42 W/(m·K)	λ = 2.52 W/(m·K)	*λ = 1.25 W/(m·K)*

The test strategies of the different groups performing TRTs in Mol were quite different. Figure 1 shows the temperature development of the tests with the German rigs. Both UBeG and Landtechnik Weihenstephan (LTW) started with a relatively low heat injection rate in the order of 2 kW. After about 16 hours the LTW crew decided to step up the heat injection rate with the aim to achieve a stronger signal, while UBeG kept the original rate to the end. All tests resulted in fairly straight lines in the semi-logarithmic scale (Figure 1, lower part), and, as discussed above, the final results matched nicely, despite the different strategies.

A re-evaluation of the original TRT data both from the UBeG and LTW tests has been performed by the authors with up-to-date evaluation software, including parameter estimation using superposition technique. The results are given in Table 3.

Table 3: Re-evaluation of TRT data obtained during comparison in Mol, Belgium, Oct. 2000, using current UBeG evaluation software in 2017

Grout type	original from 2000	new line source	new superposition
Mol-Sand (LTW data)	λ = 2.47 W/(m·K) r_b = 0.05 K/(W·m)	λ = 2.71 W/(m·K) r_b = 0.09 K/(W·m)	λ = 2.48-2.82 W/(m·K) [1] r_b = 0.08-0.09 K/(W·m)
Graded Sand (LTW data)	λ = 2.51 W/(m·K) r_b = n/a	λ = 2.57 W/(m·K) r_b = 0.07 K/(W·m)	λ = 2.62 W/(m·K) r_b = 0.07 K/(W·m)
Bentonite (UBeG data)	λ = 2.49 W/(m·K) r_b = 0.13 K/(W·m)	λ = 2.46 W/(m·K) r_b = 0.10 K/(W·m)	λ = 2.26 W/(m·K) r_b = 0.10 K/(W·m)

[1] The range in numbers is due to separate evaluation of the two power steps of the original LTW test.

