IEA ECES ANNEX 21

Thermal Response Test (TRT)

FINAL REPORT
November 2013

A. Introduction

Content

1. Introduction

Underground thermal energy storage with boreholes (BTES) and ground source heat pumps have become popular technologies in several countries worldwide. Larger systems and especially when it comes to heating and cooling require a thorough planning which is often accompanied by simulation of the thermal processes in the underground part of the system. Typically geology is not uniform and can vary significantly from site to site even if they are close together. Consequently thermal properties like thermal conductivity and heat capacity are not constant values which can be taken from tables but should be determined at the site in order to do a reliable design.

In principle drilling cores can be analysed and the thermal conductivity can be measured from core samples. Typically this is a rather extensive procedure which requires expensive core drilling, thorough sampling and many measurements of the thermal conductivity depending on the amount of different geological layers identified. This will contribute significantly to the total costs of system planning. But only reliable and well designed systems which can be built cost-effective and operated without hazardous environmental impact even on a long-term perspective will be accepted by the authorities and the market.

The Thermal Response Test carried out at a regular borehole heat exchanger has proven to be an economic alternative to the evaluation of samples delivering exactly the values which are required in most of the design tools for borehole systems available and used in the market. When first experiences were published the advantages together with practical demonstration showed convincible results. Close cooperation and knowhow transfer within the framework of the IEA ECES Annex 8, Annex 12 and Annex 13 accompanied by several national and international publications forced the market introduction of this procedure.

Since the IEA ECES Terrastock Conference in 2000 the increasing interest is documented also in an increasing number of publications on Thermal Response Tests. This technique has spread meanwhile to more than 25 countries. Due to the big interest of consultancies the research activities in several countries the IEA ECES Annex 21 “Thermal Response Test” was proposed in June 2006 at the Ecostock Conference in USA. Annex 21 started with a first workshop in autumn 2007 and lasted until 2010.

This report summarizes the results gained from research and shared experiences from practical tests in the different participating countries. It is intended to provide basic knowledge to newcomers in this field but also to improve the knowhow in of advanced testers.

2. The Thermal Response Test

Thermal Response Test (TRT) is a measurement method to determine heat transfer properties of a borehole heat exchanger and surrounding ground in order to predict the thermal performance of a ground-source energy system. The two most important parameters are the effective thermal conductivity of the ground and thermal resistance within the borehole. The TRT equipment is usually mounted on a trailer for easy transportation to test sites. This method has been very important in the rapid spreading of BTES systems. It has been a door opener for introducing the technology in "new" countries.

The first paper suggesting the mobile TRT method was presented by Mogensen at the "Stock" Conference in Stockholm in 1983. It took until the mid 90ies until TRT was developed, independently in US and Sweden, and the very first mobile TRT equipment was operated in 1996 in Sweden. The technology has since spread to about 20 countries in Europe, Asia, North America and South America and will soon be introduced in Africa. Since the TerraStock Conference in Stuttgart 2000, TRT has had a special session at the Stock Conferences.

There are basically two ways to operate the TRT equipment; to inject or extract heat from/into the tested borehole. This is done by circulating a fluid through the borehole that is warmer (injection) or colder (extraction) than the surrounding ground. There are also TRT equipments in which both modes are available. The size and shape of such equipments varies from suitcase to caravan.

The first step of the test is to determine the undisturbed ground temperature. This is usually made by temperature logging in the borehole, or by evaluating the fluid temperature of the circulating fluid before the heating/cooling is switched on.

The measured thermal response is the temperature difference between the circulated fluid's inlet and outlet temperatures. Superimposed temperature fluctuations usually depend on the varying ambient air temperature or corresponding fluctuations in the power supply to the circulation pump. Air temperature and the power consumption are therefore often measured to separate such disturbances in the evaluation.

Used evaluation methods are: the Line Source Model, which is commonly used in Europe and Numerical Simulation Models which are more often used in North America.

B. Objectives
of the IEA ECES Annex 21

1. Objectives

The overall objectives of Annex 21 are to compile TRT experiences worldwide in order to identify problems, carry out further development, disseminate gained knowledge, and promote the technology. Based on this overview, a TRT state–of–the–art, new developments and further work are studied.

The Specific Objectives of Annex 21 are:

Overview

- Worldwide use of TRT (country, type, number)
- Purpose of test (design values, research & development, quality control / failure analysis).
- Applications (BHE, energy piles, heat pipe BHE’s, etc.)
- TRT method (heating and / or cooling)
- Experimental setup (monitoring accuracy, etc.)
- Test procedure
- Evaluation models

New Developments and Further work

- Method to determine undisturbed ground temperature
- Swiss method for detailed logging of borehole temperature – swimming data acquisition ‘Fisch’, etc.
- Groundwater influence
- TRT while drilling
- Software for automatic evaluations
- Comparison of equipment and evaluation
- Initiate a common quality standard of TRT worldwide
- Invitation to “new” countries – workshop and courses on how to use TRT

2. Subtasks

The activities are organized in sub-tasks which are chaired by a responsible lead country.

Sub-task 1. TRT state-of-the-art Study

- Conduct a state-of-the-art survey covering worldwide use including TRT types, purpose, applications, experimental setup, test procedure and evaluation models

Sub-task 2. New Developments

- Method to determine undisturbed ground temperature
- Continuous temperature logging in several depths while testing
- Groundwater influence
- TRT while drilling
- TRT for special geometries like energy piles and horizontal ground collectors
- The Swiss Fish method etc.
- Pulse test

Sub-task 3. Evaluation methods and developments

- Comparison of equipment
- Comparison of test procedure
- Comparison of evaluation methods
- Software for automatic evaluations
- comparative evaluation of reference test data
- include heat capacity cp in the evaluation
- evaluation during testing e.g. to determine duration
- work out system design models which are especially based on TRT results

Sub-task 4. Standard TRT Procedures

- Initiate a worldwide TRT standard – best practice
- TRT for commissioning and past

Sub-task 5. Dissemination Activities

- Invitation to “new” countries – workshop and courses on how to use TRT
- Common website of compiled TRT information
- best practise document
- reports

- available samples of publications

3. Results

The results of this annex will be:

- A TRT state-of-the-art survey. This survey will help determine the need and direction of further R&D. The "State of the Art Report" will be published as an IEA technical document.
- Periodic documents and interim progress reports
- A final report describing the work carried out under this Annex.
- Best Practice TRT Manual
- Information database on a website.

4. Responsibilities for Subtasks

SUB-TASKS	LEAD COUNTRY
1. TRT state-of-the-art	Sweden
2. New Developments	Japan / The Netherlands
3. Evaluation methods and developments	Germany
4. Standard TRT Procedures	Canada
5. Dissemination Activities	Finland

C. SUBTASK 1
State of the Art

Content Subtask

1. ABSTRACT

Proper design of ground heat exchangers in ground source heat pump systems requires a good estimate of the thermal conductivity of the ground to avoid over-sizing or under-sizing of the ground heat exchanger. A good estimate of the thermal conductivity is also needed when designing a BTES (Borehole Thermal Energy Storage) system. The ground thermal properties may be measured at a specific location (in situ) using what is usually referred to as a thermal response test (TRT). In such tests, a heat injection or extraction (often at constant rate) is imposed on a test borehole. The resulting temperature response is used to determine the ground thermal conductivity, and to test the performance of boreholes. Since the initial mobile test rigs were built in 1995 in Sweden and the U.S.A., this technology has spread to an increasing number of countries.

Within the framework of the International Energy Agency (IEA), and the Implementing Agreement on Energy Storage through Energy Conservation (ECES), the overall objectives of the international co-operation project Annex 21 “Thermal Response Test” were to

- compile TRT experiences worldwide in order to identify problems;
- carry out further development;
- disseminate gained knowledge;
- promote the technology.

Current report is the result of the work within the Annex 21 Subtask 1 and gives a summary of known thermal response testing activities in the world and the state-of-the-art of the technology until December 2011.

2. BACKGROUND

Underground Thermal Energy Storage (UTES) is a reliable and sustainable technology for cooling and heating of buildings and industrial processes and is now widely spread in the world. In the past 30 years, various applications of UTES have been constructed. The IEA Implementing Agreement, Energy Conservation through Energy Storage (ECES), has during that time been a platform within much of the expertise on UTES has developed.

The acronym UTES refers to underground thermal energy storage in general, and is often divided into subgroups according to the type of storage medium that is used. The acronym BTES (Borehole Thermal Energy Storage) refers to storage systems using boreholes or ducts and pipes in the ground.

The thermal conductivity of the ground and thermal resistance of the ground heat exchanger (GHEX) are the two most important design parameters for BTES systems. These two parameters may be determined from in situ measurements, which give reliable design data. Such tests are usually economically feasible when designing BTES systems comprising more than a few boreholes. The measurement method has rapidly developed in the last decade and is now usually referred to as Thermal Response Test or just TRT.

2.1 Thermal Response Test (TRT)

Thermal Response Test (TRT) is a measurement method to determine heat transfer properties of a borehole heat exchanger and surrounding ground in order to design and to predict the thermal performance of a ground-source energy system. The two parameters identified are the effective thermal conductivity of the ground and thermal resistance within the borehole. The TRT equipment is commonly built in a few portable boxes or mounted on a car trailer for easy transportation to test sites.

This mobile TRT method has been important in the rapid spreading of BTES systems. It has been a door opener for introducing the technology in "new" countries.

The first paper suggesting mobile TRT equipment was presented by Mogensen (1983) at the International Conference on Subsurface Heat Storage in Theory and Practice in Stockholm. This was the second conference in a series that since 1985 became known as the "Stock" conferences. Mogensen suggested a system with a chilled heat carrier fluid being circulated through a GHEX system at constant heat extraction rate, while the outlet fluid temperature from the GHEX was continuously recorded. This method itself was used to evaluate GHEX systems, before the first mobile TRT existed. (Mogensen, 1985; Eskilson, 1987; Nordell, 1994; Hellström, 1994).

It took until the mid 90ies until TRT was developed. The first mobile measurement devices for thermal response testing were independently constructed in Sweden and USA in 1995. The Swedish response test apparatus ("TED") was developed at Luleå University of Technology as reported in a MSc Thesis by Eklöf and Gehlin (1996). At the same time a similar device was developed at Oklahoma State University (Austin, 1998). Both apparati are based on Mogensen's concept but with a heater instead of a chiller. One of the most important publications in promoting TRT is Gehlin (2002). This doctoral thesis has been downloaded more than 100,000 times from the LTU website.

The TRT technology has spread rapidly and is now available in about 40 countries in Europe, Asia, North America, South America and Africa. Each Stock conference since the TerraStock'2000 in Stuttgart has arranged a special TRT session. At Effstock'2009 two sessions were assigned for TRT (Nordell & Gehlin, 2009). Because of the world wide use of TRT a new annex within IEA ECES Implementing Agreement was started in November 2007 (Reuß et al. 2009). This annex is further described in Sections 1.3 - 1.4.

2.2 TRT Operation

There are basically two ways to operate the TRT equipment (see Figure 1); to inject or extract heat from/into the tested borehole. This is done by circulating a fluid, through the borehole, that is warmer (injection) or colder (extraction) than the surrounding ground. There are also TRT equipments in which both modes are available. Various TRT units have been developed in different countries. The size and shape of such equipments vary from suitcase, to caravan, to shipping containers.

The first step of the test is to determine the undisturbed ground temperature. This is usually made by temperature logging in the borehole, or by evaluating the fluid temperature of the circulating fluid before the heating/cooling is switched on.

The thermal response is the measured change with time in the mean temperature of the fluid's inlet and outlet temperatures. Superimposed temperature fluctuations usually depend on the varying ambient air temperature or corresponding fluctuations in the power supply to the electric heater and the circulation pump. Air temperature and the power consumption are therefore often measured to separate such disturbances in the evaluation. Several equipments compensate these fluctuations by using a control to provide constant power.

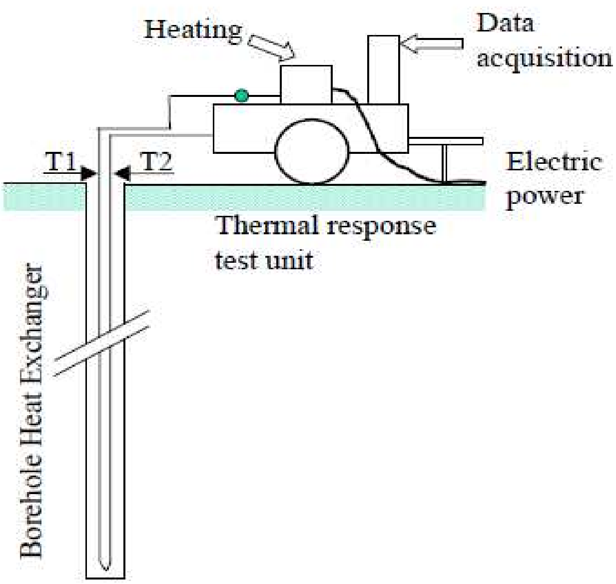


Figure 1: Thermal response test set-up (Gehlin, 2002).

2.3 IEA ECES Annex 21 – Thermal Response Test

The idea of an IEA ECES Annex on Thermal Response Test, came up at the Ecostock'2006 conference in the USA. The reason was that TRT rapidly had spread to countries around the world and the risk was that it was used in such different ways that TRT results would not be comparable. The basic idea of Annex 21 was to document and disseminate a best practice manual to safeguard the method from misuse (Reuß et al., 2009) which possibly could discredit TRT.

2.4 Objectives and Scope

The general objectives of Annex 21 were defined as:

- Compilation of TRT experiences worldwide in order to identify problems,
- Further developments,
- Dissemination of gained knowledge and
- Promotion of the technology

The following five subtasks were defined to carry out the work within Annex 21.

