More than 15 years of mobile Thermal Response Test – a summary of experiences and prospects

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ABSTRACT

The first mobile thermal response tests (TRT) were done in the USA in the year 1995 and in Sweden in early 1996. Reports from the Swedish tests were shared within an energy storage group of IEA (IEA ECES Annex 8) in 1996, and the idea soon spread to many countries. In Germany, first tests were made independently by two groups in 1999 (Sanner et al, 1999). Meanwhile, TRT is a basic tool for in-situ determination of thermal ground parameters, used in most countries where borehole heat exchangers are used, both for ground source heat pump development and for underground thermal energy storage. Knowledge and experience today allow for high accuracy and reliability of the test results.

This paper reviews briefly the development of the technology, and gives an overview of the status achieved today, as an update of the last paper of this type from WGC 2005 (Sanner et al., 2005). It then focusses on some misunderstandings of test procedure and in the use of the test results that could be found in reports and commercials. The parameters that can be achieved from a TRT are discussed, in perspective to accuracy and limitations of test evaluation methods. Further applications of TRT to other parameters than just the thermal conductivity of the ground will be listed.

1. INTRODUCTION

Today the importance of the Thermal Response Test (TRT) for design of ground source heat pump (GSHP) systems is no longer questioned. The knowledge of underground thermal properties is a prerequisite for correct design of borehole heat exchangers (BHE), energy piles, and other system that rely on conductive heat transport in the ground. The most important parameter is thermal conductivity of the ground. As this parameter is site-specific and cannot be influenced by engineering, it needs to be known with sufficient accuracy to best plan the layout of the geothermal system (e.g. number and depth of boreholes).

The TRT 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}. Advanced evaluation methods meanwhile allow for some qualitative distinction of the individual components contributing to this effective thermal conductivity.

In Sanner et al. (2005) we could report TRT in 12 countries world-wide (7 of which in Europe), with an estimated number of ca 20 rigs (11 in Europe). Today it can be estimated that some 70 TRT-rigs exist in Europe alone, based in at least 15 countries. World-wide, the main market for TRT outside Europe is in the United States and Canada, with China, Japan and South Korea also seeing TRT done.

2. HISTORY OF TRT

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). The first practical applications were made in the 1980s (Mogensen, 1983; Eskilson et al, 1986) and early 1990s, e.g. for the investigation of borehole heat storage in Linköping (Hellström, 1997). These tests were made as a-posteriori verification of completed systems. The possibilities of using the TRT as a part of site investigation preceding the design began to take shape.

In 1995, mobile thermal response test rigs were developed independently at Luleå Technical

University (Eklöf & Gehlin, 1996; Gehlin, 1998) and by both an Oklahoma-based private company and Oklahoma State University, in collaboration. (Spitler & Smith 1996, Austin 1998). Both test rigs imposed a step heat pulse on the ground, using an electric resistance heater, to measure the ground thermal properties for BHE between some 10 m to over 100 m depth. A somewhat different test rig was developed and tested in the Netherlands soon after (van Gelder et al., 1999); this rig uses 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., 1999).

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). Austin et al. (2000) validated their test results and analysis procedures against a laboratory experiment and a cored borehole where the thermal conductivities of the individual core samples were determined with a guarded hot plate.

In the beginning the only, and today still the most popular evaluation method is based on an approximation of Thomsons´s (later Lord Kelvin) approach to calculate the heat transfer from a linear source of heat (Thomson, 1884), the latter known as the Kelvin Line Source Theory. Already in the first heyday of GSHP in the USA around 1950, this calculation method was propagated for design of ground loops (e.g. Ingersoll & Plass, 1948). For the first mobile tests, Eklöf & Gehlin (1996) used an approximation that after solving towards λ, the thermal conductivity, would read:

$$\lambda = \frac{Q}{4\pi k H}$$

Q = thermal load (heat injection/extraction)

k = gradient of the measured temperature curve

H = length of BHE

Upon this formula, the evaluation of the vast majority of TRT performed until today is based. The line-source approach is a relatively simple way for evaluation, and a suitable method exists for checking the validity of the results, with the sequential, evaluation, originally called "stepwise evaluation" (Gehlin, 1998; Sanner et al., 2007). However, the validity of TRT results achieved with this evaluation method depends heavily upon stable test conditions and sufficient accuracy of sensors etc.