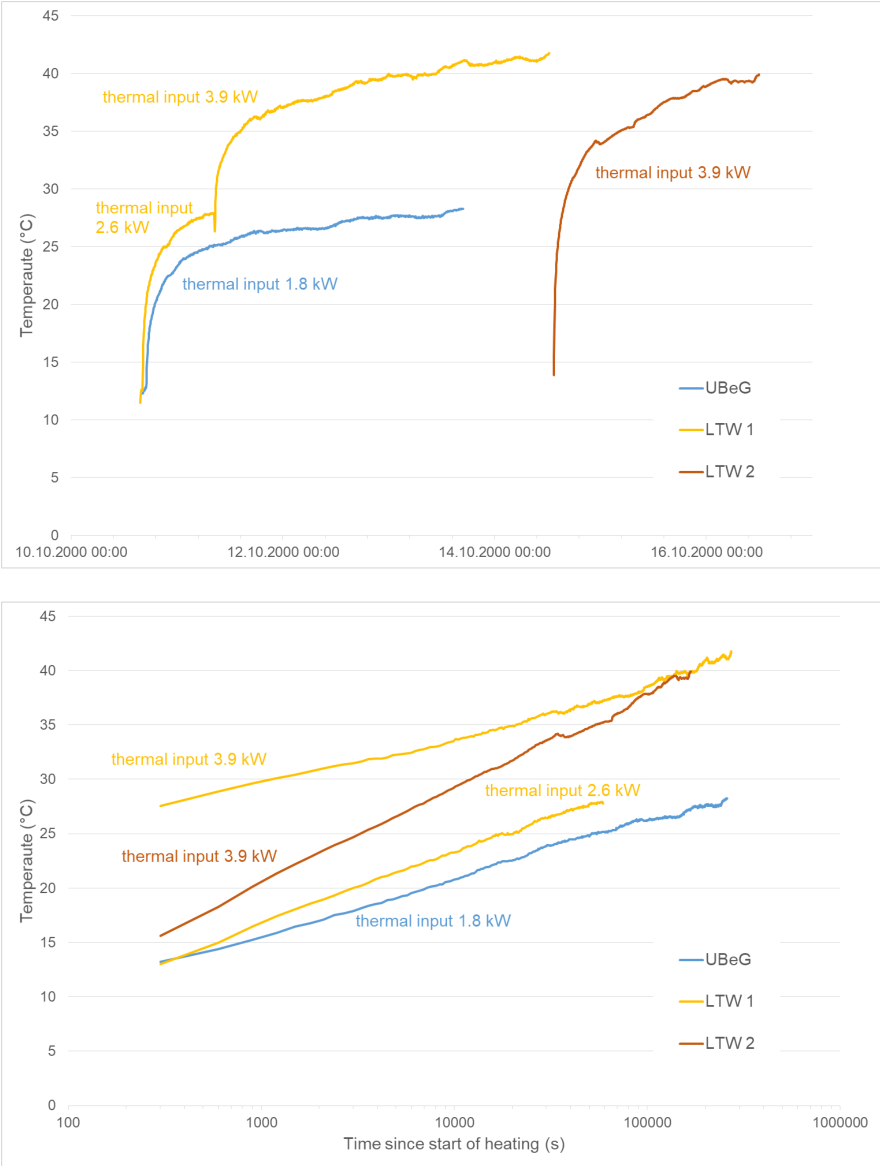

Figure 1: Development of the fluid temperature (mean of inlet and outlet) in three TRT performed in October 2000 in Mol, Belgium, by UBeG and Landtechnik Weihenstephan (LTW), on the real time axis (upper graph) and with logarithmic time (lower graph), plotted from the original data of IEA ECES Annex 13

While the single-step tests ("Graded Sand" and "Bentonite" in Table 3) show a nice match for the line-source evaluation in 2000 and in 2017, the test in "Mol-Sand" backfilling yields a higher value in 2017. The original LTW test had two power steps, the first lasting ca. 16 hours and the second ca. 76 hours, see Figure 1. Evaluation "new line source" was done with the first step only, as reliable starting data for the second step were not available; "new superposition" was performed for three scenarios with this test:

- whole curve, result 2.76 W/(m·K)
- each of the steps separately; first step 2.48 W/(m·K), second step 2.82 W/(m·K)

The results using superposition differ from those with line-source approximation also for the two single-step tests. It should be noted that the value from the UBeG test in this evaluation, showing 2.26 W/(m·K), matches exactly that of the Groenholland test at the same BHE, evaluated with 2D-model in 2000 (Table 2). While Sauer (2013) could show that results from line-source approximation and superposition are matching well for good test data (i.e. with low power fluctuation, as required for line-source application), and results from numerical simulation and superposition also match well for data with varying power input taken into account, clear divergence can be seen (Table 3) in this case, where older values are considered and some information is missing. This proves that TRT operation has to be better documented and regulated, and standards like the upcoming VDI 4640-5 are important for operation and evaluation of TRT in order to achieve comparable and reproducible results.

In the beginning, TRT-development was closely coupled to practical work for BTES installations and larger GSHP-plants. The first two tests in Germany thus considered a BHE-field for a GSHP for heating and cooling (see 2.2) and a BTES for storage of solar energy (Reuss et al., 2006). The work in IEA ECES Annex 13 allowed for systematic comparison and understanding of the methodology, and resulted in some guidelines for TRT, published e.g. in an appendix to Sanner et al. (2005). These guidelines later formed the basis for the TRT-part of EN ISO 17628 (2015). From 2006 on, IEA ECES Annex 21 (Reuss et al., 2009) concentrated fully on TRT and resulted in many ideas for system improvement, enhanced evaluation, etc., and also allowed for further dissemination of the technology to more countries world-wide. The collection of information on actual TRT equipment (see http://thermalresponsetest.org/) still provides a good overview of what exists.

The information from the Annex 21 sheets, supplemented by additional information collected, was summarised by Sanner et al. (2013), with a European focus. The number of TRT rigs in use in Europe at that time was estimated to about 70, about half of which (34 rigs) in Germany. At least 43 entities in 15 countries having own TRT were identified in Europe, including 7 research institutes or geological surveys, 6 universities and 30 private companies. While universities use TRT mainly for research, in some areas, a competition in the commercial market between public institutions and private service providers cannot be avoided. Today TRT equipment exists in at least 19 European countries, operated by more than 50 entities (companies and institutions). The uptake of TRT in Europe after the 1996 IEA workshop can be seen from Figure 2.