- TRT State-of-the-Art Study (current report)
- New Developments
- Evaluation methods and developments
- Standard TRT procedures
- Dissemination activities

Current report is the final documentation of Subtask 1 that is a summary of the TRT state-of-the-art survey of its worldwide use. The objective of this report is to summarize various aspects of how TRT is used internationally:

- Which countries are using TRT?
- Purpose of TRT data, e.g.: design, R&D, quality control, or failure analysis.
- Applications for TRT, e.g.: GHEX, energy piles, or horizontal ground collectors.
- Description of different TRT setups.
- Test procedure e.g. like heat injection or extraction
- Evaluation models – analytical or numerical models
- The basic theoretical background for TRT will be included.
- References – a list of available scientific literature
- Experiences from 'non-mobile' measurements should be included

In order to collect TRT data from around the world a fill-in form was developed (see appendix). This questionnaire was sent out to potential users and is also available in several languages at the Annex 21 website. This report gives a summary of known thermal response testing activities in the world and the state-of the art of the technology until April 2011.

3. THEORETICAL BACKGROUND OF TRT EVALUATION

TRT means that the thermal response of heat injection or heat extraction into/from a borehole is measured and analyzed. The analysis gives the apparent (effective) thermal conductivity of the ground and the thermal resistance of the borehole. The methods to evaluate response test data are based on the principle of fitting measured and calculated fluid temperatures.

The difference between the different evaluation methods is the way in which the fluid temperature is calculated. The most detailed method is to calculate the fluid temperature by 3D numerical modelling though also 2D modelling is used. In other methods the heat flow and the temperature field around the borehole are calculated by assuming the borehole to be a cylinder (heat) source or a line (heat) source.

The most common method is the line source model also known as the Kelvin Line Theorem. The theoretical background is based on a few assumptions:

- heat transfer in the ground is a result of conduction only,
- the ground is assumed to be initially at a uniform temperature,
- the ground has uniform thermal properties,
- the long borehole is drilled vertically into the ground,
- though the ground temperature varies with depth its mean temperature is used for the full depth of the borehole.

Analysis of transient 1D heat conduction (Ingersoll and Plass, 1948) gives the fluid temperature as a function of time as:

$$T_f(t) = \frac{Q}{L \cdot 4\pi \cdot \lambda} \ln(t) + q\left[\frac{1}{4\pi \cdot \lambda}\left(\ln\left(\frac{4\alpha}{r_b{}^2}\right) - \gamma\right) + R_b\right] + T_g \quad (1)$$

This equation is only valid if the time is not too short i.e. that the time criterion $t > 5 \cdot r_b^2/\alpha$ is fulfilled

T_f	Fluid temperature (°C)
T_g	Initial ground temperature (°C)
Q	Total heat injection into the borehole (W)
L	Borehole depth
r_b	Borehole radius (m)
R_b	Borehole thermal resistance (m,K/W)

λ	Thermal conductivity of the ground (W/m,K)
c	Volumetric heat capacity of the ground (J/m3K)
α	Thermal diffusivity = λ / c (m2/s)
γ	Euler's constant = 0.5722…
t	Time (s)

By replacing the constants in equation (1) by k and m the equation becomes

$$T_f(t) = k \ln(t) + m \tag{2}$$

which means that Tf versus ln (t) becomes linear with the slope k and the abscissa m. By plotting the fluid temperature against logarithmic time k and m are obtained as:

$$k = \frac{Q}{L \cdot 4\pi \cdot \lambda} \quad \Rightarrow \lambda = \frac{Q}{L \cdot 4\pi \cdot k} \tag{3}$$

from which λ is calculated and

$$m = \frac{Q}{L}\left[\frac{1}{4\pi \cdot \lambda}\left(\ln\left(\frac{4\alpha}{r_b^{\,2}}\right) - \gamma\right) + R_b\right] + T_g \qquad \Rightarrow R_b \tag{4}$$

from which Rb is obtained after fitting.

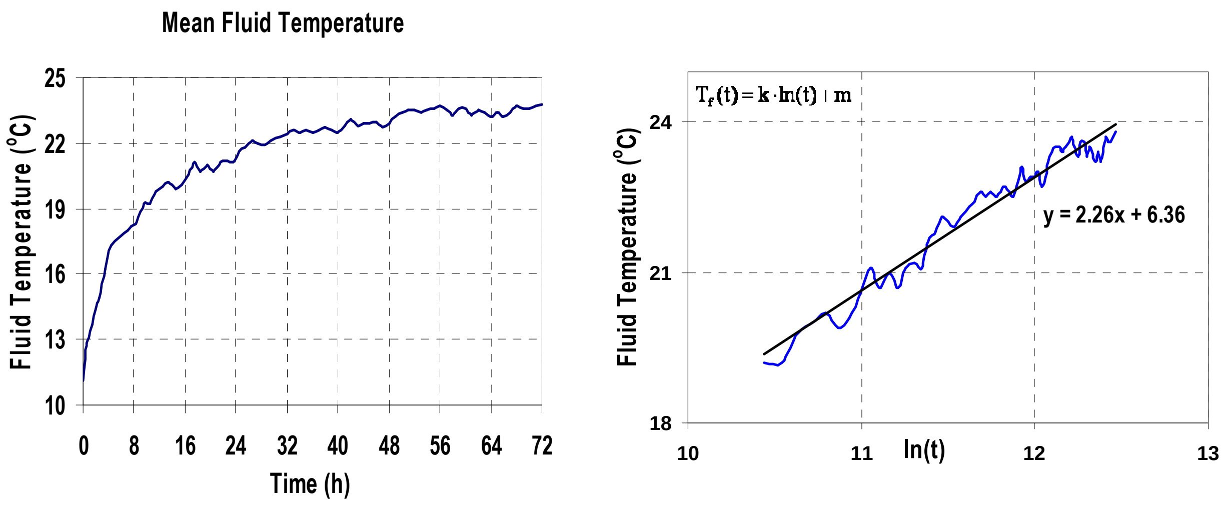


Figure 2: Left/ Measured mean fluid temperature of the borehole. Right/ Measured mean fluid temperature in a logarithmic scale and the fitting linear function y, which corresponds to the temperature function Tf(t), see Eq. (2).

Figure 2 gives an example of the mean fluid temperature [(Tinj + Text)/2] variation with time during the TRT test. The graphs show measured temperature with linear and logarithmic time scales. The thermal conductivity is determined by the slope, k, of the linear curve as shown in Eq. 3. The borehole thermal resistance Rb is derived by inserting the m value given of Fig. 2 in Eq.4.

4. OPERATIONAL EXPERIENCE

4.1 Running the Test

4.1.1 Starting and Ending the Measurement

Thermal Response Tests are conducted on one or more test boreholes, representative of the rest of the boreholes needed for the full BTES system. In case of large BTES systems more than one TRT may be conducted at several test holes on the site. The test borehole should be drilled to the design depth and fitted with the same type of piping, heat carrier and borehole filling as will be used for the rest of the BTES system. The response test facility is placed as close as possible to the test borehole and is connected to the borehole pipes. The test loop (i.e. the collector pipes and the response test device) is filled with brine and purged. All exposed parts between the borehole and the response test apparatus must be thermally insulated to minimize ambient influence, see Figure 3.

In this case however, when the air temperature amplitude is relative constant the effect on the evaluation becomes small provided that mean values of temperature and power are used in the evaluation.

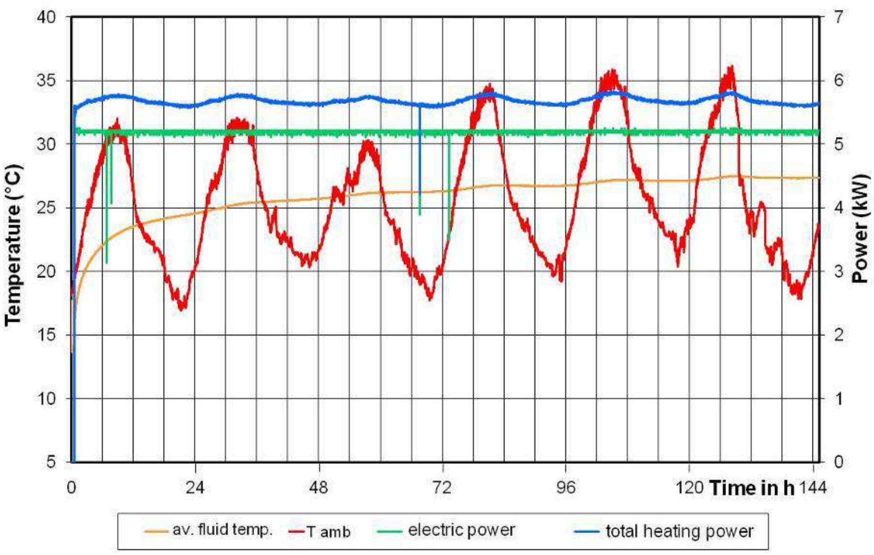


Figure 3: The graph shows how the injected heating power varies with the ambient air temperature variation. The difference in injection power results from heat losses i.e. the injection power deceases with the air temperature.

The temperature development of the circulating brine is recorded at a set time interval, normally in the range 1-10 minutes depending on the flow rate and the depth of the borehole. The temperature of the borehole changes much faster at the beginning of the test and after the first day the measurement could be made with greater intervals (hours).This might be of extra importance for manual measurements. If modern loggers are used very short measurement intervals (seconds) are recommended throughout the test. The test proceeds until steady-state conditions are obtained, i.e. the thermal conductivity converges towards a constant value, see Figure 4.

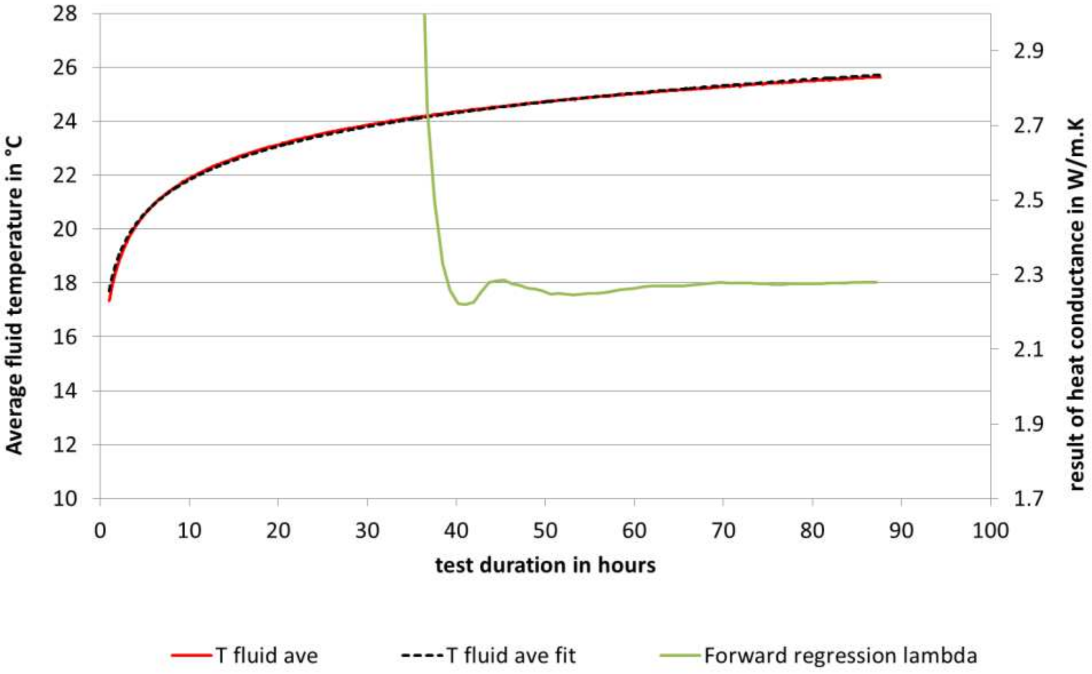


Figure 4: The graph exemplifies how the evaluated thermal conductivity converges, in this case at 2.3 W/m,K, with increasing hours of measurement data used in the evaluation.

When a sufficient number of measured hours have passed, the heat/cold injection is switched off. Normally this is the end of the measurement and the test device is disconnected, but in case the temperature decline will also be measured, the circulation pump is left on for another number of hours until the borehole temperature is back to the approximate initial conditions. After the response test, the test borehole is included in the full BTES system.

4.1.2 Determining Undisturbed Ground Temperature

To evaluate the effective ground thermal conductivity from measured TRT data the undisturbed ground temperature, often determined before the start of the test, is required.

The geothermal gradient is a factor that cannot be neglected, and causes the undisturbed ground temperature to increase with depth. This gradient is a result of the geothermal heat flow and the thermal conductivity of the ground. The continental geothermal heat flow varies normally between 40 and 80 mW/m2 though it in volcanic active areas, e.g. in Iceland, is considerably greater. The geothermal heat flow is generally greater ~0.1 mW/m2 in the oceans. The resulting temperature gradient varies globally, but is normally in the range 0.5 – 3.0 K per 100 meter. Global data of geothermal heat flows are collected and made available by the International Heat Flow Commission (IHFC, 2011)

Eskilson (1987) showed that it is not necessary to consider the temperature variation along the borehole for BTES applications. The mean temperature along the borehole may be used as a homogeneous undisturbed ground temperature around the borehole. However, in BTES systems used for cooling the undisturbed ground temperature is more important.

The undisturbed ground temperature may be determined in different ways. The most commonly used method is to lower a temperature sensor down the fluid-filled U-tube before the circulation has started and the fluid temperature is in equilibrium with the ground. A measurement should be carried out every few meters along the U-pipe and recorded. To avoid any disturbance and mixing of the fluid in the pipe special small sensors have to be used. The temperatures are used to calculate an arithmetic mean borehole temperature. There are more detailed techniques e.g. with optical fibers that measure temperatures almost continuously along the borehole at the same time.

Another method is to circulate the fluid through the borehole heat exchanger before the heater is switched on for the test. The undisturbed ground temperature can be derived by analyzing the fluid temperature from the start of circulation for the time that corresponds to the travel time of the fluid from pipe inlet to the pipe outlet. The temperature amplitude, which pictures the ground temperature at different depths of the borehole, will disappear because of mixing after some time. One problem with this method is that the circulation pump injects heat into the system, which thus induces an increased fluid temperature.