Soon after the first mobile TRT, alternative evaluation methods were tested, using parameter estimation to fit calculated temperature curves to the measured ones. The calculation of temperature curves was either by analytical formulas, or by numerical simulation (e.g. Spitler & Smith 1996; Austin et al. 2000, Wagner & Clauser, 2005). The latter allowed for including varying thermal loads, a definite advantage when dealing with poor grid stability or high external influences (e.g. sunshine). A good coverage of numerical evaluation is given by Signorelli et al. (2007). Beier and Smith (2003) presented an alternative method for removing the effects of variable heat input rates in the Laplace domain, allowing for test analysis using line-source approaches such as the Eklöf and Gehlin (1996) approach described above.

3. SOME TRT-STATISTICS

The data sheets of IEA ECES Annex 21 (see http://thermalresponsetest.org/) provide an opportunity to estimate the current number of TRT rigs and some other statistical values. In this paper, concerning statistics the scope is on Europe only. The information from the Annex 21 sheets, which reflects largely the status in 2010, is supplemented by some additional information known to the authors.

The number of TRT rigs in Europe currently in use can be estimated to about 70, about half of which (34 rigs) in Germany (figure 1). We could identify at least 43 entities having own TRT:

- 7 research institutes or geological surveys
- 6 universities
- 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.

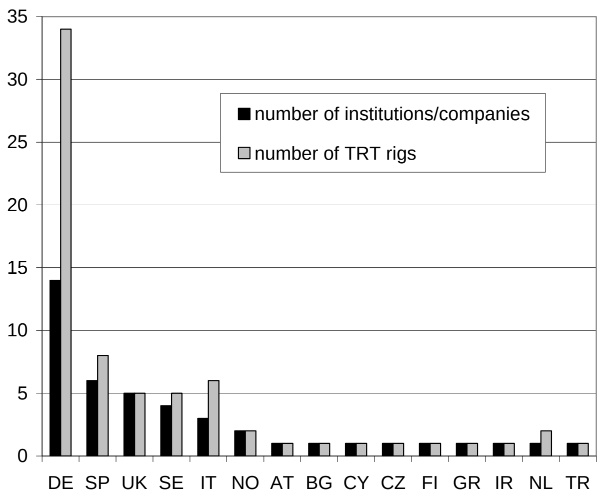

Figure 1: TRT rigs (above) based on data sheets on IEA ECES Annex 21 website and some additions (status ca 2010).

The uptake of TRT in the different European countries can be seen from figure 2. It started in Sweden, followed closely by the Netherlands and then Germany and Norway, with a total of 5 TRT rigs in Europe by the year 2000. In 2001, one Swedish TRT rig was donated to a university in Turkey, and after that for some time no new countries joined the list. Only in Germany the number of TRT operators increased further.