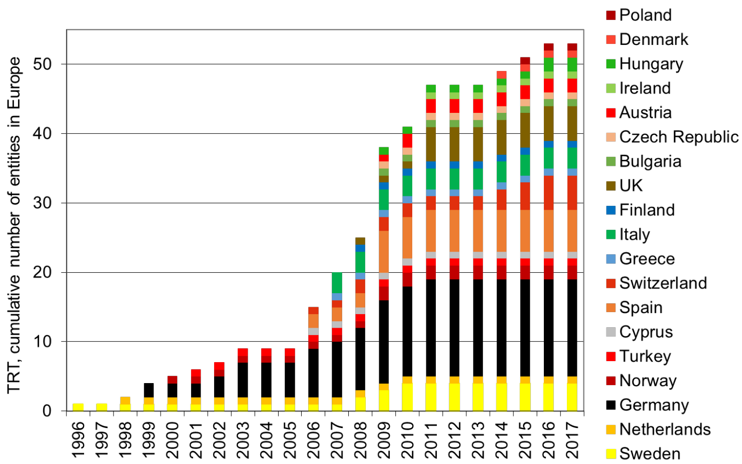

Figure 2: Uptake of TRT in Europe - cumulative number of entities performing TRT, based on datasheets from IEA ECES Annex 21 and own additions and updates

After start in Sweden, followed closely by the Netherlands and then Germany and Norway, a total of 5 entities performing TRT existed in Europe by the year 2000. The subsequent growth to 9 entities in 2003 was from Turkey and Germany only. From 2006 on, new countries with TRT joined the list, with one or two newcomers each year until recently. The numbers in Figure 2 should be regarded as a minimum, with the survey in Sanner et al. (2013) and in particular the update for this paper not claiming to be exhaustive. While some companies or institutions still build their own TRT rigs, other purchase complete rigs from the few equipment providers (e.g. UBeG, Geotechnik Lehr, etc.; also US-manufacturer Geo-Cube™ entered the European market). New technologies using sensors inside the BHE (on cable or floating freely, e.g. GEOsniff®) complement the investigations.

2.2. TRT in Langen and other early TRT by UBeG

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; the respective building and BTES is described in Seidinger et al. (2000). Table 4 summarises the result of this first test, done prior to construction at an exploration BHE 100 m deep, and of subsequent tests performed at selected BHE while the full BHE field was under development with final depth of 70 m. At the time of construction thermally enhanced grout became available and was used for the BHE field. The lower borehole thermal resistance achievable with this kind of grout is clearly visible in the TRT results. The system for DFS Langen was monitored and re-evaluated in a study by Leibniz-University Hannover in 2007-2011, and efficient operation within the predicted temperature range could be verified (Bohne et al., 2012).

Table 4: Results of TRT for Langen BTES; La1 in 1999 on 100-m-borehole before construction, La2-La4 in 2000/2001 during construction of BHE field on 70-m-boreholes

Test No.	Test duration	Undisturbed temperature	Heat input	BHE depth	BHE diameter	Thermal conductivity λ_{eff}	Borehole thermal resistance r_b
La1	50 h	12.2 °C	4.9 kW	99 m	150 mm	2.8 W/(m·K)	0,11 K/(W·m)
La2	94 h	11.9 °C	3.4 kW	70 m	160 mm	2.3 W/(m·K)	0,08 K/(W·m)
La3	*48 h*	*11,1 °C*	*~6.4 kW*	*70 m*	*150 mm*	*1.9-2.4* W/(m·K)	*wide range*
La4	70 h	11.4 °C	3.5 kW	70 m	150 mm	2.2 W/(m·K)	0,07 K/(W·m)

Test La3 (*in italics*) was done by a new TRT provider from Eastern Germany for comparison reasons; due to heat input problems during operation, no conclusive result could be given by that company despite evaluation using different methods including superposition. Grouting in La1 was standard bentonite grout, while in La2-La4 thermally enhanced grout "Stüwatherm" was used, resulting in lower borehole thermal resistance.