Gehlin and Nordell (2003) compared the result from three methods of estimating the undisturbed ground temperature for thermal response tests. A manual temperature log was first conducted on a well documented 60 m (197 ft) borehole in hard rock, fitted with a single U-pipe collector. After the manual log, the pipe was connected to the TRT rig and the collector fluid was circulated without heat injection for more than 70 minutes while inlet and outlet temperatures were recorded every 10 seconds. The undisturbed ground temperature calculated from the manual log and the temperature recordings of the first few minutes of circulation in the pipes were compared and showed an agreement within 0.1oC. These estimates were also compared to temperature readings of the fluid after 20, 30 and 60 minutes and showed clearly that the heat gain to the fluid from the circulation pump gives an over estimation of the undisturbed temperature by 0.4 °C already after 30 minutes. The value at 20 minutes circulation agreed well with the manual log. The influence of the heat gain from the circulation pump depends on the power rate of the pump related to the borehole depth, see Figure 5..

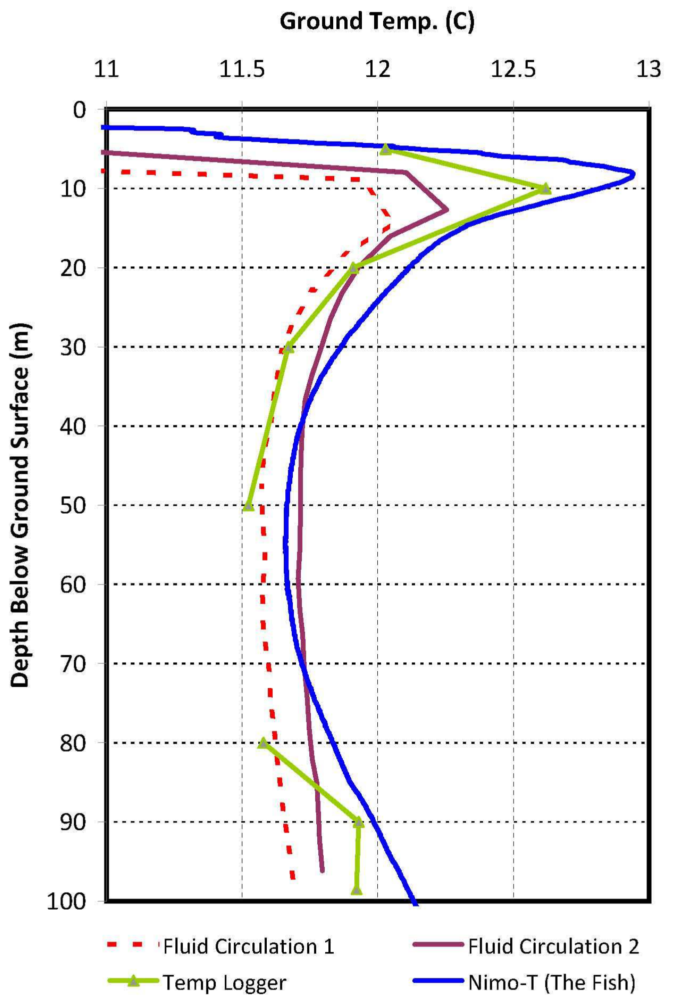


Figure 5: The graph shows temperature measurements with different methods in the same borehole at Dinslaken, Germany (2010-02-09). It is seen that the temperature outside the pipe (NIMO-T) gives a higher temperature value than measurements inside the pipes.

4.1.3 Duration of Measurement

The measurement time necessary for obtaining sufficient data for a reliable analysis has been discussed much since the beginning of response test measurements. Austin, et al. (2000) found a test length of 50 hours to be satisfactory for typical borehole installations. Gehlin (1998) recommends test lengths of about 60 hours. Smith and Perry (1999a) claim that 12-20 hours of measurement is sufficient, as it usually gives a conservative answer, i.e. a low estimate of thermal conductivity. Witte, et al. (2002) performed tests over 250 hours. Austin, et al. (2000) and Witte, et al. (2002) have compared tests of different duration. In some countries, especially in North America, test costs are related to test length. One contractor (Wells 1999) who performs in situ tests in Ohio, USA, estimated the cost to the customer for a 12 hour test at $4500; and $6800 for a 48 hour test. About $2000 represents the cost of drilling the borehole, installing the U-tube, and grouting the borehole. Labour costs for this contractor are about $42/hour. Furthermore, according to the contractor, since many of the in situ tests are done as part of utility-funded feasibility studies, the additional cost for a 50-hour test is hard to justify.

4.2 Operational Problems and Considerations

Operational experiences of the test units have shown some sources of error that can affect the results. These include heat leakage to or from the air, fluctuations in electrical power, and inaccurate measurements of the undisturbed ground temperature.

4.2.1 Heat Losses or Gains

Uncontrolled heat losses or gains to or from the environment due to insufficient thermal insulation cause problems (Austin 1998; Reuß, M. et al. 2002, Witte, et al., 2002) in the analysis of the experimental data. Even though the heat transfer to or from the environment may be relatively small compared to the heat transfer to or from the earth, it can have a significant adverse influence when the results are analysed with the line source method. This problem may be overcome by adequate insulation of the experimental apparatus and piping. In systems where the injected/extracted heat is determined by measuring the inlet and outlet fluid temperatures and flow rate, moving the temperature sensors into the piping in the ground (Witte, et al. 2002) may also help. It is helpful to measure ambient air temperatures during the test so that the effects of changing ambient air temperature may be investigated. It may be possible to correct for these effects with some analysis procedures if a good estimate of the heat loss or gain can be made.

4.2.2 Power Stability

A common problem is fluctuations in the electrical power supply (Austin 1998). This can cause problems with line source analysis, which usually assumes a constant heat injection rate. One solution is to control the temperature difference directly, while maintaining a constant flow rate or to control the temperature difference while measuring the flow rate, so as to maintain a constant heat injection or extraction rate. This approach has been utilized by Groenholland (Witte 2002) and ZAE Bayern (Zervantonakis et al. 2006a, 2006b). Another solution is to use electricity stabilization (Reuß, M., 2004) to obtain a constant supply voltage. A third solution is to use an analysis procedure that can account for fluctuating power, which requires that electricity measurement is part of the test procedure. Figure 6 gives an example of how supplied electricity (voltage) varies diurnally depending on the societies varying consumption of electricity during the day.

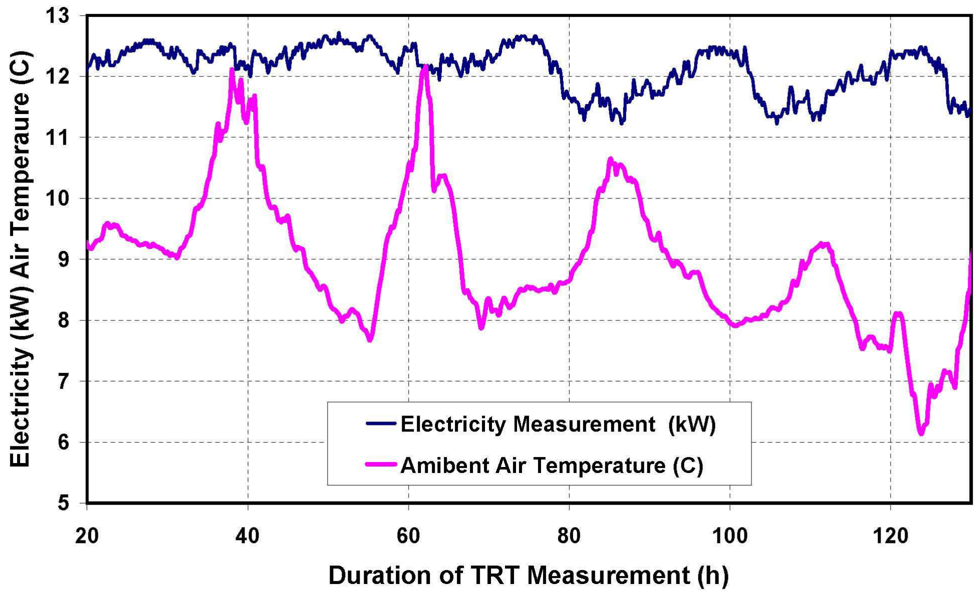


Figure 6: Measurement of supplied electricity and ambient air temperature during a TRT test in Kiruna, Sweden. The test started 3 p.m. on 2004-09-24.

4.2.3 Ground Temperature

All analysis procedures depend on the ground being thermally undisturbed. The ground is necessarily disturbed by the drilling process, which may result in the ground surrounding the borehole being warmer (due to energy input or exothermic heating with cementitious grouts) or wetter (due to circulation of drilling fluid) or dryer (due to circulation of air) than it would otherwise be. The time required for the ground to return to an approximately undisturbed state has not received enough systematic studying. Kavanaugh (2000) recommends that a thermal response test be delayed at least 24 hours after drilling, and at least 72 hours if cementitious grouts are used. Earlier work by Lilja (1981), Bullard (1947), Lachenbruch and Brewer (1959) might also be helpful in determining temperature disturbances caused by drilling.

4.2.4 Influence of Variations in Thermal Conductivity with Depth

For the analysis of a thermal response test it is normally assumed that the ground thermal conductivity along the borehole is homogeneous. However, there is normally a different top-soil layer with a considerably lower thermal conductivity than the deeper rock or sediments. According to Eskilson (1987), a numerical simulation of a deep borehole in granite (λ=3.5 W/m,K) with a 5 m thick top-soil layer (λ=1.5 W/m,K) shows that the thermal performance changes less than 2% for a 100 m (328 ft) deep borehole. His conclusion is therefore that the effect of a top-soil layer of less than 10 m (33 ft) can be neglected. If the soil layer is thick, an arithmetic mean thermal conductivity may be used.

4.2.5 Groundwater Flow

The influence of groundwater flow on the performance of borehole heat exchangers has been a topic of discussion. Field observations have suggested that there is a groundwater aspect on the borehole performance (Gehlin 1998, Helgesen 2001). Some theoretical studies have been published on the subject. Eskilson (1987), Claesson & Hellström (2000) and Chiasson et al (2000) presented models for the influence of regional groundwater flow based on the assumption that the natural groundwater movements are reasonably homogeneously spread over the ground volume. This applies well on a homogeneous and porous ground material. Eskilson and Claesson & Hellström use the line source theory for modelling the groundwater effect on a single vertical borehole. They conclude that under “normal conditions” in crystalline rock, the influence of regional groundwater flow is negligible. This is further discussed in Subtask 2 and Subtask 3 of Annex 21.

Chiasson et al. use a two-dimensional finite element groundwater flow and mass/heat transport model and come to the conclusion that it is only in geologic materials with high hydraulic conductivities (sand, gravels) and in rocks with secondary porosities (fractures and solution channels in e.g. karst limestone), that groundwater flow is expected to have a significant effect on the borehole performance. Simulations of the effect of groundwater flow on thermal response tests give artificially high conductivity values.

The influence of single or multiple fractures and fracture zones on the TRT evaluation could have great influence on the results (Gehlin, 2002) of TRT measurements.

Gustafsson (2010) studied the effect of thermally driven convection between pipes and the borehole wall, in groundwater filled boreholes. These studies were made with both injection and extraction (until freezing) in the same groundwater filled borehole. Since freezing of the water in the borehole means that no convection could occur Gustafsson was able to distinguish between heat transfers with and without convection

4.2.6 General Operational Experience

In addition to the problems described, which may have a more or less subtle influence on the results, practitioners also face problems that can have a catastrophic effect on the results. These include more or less unpredictable disturbances such as:

Blocked U-tubes: Practitioners have arrived at a test site and then found that the flow in the U-tube was blocked by pea gravel (apparently caused by spilling some of the backfill material into a U-tube) or pecans (apparently caused by a squirrel).

Power failure: Power failures will almost always require that the test be redone due to the interruption of the heat injection pulse. Power failures have occurred due to generators running out of fuel, electrical power plugs vibrating out of the generator, the power cord being disconnected by construction workers or cows.

Fluid leakage: Since the equipment is mobile, with time it is likely to develop small leaks. In the right combination, this can result in air entering the fluid loop and, with enough air in the system, the system will begin to undergo rapid transients as large air bubbles form.

5. WORLDWIDE USE OF TRT

In order to collect TRT data from around the world a fill-in form was developed (see Appendix and Table 1). This questionnaire was sent out to potential users and is also available in several languages at the Annex 21 website (Annex 21).

TRT tests have currently been performed in at least the following thirty-two countries, see Table 2. The shadowed countries have filled in and submitted the TRT Data Sheet. In some cases the TRT equipment was set-up at the tested site i.e. they were not using some kind of mobile measurement equipment. Reported TRT data are available at the Annex 21 website and will hopefully be updated in the future.

Table 1: Requested TRT Data (see Appendix)

Contact Information Country: Contact Person (s): Organization/Company:	Address: Phone: Email: URL:
General TRT data	Technical TRT Information
Type: Heat injection and/or heat extraction	Type of TRT (Suitcase, container, trailer, etc.)
No TRTs: XX	Heating/cooling
Aim: Research/development/commercial	Power range (stepwise/variable)
Powered by: Electricity, gas, oil, etc.	Control/operation (remote or not)
On/in: Trailer, pallet, container, portable, stationary, etc.	Flow rate (constant/stepwise/variable)
Size, weight: L+W+H, kg	Monitored data and accuracy
Pump: type, capacity (range)	Calibration
Heater: type and capacity (range)	Experience
HP/Cooler: type and capacity (range)	No of performed tests
Temperature measurements:	In which countries
- Measurement, type, accuracy	TRT for design, R&D, quality control/failure analysis
Flow rate measurements:	Horizontal/vertical/open/closed
- Measurement and type of sensor	Testing fluid (water or water/antifreeze)
Voltage stabilization: Yes/No	Duration of test

Electricity measurement: Yes/No, accuracy	Undisturbed ground temp (methods)
Logger: type	Evaluation models
GPS: Yes/No	Line source
Remote Control: Yes/No	Cylinder source
Remote Data Collection: Yes/No	Numerical modeling
Principle outline	Name of model:

Figure 7 shows when the first TRT measurements were performed in various countries. It started in the mid 90ies in USA and Sweden and spread rapidly to other countries. As seen from the much longer list of countries in Table 2, several countries have failed to report when their first TRT was performed.