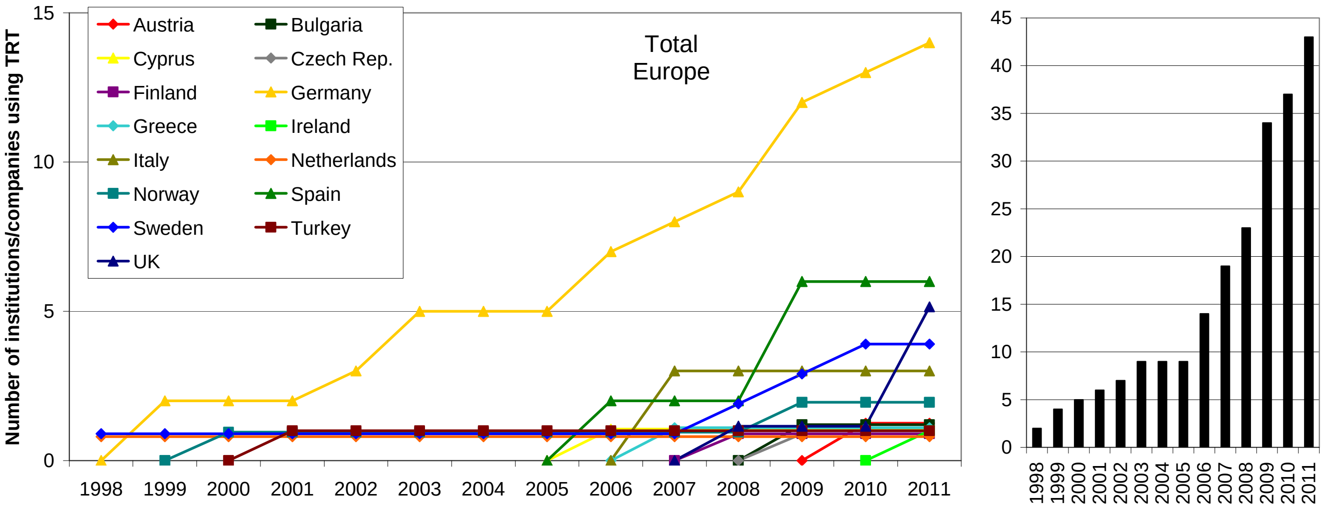

Figure 2: Uptake of TRT technology in Europe; number of institutions or companies with own TRT equipment (cumulative), based on data sheets on IEA ECES Annex 21 website and some additions.

From 2006 on, new countries with TRT could be identified, with one or two newcomers each year until today. Several commercial TRT operators have fleets of up to 6 TRT rigs. The largest number of tests performed (since 1999) by a single company was over 400 at the time of the Annex 21 sheets in 2010, and is around 500 today.

The total number of tests in Europe is at least 2200, with information from some countries lacking (figure 3, above). By German companies alone, TRT was performed in some 1500 occasions. There is not a clear proportion of the number of TRT and the size of the GSHP market in the countries. One reason is that the numbers are given by the location of the TRT operator, not by the location of the GSHP project. Some operators, in particular from Germany, the Netherlands and Sweden, are offering tests all over Europe, so that the numbers from these countries comprise TRT in other countries.

The country with the largest GSHP market, Sweden, has just an average number of TRT. For the Scandinavian countries in general it can be stated that TRT is only done for large projects, and the large number of smaller GSHP is designed using values from experience, and some safety margins. While this works well for the Northern countries with mainly crystalline geology, more emphasis is laid on TRT in countries with more variation in geology, which is the case for most of the rest of Europe.

On average, one European TRT rig performed 37 tests by about 2010, with a large variation from 1 to 60 (figure 3, below). Partly the variation can be explained by the type of use: Universities 11 tests/rig, Institutes 42 and companies 39. While universities run the tests for R&D, the institutes comprise some geological survey like in Finland with a lager number of tests, and the companies with the largest share of the rigs (81 % of the total) dictate the average.