By the end of 2000, UBeG had performed 11 TRT on BHE from 26 m to 117 m length, in various geological conditions. Temperature curves of three of the first TRT by UBeG are shown in Figure 3. The two upper graphs in Figure 3 show typical curves for underground dominated by conductive heat transport, with the tests easy to evaluate and providing reliable results. However, in one of the TRTs a phenomenon was encountered that later became the basis of testing for quality of grouting. After a quick initial temperature increase the temperatures remained almost constant over time, and after setting the heat input to a higher level, the same behaviour could be seen again (Figure 3, lower left). The reason could be identified when investigating the documentation of drilling and installation. At the site in Herford drilling had encountered Mesozoic sediments, consisting of a series of permeable and impermeable layers. Due to the dipping of the layers and the location on a hillside, the lower aquifer was confined (probably almost artesian as to the documents). The BHE was not grouted, in spite grouting being stipulated already by most water authorities at that time and by VDI 4640 (draft 1998), but backfilled with fine, rounded gravel and sealed with a solid clay plug at the top (Figure 3, lower right). As a result, the groundwater from the confined aquifer could move upwards inside the borehole annulus and dissipate into the upper permeable layer. The constant water flow along the BHE axis turned the pipes into a fluid-fluid heat exchanger, and large amounts of heat could be carried away resulting in an equilibrium with quasi-constant temperature for each of the two heat input levels. Perfect for BHE performance, but a nightmare for the water authorities!

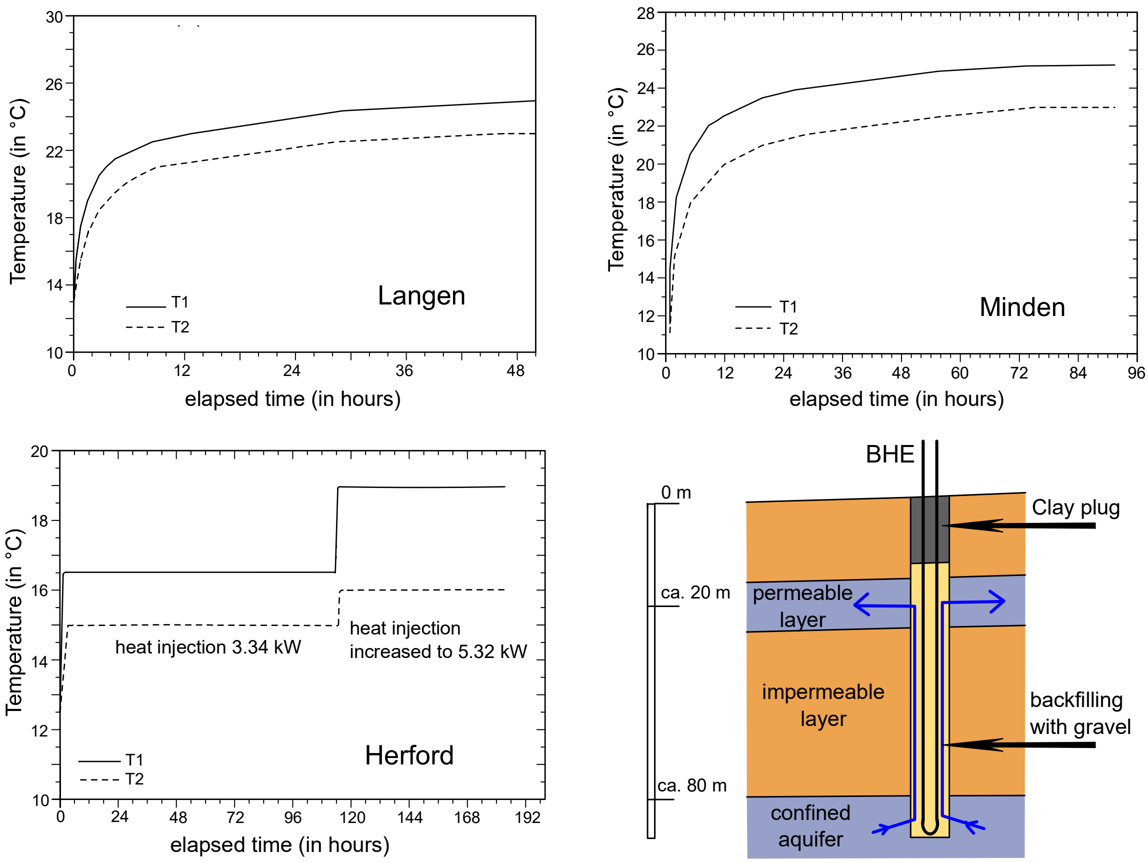

Figure 3: Temperature development in early TRTs by UBeG from 1999/2000, and explanation of behaviour of Herford BHE (lower right)

This experience from the year 2000 was, alas, repeated several times over the following years, with the latest case dating from summer 2017. Prevention of groundwater movement within the borehole is a challenge whenever a large pressure difference exists between groundwater-bearing layers. Examples range from confined or artesian groundwater situation to areas where groundwater underneath a low-permeable layer has been pumped e.g. for deep mining. Specific grout mixtures or packers to hold grout in place until setting might be required, and in many cases drilling at these sites should be avoided for good. Sauer et al. (2012) explains the use of TRT to check for this kind of grouting failure on existing BHE.