Table 2: Countries in which TRT is used (shadowed = reported TRT data)

Argentina (n.a.)	Estonia (n.a.)	Japan	Spain
Austria	Finland	Libya	Sweden
Belgium	France (n.a.)	Norway	Switzerland
Bulgaria	Germany	Pakistan (n.a.)	Syria
Canada	Greece	Serbia (n.a.)	The Netherlands
Chile	Ireland (n.a.)	Slovakia (n.a.)	Turkey
China	Israel (n.a.)	South Africa (n.a.)	United Kingdom
Cyprus	Italy	South Korea	USA

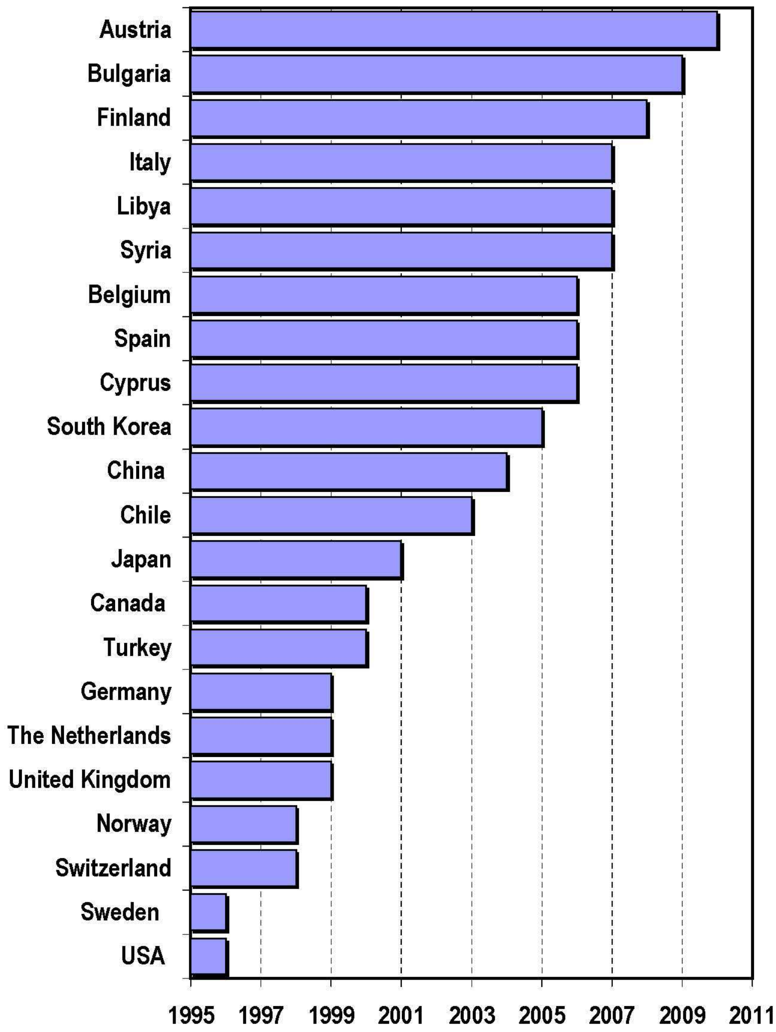


Figure 7: The reported year of the first TRT measurement in some countries.

Thermal response test equipments around the world

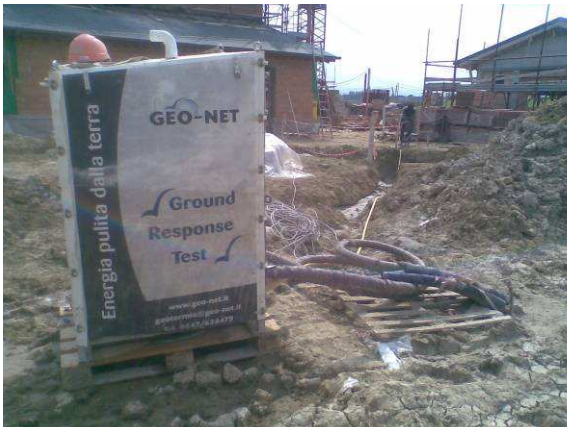
Büro f. Geowissenschaften M&O GbR, Germany

M&P Geonova GmbH, Germany

UBeG Dr. E. Mands & Dipl.-Geol. M. Sauer GbR, Germany

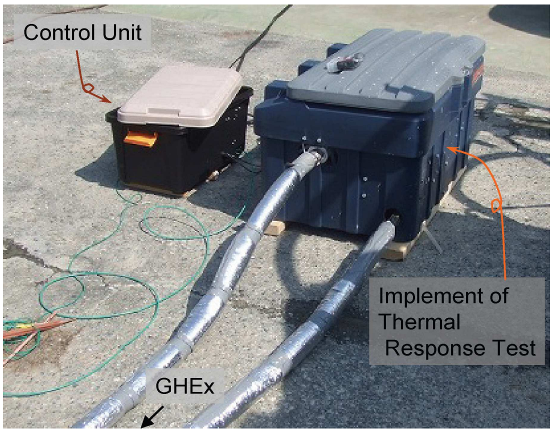
Eneren S.r.l., Italy

GEOTERMICA SAVAL SRL, Italy



Geo-Net s.r.l., Italy

Thermal response test equipments around the world



Kyushu University, Japan

Hokkaido University, Japan

NGU, Norway

NGI, Norway


KIGAM, Korea


KRRAC, Korea

Thermal response test equipments around the world

TECSE Ingenieria del Terreno S.L.L., Spain

Cidemco Tecnalia, Spain

: Energesis Ingeniería, Valencia, Spain

KTH, Sweden

Neoenegy Sweden AB

Groenholland, The Netherlands

Thermal response test equipments around the world

ZAE Bayern, Garching, Germany

Systherma GmbH, Starzach Felldorf, Germany

geoENERGIE Konzept GmbH, Freiberg, Germany

Geo-Energie inc., Canada

GTC Kappelmeier GmbH

Edwärme-Messtechnik GmbH, Bremen, Germany

Thermal response test equipments around the world

Cukurova University, Turkey

Technical University of Sofia, Bulgaria

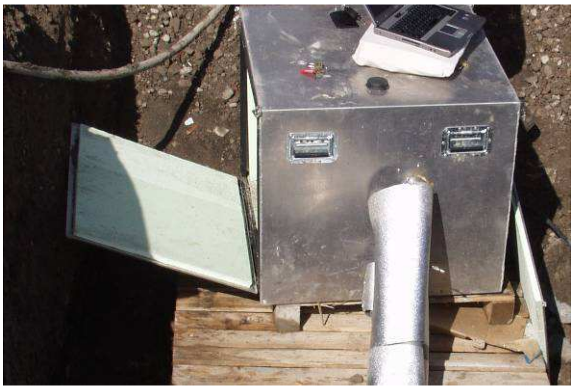
Hebei University, China

Soil & Groundwater, Amzell, Germany

Univ. Técnica Federíco Santa Maria, Chile

Neoenergy, Sweden

Thermal response test equipments around the world



Institut für Geothermie und Umwelt der Hochschule Bochum / Geothermiezentrum Bochum (GZB), Germany

LOHRconsult GmbH & Co. KG, Hannover, Germany

Cyprus University of Technology, Limasso, Cyprus

Nippon Steel Engineering, Tokyo, Japan

Blue Energy Intelligent Services, Cadiz, Spain

Sialtec Geotermia, Les Preses Girona, Spain

5.1 Reported TRT Data

5.1.1 Number of TRT Organisations

Presently, 46 organisations in 22 countries are reported to have TRT equipments at the Annex 21 website (Figure 8). TRT have also been made in at least ten more countries. In some of these like the USA and UK, which have not submitted any TRT data, there are a great number of TRT equipments. Also in Canada there are several TRT equipments. Knowledge about further TRT countries, though have not reported their activities, is based on reports, articles, and conference papers.

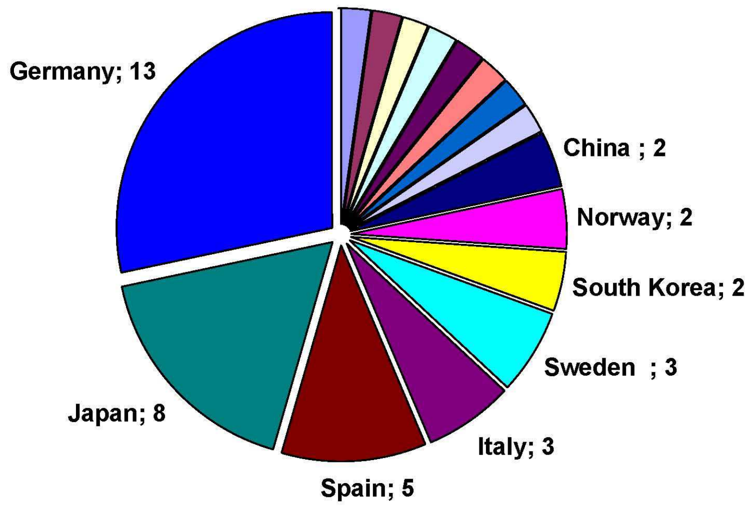


Figure 8: Number of reported TRT organisations in various countries.

Only twelve of these organisations have more than one TRT device and this group owns about half of all (74) reported TRT equipments. Figure 9 shows that most of the equipments are used for Research and Development while 23 % are used for commercial measurements only.

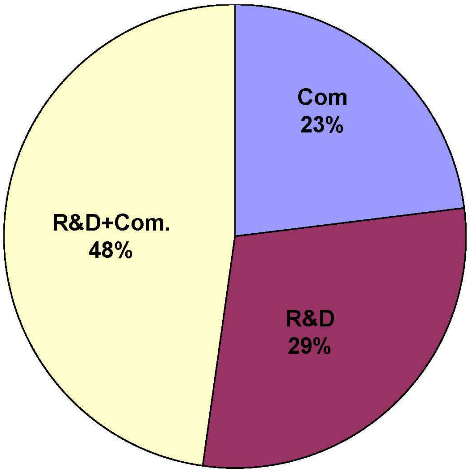


Figure 9: Most of the reported TRT equipments are used for R&D measurements though some are used for commercial measurements only.

5.1.2 Types of TRT Equipments

The first mobile TRT equipments were built on trailers that could be transported after a car. Since then many different types have been designed and constructed. Today the most common type is a TRT built in a portable box, sometimes two boxes where the control and logger system is placed in a separate box.

Other types of TRT used are stationary devices at research institutions, track driven TRT vehicles (caterpillar), and TRTs built in containers and on pallets that are usually transported by trucks to the site (see Figure 10).

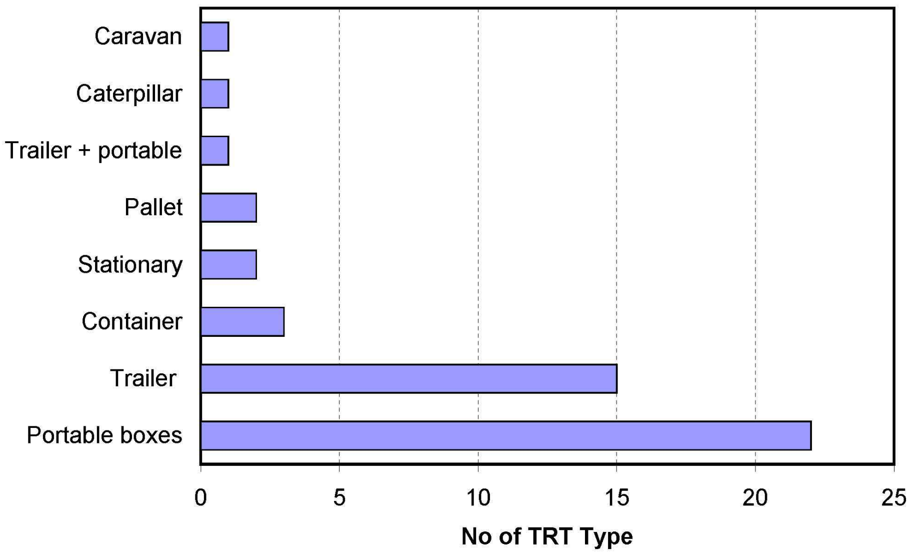


Figure 10: Reported types of TRT. It is seen that most of the TRTs are built in portable boxes or on car trailers.

5.1.3 Heat Injection or Extraction

Almost 90% of all TRT equipments are for heat injection only. Test rigs which allow both heating and cooling exist in China, Spain, Netherlands, Italy and Japan.

In areas where BTES are mainly used for heat extraction it is reasonable to do the TRT testing in the same way. One reason is that the thermo-siphon effect is more likely to occur during heat injection, which will over estimate the thermal conductivity of the ground.

By doing both heat injection and extraction as part of the same tests the effect of such conductive water movements can be reduced. It is even possible to totally stop convection in the borehole by extracting heat until the borehole freezes to ice.

All reported TRT equipments produces heating cooling by electricity driven processes. In one case a generator reportedly used to produce the electricity. This is of course possible in all other cases as well.

5.1.4 Typical Ground Temperature

The typical ground temperature from where the TRT tests have been performed is also reported at the Annex 21 website. This temperature shows mainly in which climate the TRT tests are done but it also gives an indication that TRT equipments are transported over long distances, see Figure 11. This graph mainly shows in which type of climate they are operating.