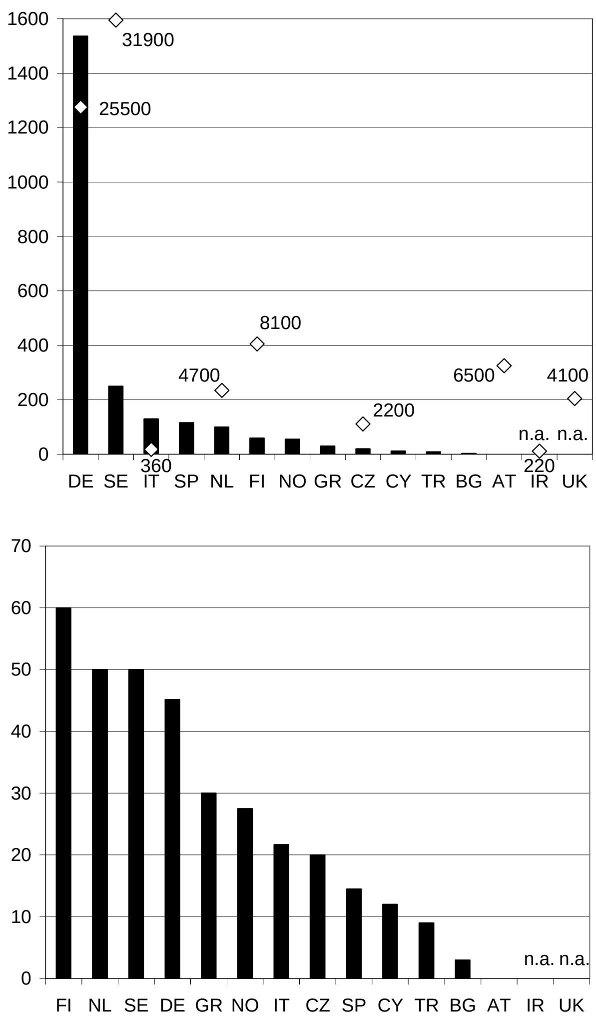

Figure 3: Total numbers of TRT performed in Europe (above, with some GSHP sales numbers for 2010 from EurObserv´er, 2011), and average number of TRT performed per rig in Europe (below), based on data sheets on IEA ECES Annex 21 website and some additions (status ca 2010).

4. HOW TO USE TRT RESULTS

4.1 State-of-the-art TRT evaluation

As stated above, the most common evaluation method for TRT is the line source approximation. This method is fully acceptable, provided the thermal power was sufficiently stable, and a check with sequential evaluation was made. A problem arises if the sequential evaluation proves either a groundwater influence or a decrease/increase of the thermal load. In this case, no result is achieved, and the evaluation has to be redone with a parameter estimation technique (see below).

Austin et al. (2000) presented an error analysis of their experimental methodology and parameter-estimation-based analysis procedure, giving an estimated uncertainty of about 10% for typical (non-dry) soils. The largest contributions to the uncertainty were the recommended 50-hour test length and the estimate of the undisturbed ground temperature. Javed et al. (2011) presented an error analysis for nine adjacent boreholes, finding that thermal conductivities all lay within ±7% of the mean value, but borehole resistances varied in a range of ±20% of the mean. In a thorough analysis of the error of TRT, Witte (2012) gave an uncertainty for a case with thermal conductivity of 2.5 W/mK of 5.1%. He showed that, when determining the heat input rate based on measured flow rate and temperature difference, the uncertainty in the temperature difference is the main cause of error in the thermal conductivity estimate, contributing about 70 % of the error, followed by uncertainty in the fluid heat capacity contributing about 16%. Beside these, misinterpretation of the slope k is good for around 7 % of the total error if the line-source evaluation technique is used.

Initial TRT tests were done using a heat input rate that was as constant as possible. Witte and van Gelder (2006) introduced a test protocol with multiple heat input rates to help quantify the effect of groundwater flow in the surrounding ground. Heat injection and heat extraction pulses of duration between 24 and 45 hours were used. Gustafsson and Gehlin (2006, 2008) utilized a multi-level heat injection test to show the effects of heat input rate and temperatures on thermal resistances of groundwater-filled boreholes.

To overcome the limitations of the line-source approximation by taking into account variable thermal loads and external factors, parameter estimation technique can be 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 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 required to set up the proper model and some time for execution. Hence simpler methods have been tested for calculating the temperature curve in those cases where the external factors are limited and mainly the thermal load variation needs to be considered. The most promising method is parameter estimation using line-source superposition. The latest report on this method (Sauer, 2013) compares a temperature curve from a TRT with large fluctuations in thermal load to calculated curves using line-source superposition and numerical simulation with the finite element (FEM) software FEFLOW, showing a good match (figure 4). A comparison of test results for 5 TRT with instable thermal load showed an average deviation between line-source superposition and FEM of 3.1 %, with a maximum of 4.8 %; another comparison of 21 TRT with stable thermal loads resulted in a deviation of 2.7 % an overage between standard line-source approximation and superposition.