3. Practical Recommendations for TRT

Over the years a wealth of experience in TRT operation 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, with the other part, data evaluation, being equally important. 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. This chapter limits the scope to the type of TRT used commercially for design of borehole heat exchangers and its practical application.

3.1. Test equipment

A typical TRT setup of today is shown in Figure 4 (left). 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. For very confined sites or for transport by air, even smaller TRT rigs have been used successfully (Figure 4, right). 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.

Figure 4: Typical TRT-setup at BHE on a site under development (left) and miniaturised, highly mobile TRT (right), both devised and built by UBeG (photos Kahl)

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 start of operation

Based upon many years of experience, we exercise some mandatory routine procedures 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[2]. 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.
- Proper 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.
- Site disturbances. 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

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

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 5. 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, either on wire with data logging on the surface, or floating downwards in the pipe and then flushed out, with internal data collection. Glass-fibre cables for temperature measurement inside BHE can yield a wealth of information for R&D on BHE, as e.g. the work of Acuña (2013) has shown; however, this technology is not necessary for commercial TRT, and may even hamper test operation. The temperature log yields some further information. Quite often not the perfect geothermal gradient as in Figure 5 is found, as groundwater layers, convection in highly permeable ground or in not properly grouted boreholes (see 2.2), surface influences (mainly in cities),

[2] Depending on the type of equipment, also a boiler burning fossil fuels like LPG or fuel oil can be used for heating the circulating fluid. The authors prefer electric heating, for ease of control.

recent drilling activity, etc. can disturb the temperature field. The log can give indications of such problems and is one part of the toolbox for identifying them in detail.

Once the undisturbed temperature is known and the functioning of the data logger checked, the heater can be switched on. 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. Thus thermal load for TRT must be adjusted for borehole depth and geology (expected thermal conductivity). Figure 5 shows some examples for different depth and rock type, the respective specific injection rate varying from 31 W/m to 94 W/m, with an average value of 55 W/m.