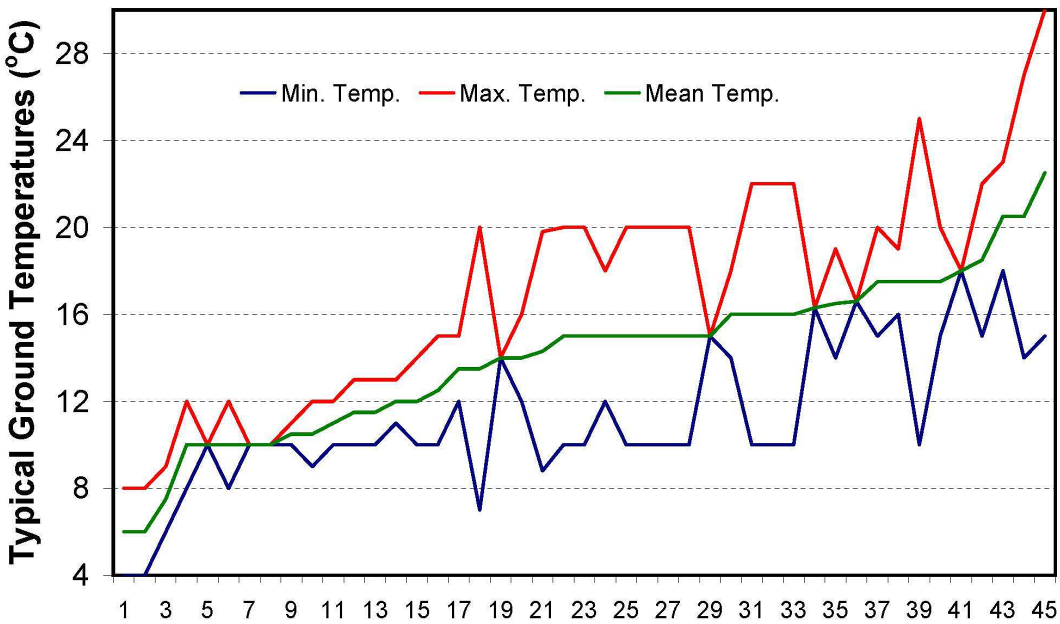


Figure 11: Reported ground temperatures where TRTs have been performed by the diifferetnt TRT organisations.

5.1.5 Type of Applications

Figure 12 shows the reported types of applications that are tested by TRT around the world. So, all of TRT providers perform BHE testing while more than 50% also performs TRT testing on energy piles. TRT testing on heat pipes have been performed by about 20% while horizontal systems are only tested by a few. The main reason might be that the evaluation methods for horizontal pipes are not commonly available.

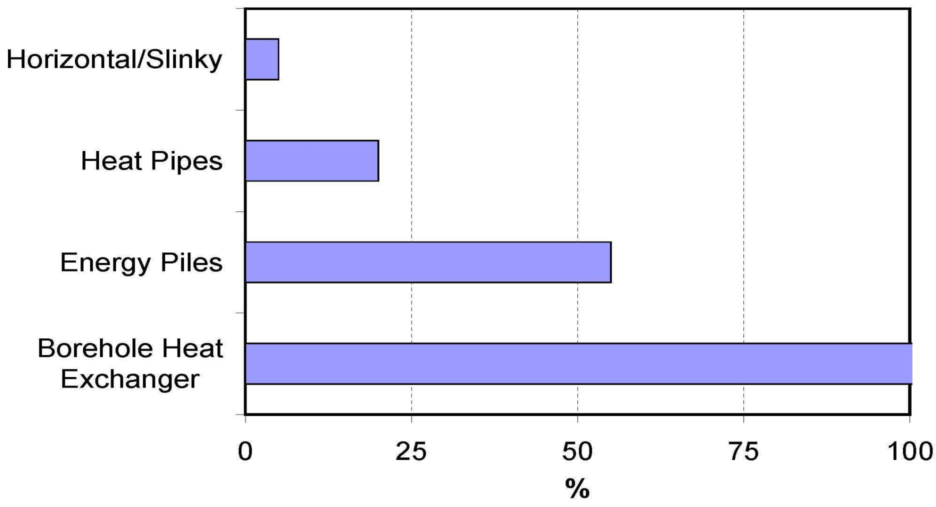


Figure 12: **Reported TRT tests are performed on different applications.**

5.1.6 Type of Fillings

The TRT providers have reportedly performed their testing in groundwater filled boreholes (43%), grouted boreholes including bentonite and clays (38%) and in sand filled holes (20%).

5.1.7 Type of Pipes

Almost all providers perform there TRT tests on single U-pipes (1-U) and double U-pipes. A few have been testing 6-U and heat piles while 40% of the TRT providers have made tests also on coaxial pipe systems, see Figure 13.

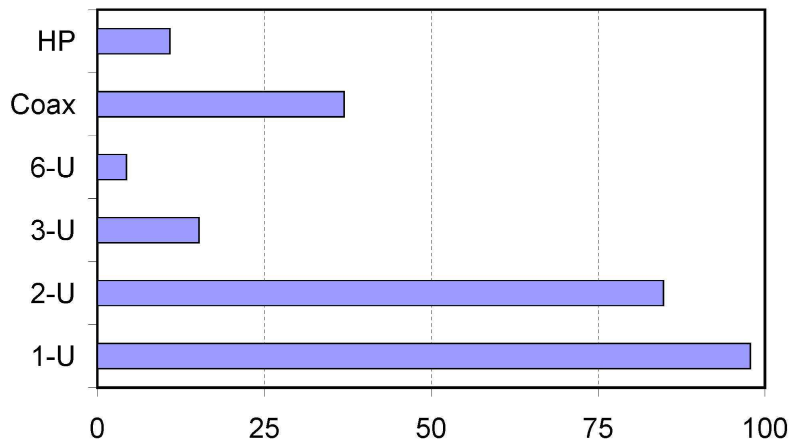


Figure 13: **TRT tests are performed on different collector types.**

5.1.8 Borehole Depth

Most of the tested boreholes are drilled to a depth of 100 - 200 m. However, Figure 14 shows also that some unusual TRT testing has been performed. Some very shallow boreholes (5-10 m) have reportedly been tested. The most extreme TRT test concerns the testing of a 700 m deep borehole, performed by GTC Kappelmeyer Gmb, in Karlsuhe, Germany.

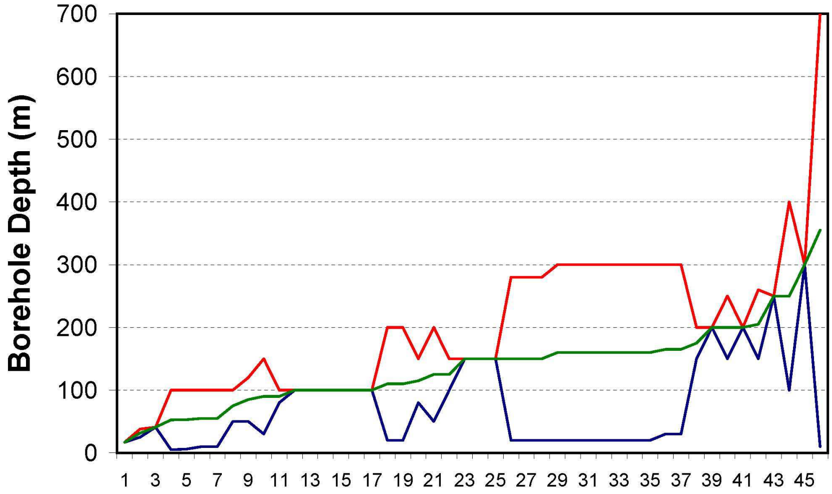


Figure 14: TRT tests are reportedly performed to very different depths; red blue and green graphs represent maximum, minimum and mean borehole depths.

5.1.9 Heat Injection/Extraction Power

The reported injection/extraction powers used vary from a few kW up to 28 kW, see Figure 15. Normally this heat power can be varied in steps, e.g. a 12 kW heater would be built up by 4 x 3 kW heaters. This power, 12 kW, which is also the most common injection power used indicates that these rigs are used for boreholes not deeper than about 300 m i.e. a heat injection of 40 W/m of borehole.

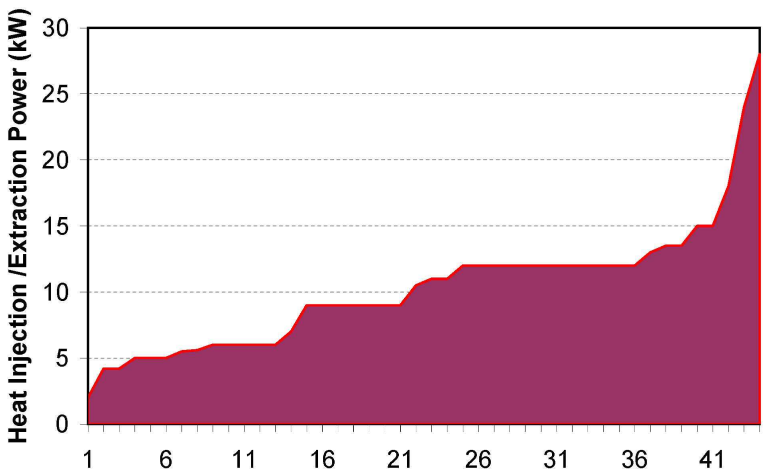


Figure 15: Maximal injection / extraction power of reported TRT equipments.

5.1.10 *Weight of TRT Equipment*

The reported weight of the TRT equipments varies from 20 kg to 2000 kg, see Figure 16. This is true with some modification since in many cases it is divided into several pieces. Usually the logger and the control systems or PC is separated from what is called TRT equipment. Normally, the tools need to connect the piping system have a weight that exceeds 20 kg.

However, the heaviest systems means that the TRT is build in a container or on a trailer that usually include workspace, tools, electricity generator, heat carrier fluid, pipes etc.

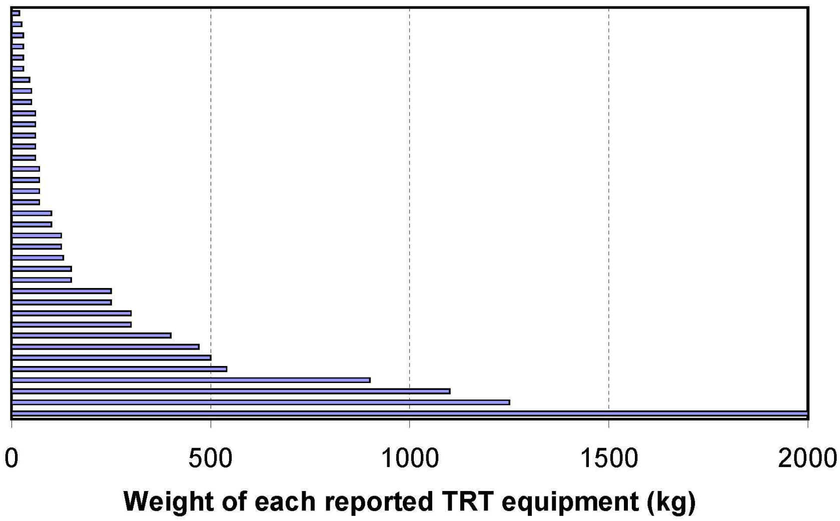


Figure 16: Weight of reported TRT equipments.

5.1.11 *Miscellaneous Functions*

<u>Electricity Supply</u>

The importance of measuring and/or stabilizing the electrical supply power has been proven to be important. In most countries the quality of electricity varies which means that the supply voltage varies at least ±5%. This variation occurs as random spikes but there is also a systematic diurnal voltage variation. This change in voltage affects the supply power and thus the pump and heat capacities.

Figure 17 shows that 88% of reported TRT rigs monitor electricity supply and that 43% are equipped with supply power stabilization.

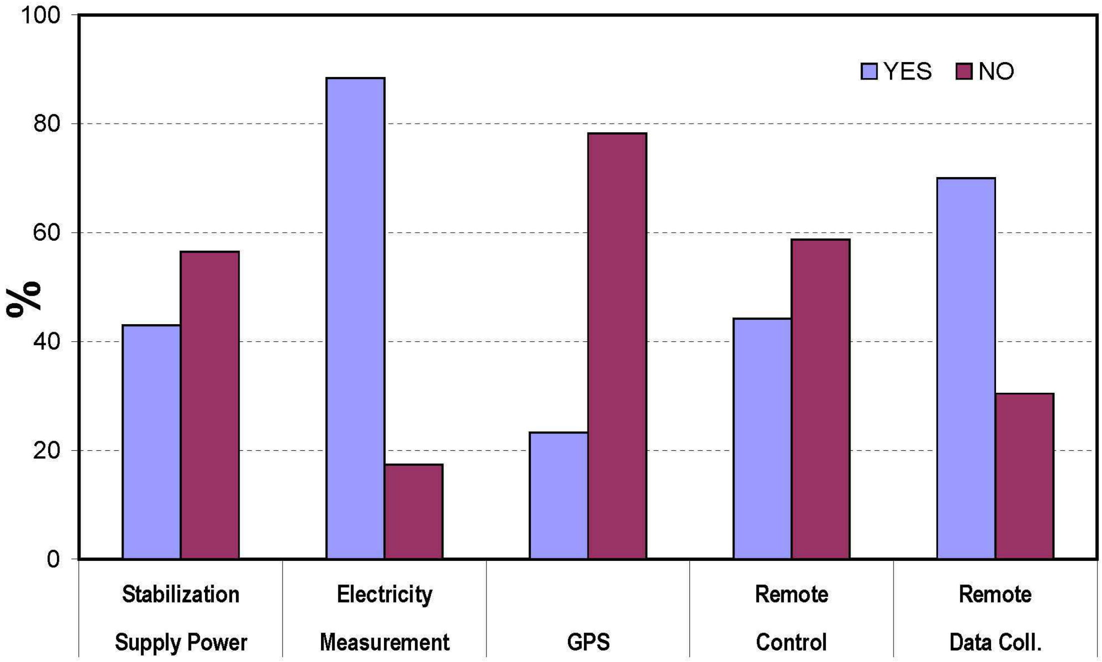


Figure 17: Miscellaneous functions on reported TRT equipments.