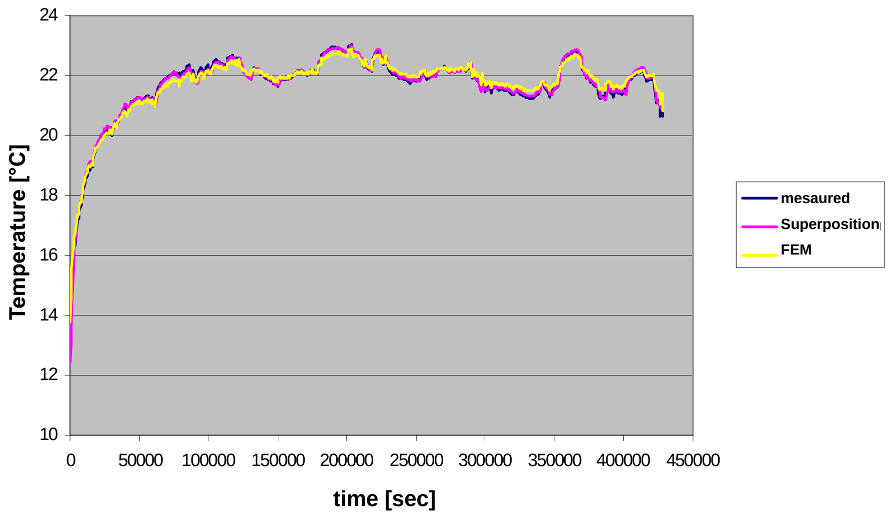

Figure 4: Measured temperatures, temperatures simulated with superposition method, and temperatures simulated with FEM of an instable test run (from Sauer, 2013)

4.2 Some problems in how to use TRT results

In the routine case, and with heat transport dominated by conduction, the values for thermal conductivity can directly be used in design tables or as input to software like EED. However, caution is advised towards the validity of tests, in mainly two areas:

- With line-source approximation, the validity has to be confirmed by sequential evaluation (figure 5):
- 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. A thermal conductivity derived from a curve fit where specific heat of the rock has to be >8 MJ/m^3 for the lowest deviation is simply nonsense.

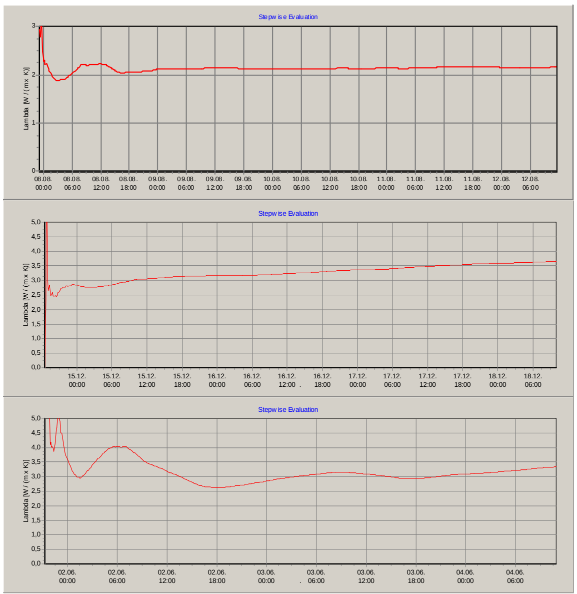

Figure 5: Sequential evaluation of TRT showing a stable result (top), a steady increase of thermal conductivity over test time (groundwater influence, centre) and erratic variations (e.g. due to power fluctuations, bottom), from Sauer & Sanner (2011)

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 5, centre), 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 real thermal conductivity. If TRT data like these are evaluated by use of numerical simulation including the advective heat transport, values for both the thermal conductivity and the remaining part can be obtained. In both cases, the question is what to do with these values for the subsequent design calculations.