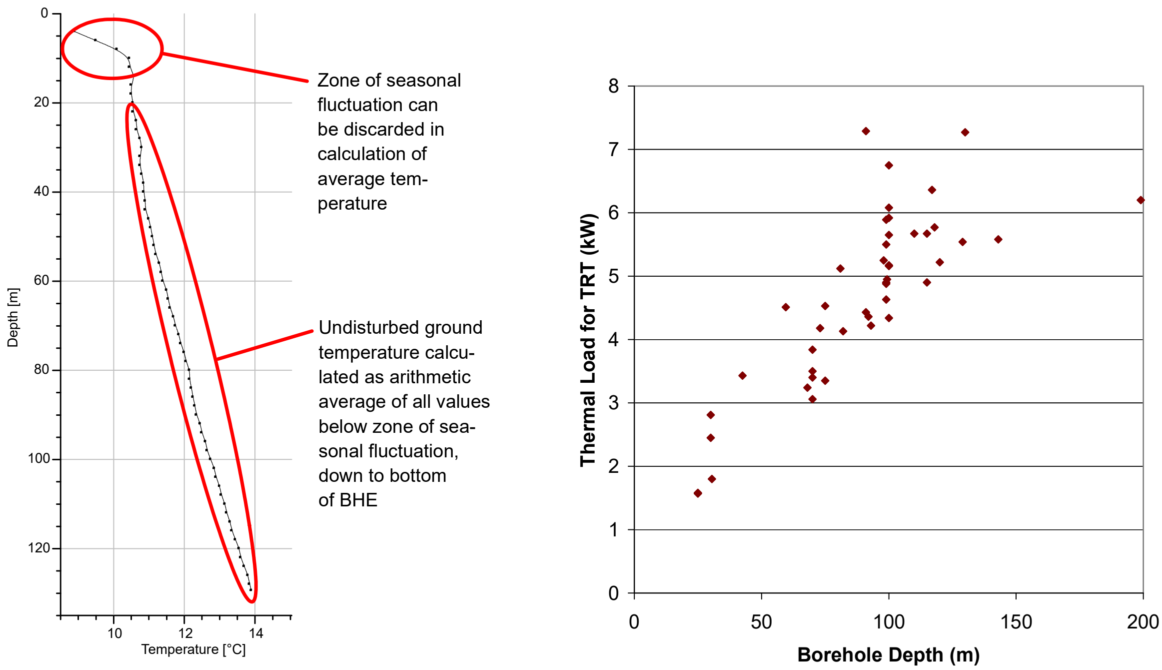

Figure 5: Example of temperature log in BHE to determine undisturbed ground temperature (left, taken towards the end of winter) and thermal load for TRT versus borehole depth for a number of tests (right)

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.

3.3. During test operation

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 challenge 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 temperatures taken directly at the top of the BHE (and the flow rate, of course).

Figure 6 gives an example of thermal output and the resulting temperature development at the BHE. As long as fluctuations are small and do not show an upward or downward trend, and the test time is sufficiently long, the evaluation can be done by using the average heat load. A sequential evaluation can confirm the validity. In cases were a trend is visible as in the example in Figure 7, or where larger fluctuations occur, parameter estimation with the actual heat load curve is required (Sauer, 2013). When evaluating test data with heat load development as in Figure 7 and using the average value, the actual load will be higher in the beginning and lower towards the end of the test, and the values for thermal conductivity will be under-estimated.

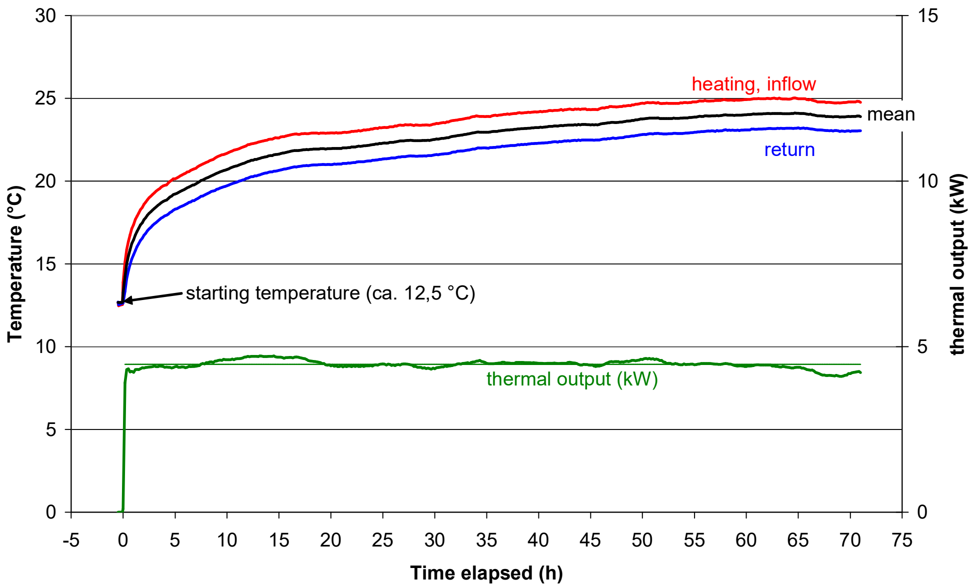

Figure 6: Example of temperature and load curve for TRT, from real data over >70 hours; small fluctuations in thermal load can be seen, but no upward or downward trend