Remote Data Collection and Control

Remote data collection is very attractive (67%) and saves a lot of time for the TRT operator. This makes it handy to get an indication that the TRT test is going well at a distance from the test site. Remote operation of the TRT test is used (or at least possible) in the operation of 44% of all TRT rigs, see Figure 12.

GPS i.e. a system that allows the operator to see where the TRT rig is located is used in 23% of all rigs. This is a nice but not necessary option unless the TRT rig is stolen and it is possible to retrieve it this way,

Data Recording and Monitoring

Not all of the reported rigs have specified what kind of logger systems they are using but reported monitoring and control systems are most commonly commercial systems or PC based software. In at least one the measurements were taken manually.

5.1.12 Analysis Methods

The most common analysis method of TRT data is the Line Source (LS) model, which is used by 93% while 10% are using the Cylinder Source model, see Figure 18. Slightly more than half are using Numerical models. Many of those using LS are using nothing else while almost all of those using numerical models are also using LS. One quarter of the numerical models analyse the TRT data automatically.

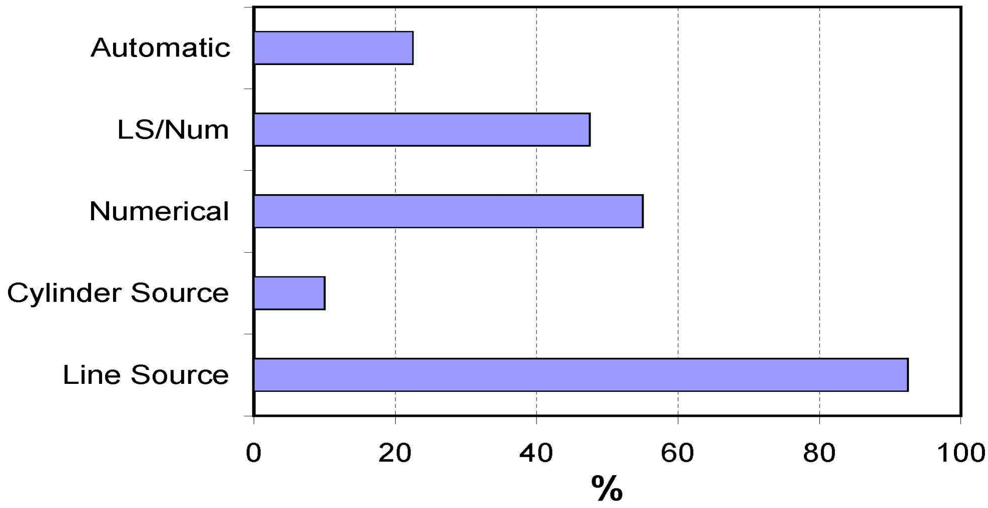


Figure 18: Reported analyses methods used in reported TRT data.

6. CONCLUSIONS

The main challenge with this TRT state-of-the-art study was to obtain data from various TRT providers in various countries. Presently, the study is based on TRT data from 46 organisations in 16 countries. Reported TRT data and fill-in forms for submission of data are available at the Annex 21 website.

- Since the introduction of mobile thermal response tests in Sweden and USA in 1995, the method has developed and spread rapidly to several other countries around the world. We know for sure that it has been used in 32 countries and estimate that TRT tests have been made in further 10 countries.
- All TRT providers have reported that they perform testing of BHEs and more than half have also performed TRT tests of energy piles.
- Most TRT equipments are built in portable boxes or on car trailers. There are examples also of TRT equipments built on pallets or shipping containers.
- Most TRT equipments (90%) rely on imposing a heat injection into the ground, which is intended to be held constant by providing a constant power supply to an electric resistance heater element. TRT rigs which allow both heating and cooling exist in China, Spain, Netherlands, Italy and Japan. There was one such TRT also in Sweden but this rig was rebuilt for heating only after it was sold to Norway. However, considerably more than 90% of all TRT tests have been performed by heat injection.
- Of the reported TRT equipments 77% are used for R&D while the rest are for commercial tests only.
- Reported TRT tests have been made on water filled boreholes (41%), grouted boreholes (37%), and sand filled holes.
- The TRT providers perform tests on various BHEs; 1U (98%) and 2U (85%) and Coaxial pipes (37%).
- Most of the tested boreholes are normally drilled to a depth of 100-200 m. However, some very shallow boreholes (5-10 m) and one very deep borehole (700 m) have also been tested.
- The average heat injection power of reported TRT rigs is 12 kW. This is normally supplied by 4 x 3 kW heaters i.e. the power can be increased in steps.
- The electricity supply to the TRT rig is in 43% equipped with supply power stabilization.
- Remote data collection is commonly used (70%) as it saves time for the TRT operator. Remote TRT testing is an option in 44% of all TRT rigs.
- All TRT rigs have some electronic monitoring and control systems.
- A variety of data analysis models have been developed. Most providers use more than one evaluation model.

- Line Source model (93%).
- Cylinder Source model (10%)
- Numerical model (55%)

The current study includes most of the countries (30 out of 40-45) where TRT is used today. However, it is estimated that less than 30% of the existing TRT rigs are included. The main reason is that it was difficult to reach out to the TRT suppliers or that they cannot see any value of submitting their data to this study (and the Annex21 website).

Thermal response testing will continue to spread around the world and it is of great importance that Annex 21 succeeds in promoting a best TRT practice manual world wide.

The fill in form will be continuously available on the IEA ECES Annex 21 website. You are all welcome to add your data http://www.thermalresponsetest.org/ and you are all welcome to

.

7. Acknowledgments

The aim of Annex 21 Subtask 1, which had a Swedish task leader, was to map where and how thermal response testing is done worldwide. Economic support by the Swedish Energy Agency, grant No. 30786-1, is gratefully acknowledged.

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This report is partly compiled from the TRT State of the Art 2001 within IEA ECES Annex 13 which is part Gehlin, 2002.

Thermal Response Test for BTES Applications

State of the Art 2001

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8. REFERENCES AND USEFUL TRT LITERATURE

Annex 21 website. IEA ECES Annex 21 website. http://www.thermalresponsetest.org/

Austin III, W. A. (1998). Development of an In-Situ System for Measuring Ground Thermal Properties. Master's thesis. Oklahoma State University. Stillwater, Oklahoma. (Also available at ttp://www.mae.okstate.edu/Faculty/spitler/Austin_thesis.pdf.)

Austin III, W.A., C. Yavuzturk, J.D. Spitler. (2000). Development of an In-Situ System for Measuring Ground Thermal Properties. ASHRAE Transactions. 106(1): 365-379.

Bandos, T. V. et al. Finite line-source model for borehole heat exchangers: effect of vertical temperature variations. Geothermics 38, 263-270, doi:10.1016/j.geothermics.2009.01.003 (2009).

Bandyopadhyay, G., Gosnold, W. & Mann, M. Analytical and semi-analytical solutions for short-time transient response ground heat exchangers. Energy Build. 40, 1816-1824, doi:10.1016/j.enbuild.2008.04.005 (2008).

Bozdag, S. et al. Ground water level influence on thermal response test in Adana, Turkey. International Journal of Energy Research 32, 629-633, doi:10.1002/er.1378 (2008).

Brandt W. (2001). Faseroptische Temperaturmessung in einer Erdwärmesonde birgt Überraschungen. Geotermische Energie. Nr. 32/33, März/Juni 2001.

Bruno, R., Focaccia, s. & Tinti, F. Geostatistical modeling of a shallow geothermal reservoir for air conditioning of buildings. IAMG 2011, Mathematical Geosciences at the Crossroads of Theory and Practice. Salzburg. September 5 - 9 2011. (pp. 146 - 163).

Bullard E C (1947). The time necessary for a borehole to attain temperature equilibrium. Monthly Notices Roy. Astron. Soc. Geophysical Suppl. 5, 1947, pp. 127-130.

Carslaw H. S. and J. C. Jaeger (1959). Conduction of Heat in Solids, Second ed. , Oxford University Press, Great Britain.

Chiasson, A., S.J. Rees, and J.D. Spitler, 2000. A Preliminary Assessment of the effects of Ground-water Flow on Closed-Loop Ground-Source Heat Pump Systems. ASHRAE Transactions. 106(1):380-393.

Claesson J., G. Hellström (2000). Analytical studies of the influence of regional groundwater flow on the performance of borehole heat exchangers. Proc. of the 8th International Conference on Thermal energy storage, Terrastock 2000, 28 August – 1 st September 2000, Stuttgart, Germany.

Cruickshanks, F., J. Bardsley, H.R. Williams. (2000). In-Situ Measurement of Thermal Properties of Cunard Formation in a Borehole, Halifax, Nova Scotia. Proceedings of Terrastock 2000, Stuttgart, Germany, August 28-September 1, 2000. pp. 171-175.

Curtis R., (2000). GeoScience Internet newsletter, GroundSwell, http://www.earthenergy.co.uk/eegrswel.html

Curtis R., (2001). GeoScience, Falmouth, Cornwall, United Kingdom. Personal Communication.

De Carli, M. A computational capacity resistance model (CaRM) for vertical ground-coupled heat exchangers. Renewable energy 35, 1537-1550 (2010).

Deerman J.D. and S. P. Kavanaugh (1991). Simulation of Vertical U-Tube Ground-Coupled Heat Pump Systems Using the Cylindrical Heat Source Solution. ASHRAE Transactions 1991, Vol. 97 (1), pp. 287-295.

Eklöf C. and S. Gehlin. (1996). TED – A Mobile Equipment for Thermal Response Test. Master Thesis 1996:198E. Lulea University of Technology, Sweden.

Esen, H. & Inalli, M. In-situ thermal response test for ground source heat pump system in Elazig, Turkey. Energy Build. 41, 395-401, doi:10.1016/j.enbuild.2008.11.004 (2009).

Eskilson P. (1987). Thermal Analysis of Heat Extraction Boreholes. Lund-MPh-87/13. Dept. of Mathematical Physics, Lund Institute of Technology, Sweden.

Fujii, H. et al. An improved thermal response test for U-tube ground heat exchanger based on optical fiber thermometers. Geothermics 38, 399-406, doi:10.1016/j.geothermics.2009.06.002 (2009).

Gehlin S (2002). Thermal Response Test - Method Development and Evaluation. Doctoral Thesis. Luleå University of Technology, Sweden. pp. 191.

Gehlin S, Nordell B (2003). Determining Undisturbed Ground Temperature for Thermal Response Test. ASHRAE Transactions 2003, Vol. 109, Part 1, pp. 151-156.

Gehlin S (1998). Thermal Response Test, In-Situ Measurements of Thermal Properties in Hard Rock. Licentiate Thesis, Luleå University of Technology, 1998:37. 41 pp. http://pure.ltu.se/portal/files/493306/LTU-LIC-9837-SE.pdf

Gehlin S. and B. Nordell (1997). Thermal Response Test - A Mobile Equipment for Determining Thermal Resistance of Boreholes. Proc. Megastock'97, Sapporo. Japan. June 18-21 1997,. p. 103-108.

Gehlin S. and B. Nordell. (1998). Thermal Response Tests of Boreholes – Results from In Situ Measurements. Proc. Second International Stockton Geothermal Conference. 15-16 March 1998. Richard Stockton College of New Jersey, Pomona, USA

Gehlin S. and G. Hellström (2001). Comparison of Four Models for Thermal Response Test Evaluation. Div. of Water Resources Engineering, Luleå University of Technology. (Unpublished).

Gehlin S. and G. Hellström. (2000). Recent Status of In-situ Thermal Response Tests for BTES Applications in Sweden. Proceedings of Terrastock 2000, Stuttgart, Germany, August 28-September 1, 2000. pp. 159-164.

Gehlin, S. E. A. & Hellstrom, G. Influence on thermal response test by groundwater flow in vertical fractures in hard rock. Renewable energy 28, 2221-2238, doi:10.1016/s0960-1481(03)00128-9 (2003).

Gehlin, S. Thermal Response Test - Method Development and Evaluation. 191 (2002). PhD Thesis, Luleå University of Technology., Sweden. http://pure.ltu.se/portal/files/153860/LTU-DT-0239-SE.pdf

Georgiev, A., Busso, A. & Roth, P. Shallow borehole heat exchanger: Response test and charging-discharging test with solar collectors. Renewable energy 31, 971-985, doi:10.1016/j.renene.2005.06.002 (2006).

Gustafsson, A. M. (2010).Thermal response tests : influence of convective flow in groundwater filled borehole heat exchanger. PhD Thesis. Luleå University of Technology, Sweden. http://pure.ltu.se/portal/files/5049770/Anna-Maria_Gustafsson_Doc2010.pdf

Gustafsson, A. M. Multi-injection rate thermal response test in groundwater filled borehole heat exchanger. Renewable energy 35, 1061-1070 (2010).

Gustafsson, A. M., Gehlin, S. & Ashrae. in Ashrae Transactions 2008, Vol 114, Pt 1 Vol. 114 ASHRAE Transactions 416-423 (Amer Soc Heating, Refrigerating and Air-Conditioning Engs, 2008).

Gustafsson, A. M., Westerlund, L. & Hellstrom, G. CFD-modelling of natural convection in a groundwater-filled borehole heat exchanger. Applied Thermal Engineering 30, 683-691, doi:10.1016/j.applthermaleng.2009.11.016 (2010).

Hajovsky, R. & Pies, M. TRT system for heat pumps. (Ieee Computer Soc, 2008).

Helgesen R. et al. (2001). Evalueringsrapport. Termisk responstesting av energibrønner. E-CO Smart, NGU, Geoenergi. Oslo 2001. (In Norwegian).

Hellström G. (1994). Fluid-to-Ground Thermal Resistance in Duct Ground Heat Storage. Proc. . 6th International Conference on Thermal Energy Storage Calorstock'94. Espoo, Finland, August 22-25, 1994, p. 373-380.