A simple, conservative approach would be to take only the thermal conductivity into account and keep the heat transport by groundwater as a reserve (not applicable in the case of UTES systems, of course). The only other way is to also investigate the hydraulic situation, and use a coupled thermo-hydraulic model for the design.

TRT-evaluation using line-source approximation can also provide a value for r_b, the borehole thermal resistance. This value is, however, only valid for the type of BHE, borehole diameter, grouting, etc. as used in the test BHE. In case changes are made to the BHE design as such, it is better to calculate the new value for r_b than to use the measured value for a different design.

In groundwater-filled, non-grouted boreholes in Sweden, the largest influence (both on thermal conductivity and r_b) is from groundwater moving vertically in the borehole between permeable zones (fractures). The problem is that the magnitude of this vertical flow may decrease with time. The hydrogeological situation may not be able to sustain the flow if numerous adjacent boreholes are drilled in the same area. Similar considerations arise with regional (lateral) groundwater flow which may be caused by injection/extraction through wells nearby. Again, a conservative approach focusing on the conductive part of heat transport is recommended.

4.3 Unrealistic expectations

The typical design method for small-to-medium GSHP plants still is the unit heat extraction per meter of BHE ("specific heat extraction rate"), dating from the early days of GSHP in Germany and Switzerland around 1980. For small systems, this method is adequate and is recommended in guidelines like the German VDI 4640 or the British MIS 3005. The thermal conductivity (or simply the rock type) is an input parameter for tables in these guidelines.

The expectation of many GSHP designers is that the TRT should yield a value for the specific heat extraction rate directly. The results of a TRT, however, can only be used as input data for the MIS 3005 tables (or for the upcoming tables in the revised VDI 4640 part 2), or as input for calculations of BHE length. No TRT result can be converted directly into number and depth of boreholes.

Some commercial TRT operators have spurned exaggerated expectations by promoting the TRT as the key to fail-safe design, high GHSP efficiency, etc. This basically is true, but it cannot be attained from the TRT results as such, as it requires a thorough calculation based upon the TRT results and many other factors. And after all, a test under poor conditions, evaluated with simple line-source approximation and not checked for error and general validity (in particular groundwater influence), is prone to deliver more erratic values than a simple estimate based on the rock type!

6. OTHER USES OF TRT

6.1 Interpretation of temperature profiles

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 (figure 6) and allows for various conclusions (Sanner et al., 2007). It should be noted that the exact time of the temperature measurement is not the same over the depth of the BHE, as the logging takes some time (up to 30 minutes for 100 m). So the signal time is slightly different with depth (resulting in the oblique shape of the curves after the test). However, the alternative, using fibre-optic cable for a quasi-constant temperature log, is more pertinent to R&D yet (see below).

Among the features visible are groundwater flow, layers with different conductivity, or missing grout (figure 6). 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). The “bottom heat dissipation” (figure 6) gives a prove for having reached the bottom, as at this point the heat is also transported in vertical direction downwards and a faster cooling can be seen.

A recent development is the distributed thermal response test, summarized by Acuña (2013). A fibre optic cable is used to measure the vertical temperature profile in the borehole. From this, additional information, such as vertical variation in local thermal conductivity, groundwater inflows, undisturbed ground temperature, and borehole thermal resistance may be determined. While promising, use of all this additional information in design tools, improvement of ground heat exchangers and in energy analysis simulations remain topics for further research and development. Similar information can to some extent be obtained by accurate temperature logging before and after the test (see above).

It should be noted that there is already a patent in Germany on a method to calculate vertical variations in thermal conductivity from TRT and temperature logs: Patent DE 10 2007 008032 B4, applied for on 17.2.2007 and granted on 13.11.2008 to the Swiss company Geowatt AG.

6.2 Determination of BHE length

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. The method is called Thermo-Impulse and was first published in Sauer et al. (2010). It comprises of 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.