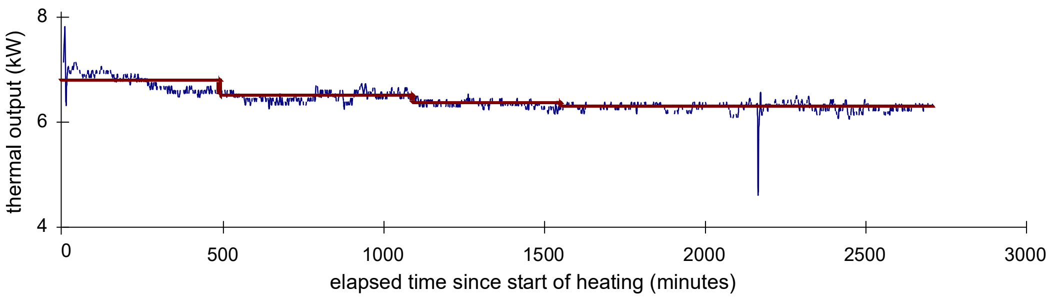

Figure 7: Thermal load curve for TRT from 2001 (TRT No. La3 in Table 4); a clear downward trend (decreasing thermal output) can be seen

Also TRT rigs 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. In this case of increasing heat load, using the average load will result in over-estimation of the thermal conductivity. Hence in case temperature difference control is preferred, also simultaneous control of fluid flow is required.

The test duration usually is set to a minimum of 48 hours. This is a generally accepted value (cf. VDI 4640-5, 2016) and in most cases yields sufficient accuracy (Gehlin, 2002). However, there are many factors influencing the minimum duration of a TRT, e.g. the borehole diameter, thermal load, etc. The longer the tests duration, the wider the thermal influence around the BHE and the more of the surrounding ground is represented in the result. Features like groundwater flow become more visible in longer tests. If a sequential evaluation (see 3.4) can be done with datasets from a test while the test still is running, the necessary minimum duration can be determined in real time.

3.4. Test evaluation

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 timespan 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. With substantial influence of flowing groundwater, the curve rises upwards steadily after some time. In this case the test resulting 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 definite 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. This procedure is a useful tool to check the quality of the data collected and the validity of the results; it is stipulated in standard VDI 4640-5 (2016), where also further detail on different analysis strategies (forward, backward) is given.

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.

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 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. 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.

3.5. Test reliability

The accuracy, reliability, comparability and reproducibility of TRT results has been discussed intensely since the first mobile TRTs, and comparative tests have been executed as early as in 2000; usually some margin of error was found. VDI 4640-5 (2016) calls for sufficient accuracy of sensors etc. to guarantee a margin of error of ±5 % for the final value of thermal conductivity. In the Mol-test in 2000 (see 2.1), six individual TRT had been done, with one deemed improper for line-source evaluation. Considering the results of all TRT, obtained with line-source evaluation, the highest error against the mean was +6/-21 %. When using evaluation by parameter estimation for the “improper” test, the error for all was reduced to +3.2/-7.1 %. And finally, considering only the five “proper” TRT, the error was only +1.7/-2.8 %, falling nicely into the VDI 4640-5 limits.

A recent TRT comparison was done in Switzerland in 2016/17 (Badoux et al., 2017). One BHE about 240 m deep was used to perform five TRT with different equipment, separated by some weeks between tests to allow for the temperature field to recover. The main results are summarised here in Table 5.

Table 5: Main results of TRT comparison in Zollikofen (after values from Badoux et al. 2017)

	TRT 1	TRT 2	TRT 3	TRT 4	TRT 5
Undisturbed temperature	13.4 °C	13.7 °C	13.7 °C	13.7 °C	13.3 °C
Thermal conductivity	2.33 W/(m·K)	2.42 W/(m·K)	2.47 W/(m·K)	2.05 W/(m·K)	2.45 W/(m·K)
Borehole thermal resistance	0.09 K·(m/W)	0.08 K·(m/W)	0.07 K·(m/W)	0.08 K·(m/W)	0.09 K·(m/W)

The values listed in Table 5 show good agreement in thermal conductivity among four of the tests. The lower value in TRT 4 is attributed to an insufficient heat input rate by Badoux et al. (2017). Here the highest error against the mean for all tests is +5.4/-12.5 %, and when excluding TRT 4, the error is reduced to only +2.2/-3.6 % (again within the limits stipulated in VDI 4640-5). This is a clear indication that reliable results are possible, provided the equipment and operation are suitable. Further comparative tests for calibration/validation are planned within EU-project GeoPLASMA-CE (Geoplasma-CE, 2017).

4. 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 (3.4).
- 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 convection) simply had to be rejected. In that case, the apparent value for thermal conductivity resulting from line-source evaluation increases steadily with test time, 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 convective heat transport, values for both the thermal conductivity and the remaining part of heat transfer can be obtained. If the convective 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

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