Hellström G., (1997). Thermal Response Test of a Heat Store in Clay at Linköping, Sweden. Proc. 7th International Conference on Thermal Energy Storage Megastock'97. Sapporo, Japan. June 18-21 1997. Vol. 1 s. 115-120.

Hwang, S. Evaluation of estimation method of ground properties for the ground source heat pump system. Renewable energy (2009).

IHFC (2011). International Heat Flow Commission. http://www.geophysik.rwth-aachen.de/IHFC/heatflow.html

Ingersoll, L R. and H.J. Plass (1948). Theory of the Ground Pipe Heat Source for the Heat Pump. ASHVE Transactions vol. 54 p. 339-348

Ingersoll, L R. et al. (1951). Theory of Earth Heat Exchangers for the Heat Pump. ASHVE Transactions vol. 57 p. 167-188.

Ingersoll, L. R. et al. (1954). Heat conduction with engineering, geological, and other applications. New York, McGraw-Hill.

Jain, N. K. (1999). Parameter Estimation of Ground Thermal Properties. Master's thesis. Oklahoma State University. Stillwater, Oklahoma. (Also available at: http://www.hvac.okstate.edu/pdfs/Jain_Thesis.pdf.)

Kavanaugh, S. P., K. Rafferty. (1997). Ground Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Kavanaugh, S.P. (2000). Field Tests for Ground Thermal Properties – Methods and Impact on Ground-Source Heat Pump Design. ASHRAE Transactions. 106(1):851-855.

Kharseh, M. (2011). Reduction of prime energy consumption by ground source heat pumps in a warmer world. PhD Thesis, Luleå University of Technology, Sweden. http://pure.ltu.se/portal/files/33934735/Mohamad_Kharseh.pdf

Kim, S. K., Bae, G. O., Lee, K. K. & Song, Y. Field-scale evaluation of the design of bore-hole heat exchangers for the use of shallow geothermal energy. Energy 35, 491-500, doi:10.1016/j.energy.2009.10.003 (2010).

Lachenbruch and Brewer (1959). Dissipation of the temperature effect of drilling a well in Arctic Alaska. U.S.G.S. Bulletin 1083-C, 1959, pp. 73-109.

Lilja A (1981). Störning av berggrundens temperaturförhållande vid hammarborning (Disturbance of the ground temperature distribution at hammer drilling). SGU (The Swedish Geological Survey). Uppsala 1981. In Swedish.

Lim, K., Lee, S. & Lee, C. An experimental study on the thermal performance of ground heat exchanger. Exp. Therm. Fluid Sci. 31, 985-990, doi:10.1016/j.expthermflusci.2006.10.011 (2007).

Marcotte, D. & Pasquier, P. On the estimation of thermal resistance in borehole thermal conductivity test. Renewable energy 33, 2407-2415, doi:10.1016/j.renene.2008.01.021 (2008).

Mattsson, N., Steinmann, G. & Laloui, L. Advanced compact device for the in situ determination of geothermal characteristics of soils. Energy Build. 40, 1344-1352, doi:10.1016/j.enbuild.2007.12.003 (2008).

Midttomme K., (2000). Geological Survey of Norway, NGU. Personal communication.

Mogensen P (1985) Fullskaleförsök med berg som värmekälla för värmepump i Järfälla – Mätning och utvärdering (Full scale experiment with rock as a heat source for a heat pump i Järfälla – Measurement and evaluation). BRF Report R123:1985. Byggforsknings Rådet (Swedish Council for building Research). In Swedish.

Mogensen P. (1983). Fluid to Duct Wall Heat Transfer in Duct System Heat Storages. Proc. Int. Conf. On Subsurface Heat Storage in Theory and Practice. Stockholm, Sweden, June 6-8, 1983, p. 652-657.

Nagano, K., Katsura, T. & Takeda, S. Development of a design and performance prediction tool for the ground source heat pump system. Applied Thermal Engineering 26, 1578-1592, doi:10.1016/j.applthermaleng.2005.12.003 (2006).

Nagano, K., Mochida, T., Takeda, S., Domanski, R. & Rebow, M. Thermal characteristics of manganese (II) nitrate hexahydrate as a phase change material for cooling systems. Applied Thermal Engineering 23, 229-241 (2003).

NGU (2000) (Midttomme et al. Editor). Bruk av grunnvarme ved sentralsykehuset i Lorenskog – testboring, systemlosning og okonomiske beregninger. (Use of ground source heat at the central hospital in Lorenskog – testdrilling, technical system and economic calculations). NGU Report 2000.091. Norway. (In Norwegian).

Nordell B. (1994). Borehole Heat Store Design Optimization. Doctoral Thesis 1994:137D. Division of Water Resources Engineering, Luleå University of Technology, Sweden.

Nordell B., Gehlin S. (2009). 30 years of thermal energy storage – a review of the IEA ECES Stock conferences. Plenum Session. Proc. 11th Int. Conf. on Thermal Energy Storage; Effstock 2009 - Thermal Energy Storage for Energy Efficiency and Sustainability. Stockholm , Sweden, June 14-17 2009.

Pahud, D. & Matthey, B. Comparison of the thermal performance of double U-pipe borehole heat exchangers measured in situ. Energy Build. 33, 503-507 (2001).

Paksoy H. Ö., (2000). Centre for Environmental Research, Cukurova University, Adana, Turkey. Personal communication.

Remund, C.P. (1999). Borehole Thermal Resistance: Laboratory and Field Studies. ASHRAE Transactions. 105(1):439-445

Reuß, M., Busso A. and J.-P. Mueller (2002). Thermal Response Test – Experimente und Auswertungen. In proceedings of Otti Fachseminar Oberflaechennahe Geothermie in Garching, Germany, February 19.-20., 2002, pp. 77-86.

Reuß, M. (2004). Auslegung von Wärmequellenanlagen nach VDI und Verfahren zur Standortuntersuchung – Thermal Response Test. In proceedings of Otti Profiforum Oberflaechennahe Geothermie in Garching, Germany, February 17.-18., 2004, pp. 53-73.

Reuß M., Proell, M. , Nordell B. (2009) IEA ECES -ANNEX 21 – Thermal Response Test. Proc. 11th Int. Conf. on Thermal Energy Storage; Effstock 2009 - Thermal Energy Storage for Energy Efficiency and Sustainability. Stockholm , Sweden, June 14-17 2009.

Roth, P., Georgiev, A., Busso, A. & Barraza, E. First in situ determination of ground and borehole thermal properties in Latin America. Renewable energy 29, 1947-1963 (2004).

Saljnikov, A., Goricanec, D., Dobersek, D., Krope, J. & Kozic, D. Thermal response test use of a borehole heat exchanger. (World Scientific and Engineering Acad and Soc, 2007).

Sanner, B. et al. (2001). Erfahrungen mit dem Thermal Response Test in Deutschland. Proceedings of the 6th Geotermische Fachtagung, Herne, October 2000, Germany.

Sanner, B., (2001). Institute of Applied Geosciences, Justus-Liebig-University, Giessen, Germany. Personal communication.

Sanner, B., Karytsas, C., Mendrinos, D. & Rybach, L. Current status of ground source heat pumps and underground thermal energy storage in Europe. Geothermics 32, 579-588, doi:10.1016/s0375-6505(03)00060-9 (2003).

Sanner, B., M. Reuss, E. Mands, J. Müller. (2000). Thermal Response Test – Experiences in Germany. Proceedings of Terrastock 2000, Stuttgart, Germany, August 28-September 1, 2000. pp. 177-182.

Sharqawy, M. H. et al. Energy, exergy and uncertainty analyses of the thermal response test for a ground heat exchanger. International Journal of Energy Research 33, 582-592, doi:10.1002/er.1496 (2009).

Sharqawy, M. H. et al. First in situ determination of the ground thermal conductivity for borehole heat exchanger applications in Saudi Arabia. Renewable energy 34, 2218-2223, doi:10.1016/j.renene.2009.03.003 (2009).

Sharqawy, M. H., Mokheimer, E. M. & Badr, H. M. Effective pipe-to-borehole thermal resistance for vertical ground heat exchangers. Geothermics 38, 271-277, doi:10.1016/j.geothermics.2009.02.001 (2009).

Shonder, J.A., J.V. Beck. (1999). Determining effective soil formation properties from field data using a parameter estimation technique. ASHRAE Transactions. 105(1):458-466.

Shonder, J.A., J.V. Beck. (2000). Field Test of a New Method for Determining Soil Formation Thermal Conductivity and Borehole Resistance. ASHRAE Transactions. 106(1)843:850.

Signorelli, S., Bassetti, S., Pahud, D. & Kohl, T. Numerical evaluation of thermal response tests. Geothermics 36, 141-166, doi:10.1016/j.geothermics.2006.10.006 (2007).

Skarphagen H., and J. Stene, (1999). Geothermal Heat Pumps in Norway. IEA Heat Pump Centre Newsletter, Volume 17 – No1.

Skouby, A. (1998). Proper Engineering + Thermally Enhanced Grouts = GeoExchange Savings. The Source. Vol. 11, No. 6, November/December 1998. pp. 4-5.

Smith M and R Perry, (1999a). In-Situ Testing and Thermal Conductivity Testing. Proc. of The 1999 GeoExchange Technical Conference & Expo, Oklahoma State University, Stillwater, Oklahoma, May 16-19, 1999.

Smith M and R Perry, (1999b). Borehole Grouting: Field Studies and Thermal Performance Testing. ASHRAE Transactions 105(1):451-457.

Smith, M. (1998). Private communication. Oklahoma State University, U.S.A.

Smith, M. D. (1999a). Director of Ground Source Heat Pump Research at International Ground Source Heat Pump Association, Oklahoma State University. Personal communication

Smith, M. D. (1999b). Comments on In-Situ Borehole Thermal Conductivity Testing. The Source, IGSHPA Newsletter. Volume 12, Number 1. January/February 1999 issue. International Ground Source Heat Pump Association, Oklahoma State University.

Spilker, E.H. (1998). Ground-Coupled Heat Pump Loop Design Using Thermal Conductivity Testing and the Effect of Different Backfill Materials on Vertical Bore Length. ASHRAE Transactions. Vol. 104, Pt. 1B, pp. 775-779.

Spitler, J.D., C. Yavuzturk, S.J. Rees,. (2000). In Situ Measurement of Ground Thermal Properties Proceedings of Terrastock 2000, Vol. 1, Stuttgart, August 28-September 1, 2000, pp. 165-170.

Spitler, J.D., S.J. Rees, C. Yavuzturk. (1999). More Comments on In-situ Borehole Thermal Conductivity Testing. The Source. Vol. 12, No. 2, March/April 1999. pp. 4-6.

Stritih, U., Rajver, D., Turgut, B. & Paksoy, H. Borehole thermal energy storage applications and in-situ thermal response test - Example from Turkey and situation in Slovenia. Strojniski Vestn.-J. Mech. Eng. 50, 328-340 (2004).

Syed Ahmad M. Said, M. A. H., Esmail M.A. Mokheimer and Mostafa H. El-Sharqawi. Feasibility of using ground-coupled condensers in A/C systems. Geothermics, 4, doi:doi:10.1016 (2010).

van Gelder G et al (1999). In situ Measurement of Thermal Soil Properties with Heat Extraction. Proc. of The 1999 GeoExchange Technical Conference & Expo, Oklahoma State University, Stillwater, Oklahoma, May 16-19, 1999.

Wang, H. Improved method and case study of thermal response test for borehole heat exchangers of ground source heat pump system. Renewable energy 35, 727-733 (2010).

Wells, G. (1999) Middleton Geothermal, Akron, Ohio. Personal communication to J.D. Spitler.

Witte H., (2001). GroenHolland, Netherlands. Personal communication.

Witte, H., G. van Gelder, J. Spitler (2002) In-Situ Thermal Conductivity Testing: A Dutch Perspective Accepted for publication in the ASHRAE

Witte, H., S. Kalma, and G. van Gelder. (2000a). In-Situ Thermal Conductivity Testing: The Dutch Perspective (Part 1). The Source. Vol. 13, No. 3, May/June 2000, pp. 3-5.

Witte, H., S. Kalma, and G. van Gelder. (2000b). In-Situ Thermal Conductivity Testing: The Dutch Perspective (Part 2). The Source. Vol. 13, No. 4, July/August 2000, pp. 3-5.

Wu, S. Y., Zhu, D. S., Li, X. F., Li, H. & Lei, J. X. Thermal energy storage behavior of Al2O3-H2O nanofluids. Thermochim. Acta 483, 73-77, doi:10.1016/j.tca.2008.11.006 (2009).

Zervantonakis I. K. and Reuß,M. (2006a). Modellierung eines Thermal Response Tests. In proceedings of Otti Profiforum Oberflaechennahe Geothermie in Freising, Germany, April 05.-06., 2006,pp. 147-159.

Zervantonakis I. K. and Reuß, M. (2006b). Quality Requirements of a Thermal Response Test.. In proceedings f ECOSTOCK Conference at The Richard Stockton College of New Jersey, Pomona NJ, USA, May 31 – une 2, 2006, published on CD.

D. Subtask 2

New Developments

Content Subtask

1. Use of fibre optics

1.1 Developers

In this section we list, per development, the different people and organisations involved in the development.

Name	Organisation	Email
Hikari Fujii	Kyushu University	fujii@mine.kyushu-u.ac.jp

1.2 Summary and examples

The knowledge of the thermal properties of different layers in heterogeneous subsurface is important for an optimum design of ground-coupled heat pump systems. Hence, detailed temperature information must be measured during thermal response tests. One possibility to get these data is the application of fibre optic cables. Figure 2.1 shows installing fibre optics in the borehole ground heat exchanger. A fibre optic sensor is installed in the U-tube or coaxial pipe. The sensor can be place either inside or outside the U-tube or coaxial pipe The optic sensor is connected to the optical fiber temperature laser radar (Figure 2.2). The thermal medium (water or antifreeze liquid) is circulated under constant flow and heat rates. The procedure is the same as at a common TRT. During and after the circulation, characteristic, vertical temperature distributions are obtained such as shown in Figure 2.3 and Figure 2.4.