Figure 7 shows the test principle. The method can yield reproducible results within an error margin of less than 1 % of the BHE length,.

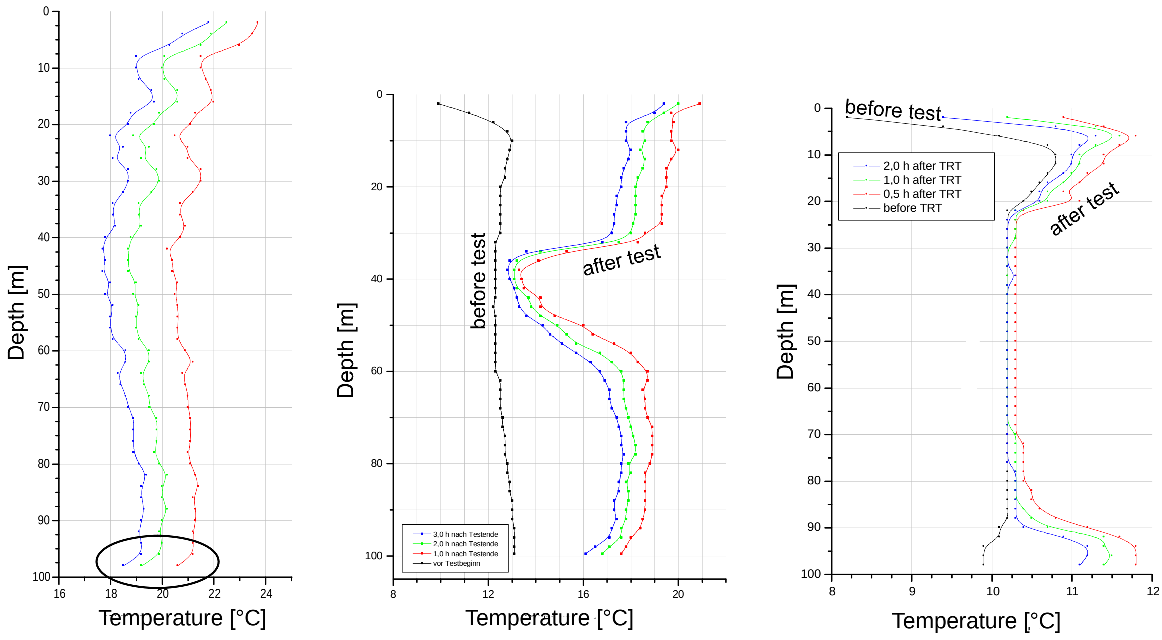

Figure 6: Temperature logs 1, 2 and 3 hours after a TRT in a relatively homogeneous lithology, showing the effect of “bottom heat dissipation” (encircled in black, left); a zone of high groundwater flow elucidated by temperature logs (centre), and a BHE with grout missing over a certain depth range (right), from Sauer & Sanner (2011).

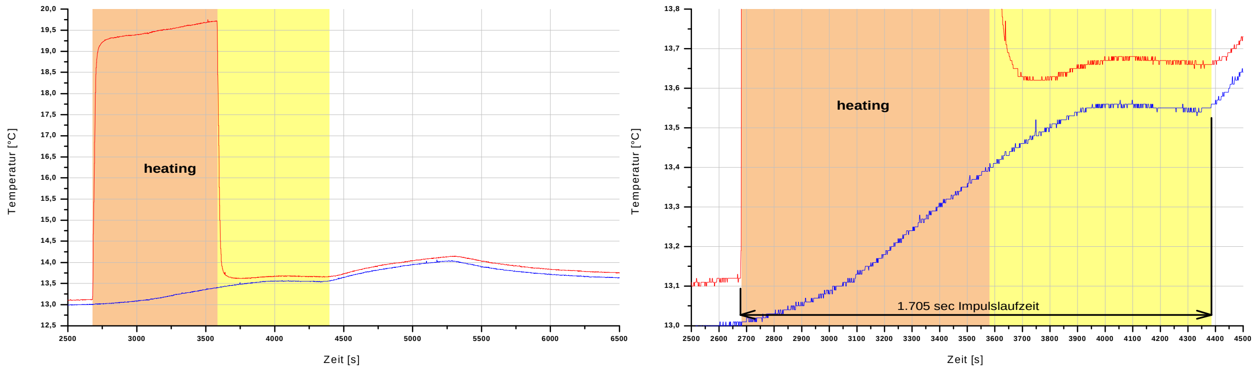

Figure 7: Principle of Thermo-Impulse method (recurrence of impulse), from Sauer & Sanner 2011).

6.3 Possible use of TRT for investigation of deep geothermal potential

As a side note, some thoughts are presented here on measurements in TRT that could be of interest for deep geothermal projects. From temperature logs before TRT, the geothermal gradient (temperature increase with depth) and, with knowledge of the thermal conductivity as a result of the TRT, the geothermal heat flux can be determined as:

$$Q_g = k_g * \lambda$$

with: Q_g = Geothermal heat flux (W/m^2)

k_g = geothermal gradient, in K/m

λ = thermal conductivity (W/m/K)

It should be observed that the accuracy of determining the geothermal gradient is limited, if the TRT is performed shortly after drilling. Heat from drilling, perturbations by the drilling fluid, heat from grout solidification, etc. need sufficient time to settle down before a proper geothermal gradient can be obtained.

Estimates on the expected lithology under the site allow for extrapolation of these values down to the depth required for geothermal power (cf. project Geoelec at http://www.geoelec.eu/). 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.

5. STANDARDS AND GUIDELINES

The first attempt to give some definition and rules for TRT was made in IEA ECES Annex 13. A draft guideline has been developed by an expert group in Annex 13, and was published as an appendix to the proceedings of the first TRT workshop (Eugster & Laloui, 2001). The draft was reprinted in Sanner et al. (2005).

The Technical Committee TC 341 of CEN on "Geotechnical investigation and testing" has proposed a draft for a TRT standard, already in a second version (CEN, 2011). This draft focuses mainly on the construction of the BHE for testing, and on the documentation of construction and test. The TRT part proper is taken directly from the Annex 13 draft. While CEN/TC 341 N525 is not yet in a final version, the description of the TRT contained therein is based on a document more than 10 years old and already outdated in several aspects.

The committee for the German guideline VDI 4640 had worked on inclusion of TRT into the revised version of part 2 of the VDI 4640 since several years. Due to problems in other areas of the guideline, the revision of part 2 is not yet finalised, and thus a decision was taken to prepare a separate VDI 4640 part 5 on TRT exclusively. The draft of this TRT guideline is more or less complete and encompasses the latest development in commercial TRT operation. Publication expected for autumn 2013.

7. CONCLUSIONS AND OUTLOOK

The mobile Thermal Response Test is coming of age, with now 18 years since the first tests. It has proven its worth in R&D and in the commercial design of shallow geothermal systems with borehole heat exchangers (BHE), both for geothermal heat pumps and UTES. TRT is done on most continents, and the full number of TRT-rigs world-wide can be assumed to some 100-200, with around 70 rigs operational in Europe alone.

Development has led to a proven technology appli-cable in routine design work (albeit not all TRT operators yet have achieved the possible degree of accuracy). In Europe it is about time to introduce standards and quality control in order to protect costumers of TRT providers (as we already claimed in our last summary, Sanner et al., 2005), and the upcoming VDI 4640 part 5 could be an example for that.

A number of additional applications of TRT and an enlarged range of information that can be derived from TRT has been devised. In general, two different paths for further development of TRT can be seen:

- High accuracy and complex evaluation, for research purposes and larger projects
- Simplification of test (including shortening of test duration) and standardised evaluation, for commercial applications

Another area where further work is required is to make TRT applicable to “thermoactive structure”, like energy piles.

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