The vertical distribution of soil effective thermal conductivity around the BHEX can be estimated on the basis of temperature measurements with the fiber optical sensor. The multi layer model shown in Figure 2.5 and interpretation method is applied in the estimation. In the interpretation, an objective function F for the simultaneous matching of outlet temperatures of the heat medium and temperature profiles in the GHE was defined as shown in Equation 2.1.

$$F = \alpha \sum^{nstep} \left(T_{out(obs)} - T_{out(cal)}\right)^2 + (1-\alpha) \sum^{ntest} \left(\sum^{nlayer} \left(T_{ro(obs)} - T_{ro(cal)}\right)^2 \right) \quad (2.1)$$

nstep: number of computation time steps
nlayer: number of layers
ntest: number of comparisons of measured and calculated Tro [K]
Tout: Outlet temperature of heating medium [K]
Tro: Temperature at outer face of U-tube [K]

Weighting factor α was determined between 0.1 and 0.5 by trial and error. The "ntest" in Equation 2.1 indicates the number of time steps at which the difference between the measured and calculated Tro are compared. Parameter "ntest" is usually set between one and three. The objective function F is minimized using the polytope nonlinear regression method of Nelder and Mead (1965) treating the thermal conductivities of each sub-layer as matching parameters. Consequently, the vertical distribution of soil effective thermal conductivity is ascertained, as shown in Figure 2.6.

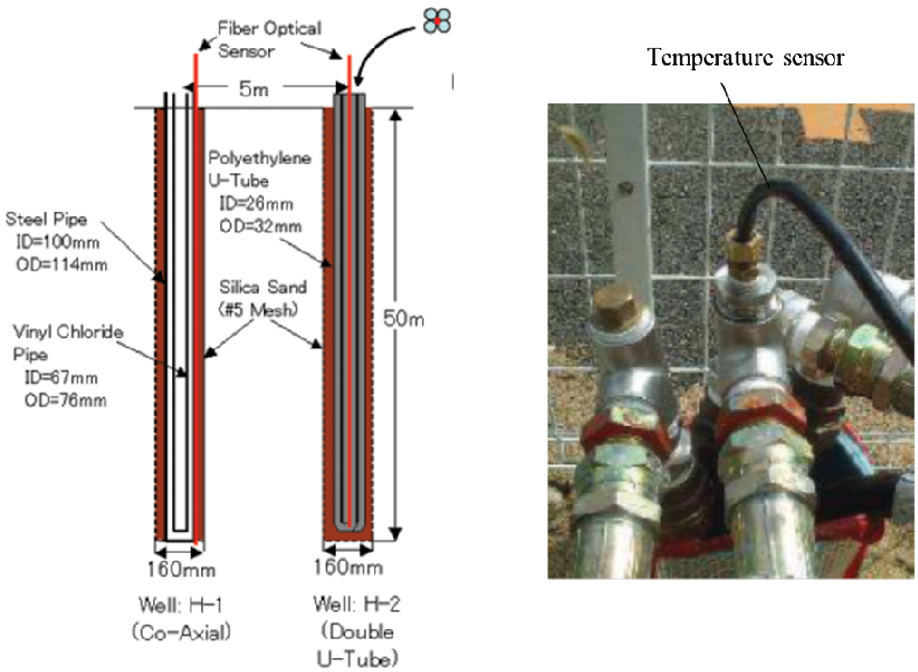


Figure 2.1: Concept diagram of installing fibre optical sensor (Left)
and example (Right).

Figure 2.2: Optical fiber temperature laser radar.

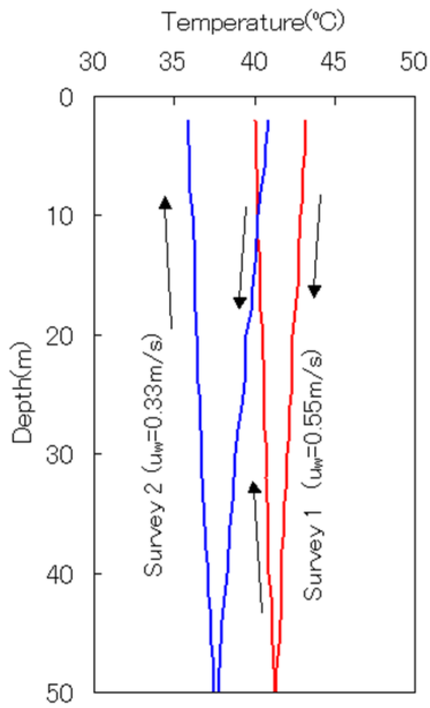


Figure 2.3: Vertical temperature distributions during heating.

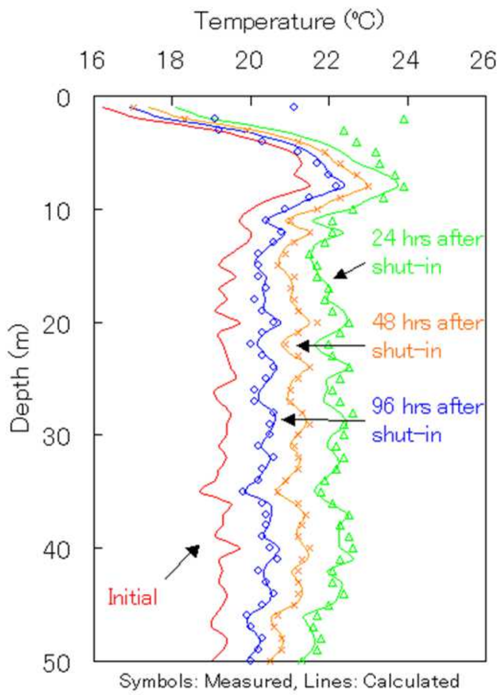


Figure 2.4: Change of vertical temperature distribution after heating.

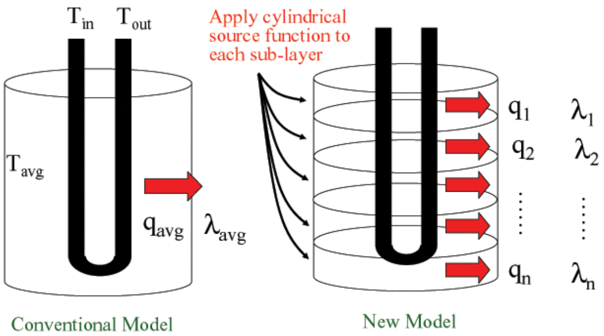


Figure 2.5 Concept diagram of multi-layer model.

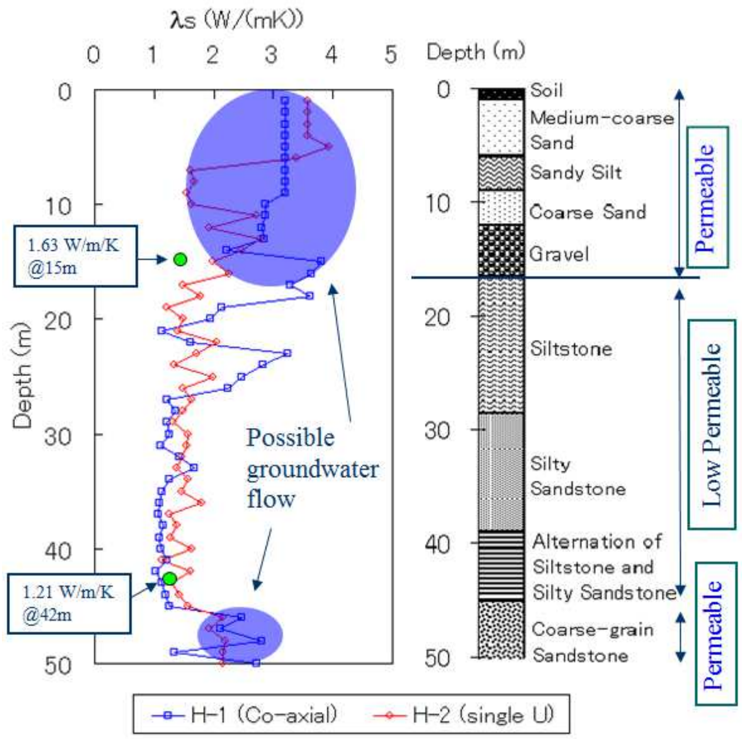


Figure 2.6: Vertical temperature distribution of effective thermal conductivity.

1.3 Advantages and benefits

Fibre optic cable can measure vertical temperature distribution in the borehole ground heat exchanger. With these data the vertical distribution of soil effective thermal conductivity around the BHEX can be calculated. In addition, sectional groundwater flow can be found by compared to the estimated effective thermal conductivity each other.

1.4 Problems

1) The disadvantages of the fibre optic cable measurements are the accuracy of only ~0,2°C.

2) Disturbing of the fluid convection inside the tubes.

3) The following points are also raised:

a) Fracture effects

b) May introduce more error

c) Better description of merits needed.

1.5 References

(This is already written in 2.1)1) Fujii, H., Okubo, H. and Itoi, R. (2006). Thermal response tests using optical fibre thermometers.- Geothermal Resources Council Transactions, 30, 545-551.

2) Fujii, H., Okubo, H., Chono, M., Sasada, M., Takasugi, S. & Tateno, M. (2009). Application of optical fibre thermometers in thermal response tests for detailed geological descriptions.- Effstock 2009.

3) Nelder & Mead (1965): A simplex method for function minimization.- Computer Jornal, /, 308-313.

4) (Or) Chun Ho Tse, Ming Tang, Perry Ping Shum (2010): Nelder-Mead simplex method for modeling of cascaded continuous-wave multiple-Stokes Raman fiber lasers.- Optical engineering Bd. 49 (9), 091009-1-091009-6.

2. Enhanced Geothermal Response Test (EGRT)

2.1 Developers

In this section we list, per development, the different people and organisations involved in the development.

Name	Organisation	Email
Katsunori Nagano	Hokkaido University	nagano@eng.hokudai.ac.jp
Jürgen Dornstädter	GTC-Kappelmayer GmbH	gtc@gtc-info.de

2.2 Summary and examples

An "Enhanced Geothermal Response Test" (ERGT) is a new technology to get more information about den borehole heat exchanger (BHEX) and the thermal data of the subsurface including the influence of groundwater flow. In principle there are two different methods and two different cables to realise an ERGT. First, it is possible to install a hybrid cable into the backfill material during the installation of the BHEX or secondly to insert the cable inside the plastic tube of the BHEX. The advantages of installing the cable inside the backfill material are that it is possible to repeat the ERGT without any further installations and furthermore a temperature measurement during the operation of the BHEX is feasible. Another advantage is that the convection of the fluid inside the BHEX wasn't disturbed by the cable.

For the realisation of the ERGT two kinds of cables are available:

1. A hot wire cable shown in Figure 3.1 is inserted in the tube of borehole heat exchanger (BHEX). Pt-100 sensors are equipped on the surface of hot wire cable and connected to a data logger. Temperature variations are measured by using Pt-100 sensors during heating. The heating time is 50~100 hours. The temperature measuring is continued for several days after the heating. An example of temperature variation during and after heating is demonstrated in Figure 3.2.

The effective thermal conductivity of soil surrounding the borehole heat exchanger is estimated basis on the following equation:

In the case of:

t≤ t' $$T(r,t) \cong \frac{\dot{q}}{4\pi\lambda}\left(-0.5772 + ln\frac{4at}{r^2}\right) \quad (3.1)$$

t > t' $T(r,t) \cong \frac{\dot{q}}{4\pi\lambda}\left(ln\frac{4at}{r^2} - ln\frac{4a(t-t')}{r^2}\right) = \frac{q}{4\pi\lambda} ln\frac{t}{(t-t')}$ (3.2)

T	Temperature	[K]
$\dot{q}$	specific heat extraction/injection	[W/m]
λ	heat conductivity	[W/mK]
a	thermal diffusivity	[m²/s]
r	radial distance from center of the drilling	[m]
t	time	[s]

Figure 3.1: Example of hot wire cable (left) and example of installation (right)

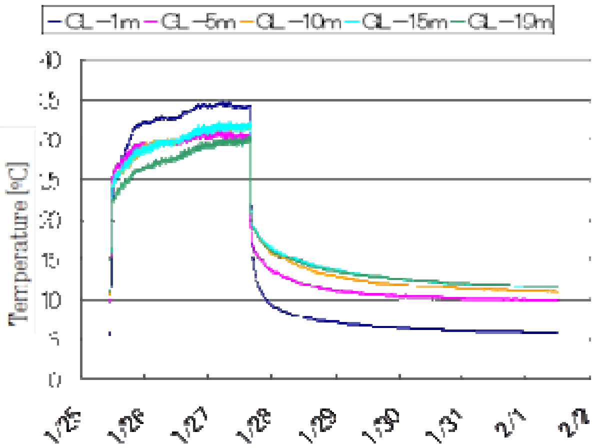


Figure 3.2: Example of temperature variation in BHEX during and after heating.

2. At the other hand the combination of a hot wire cable with a fibre optic sensor (hydride cable) allows the heating and the measurement of the temperature response over the whole bore hole (Figure 3.3). Hence, it is possible to calculate □eff and Rb as a function of the different geological formations. Another benefit of the ERGT is to quantify the influence of the groundwater flow. In the first step of the experiment, the

hot wire cable is applied to an AC voltage of about 220V witch causes a heating load of about 30 W/m in dependency of the material, the lengths and the area of the wires. In order to get the undisturbed soil temperature the temperature measurement starts before the heating period and finishes 2-3 days after this period (Figure 3.4). The developments of temperature during an ERGT are shown in Figure 3.5. Furthermore, the calculated □eff and Rb in dependency to the depth are shown Figure 3.5.

Figure 3.3: Installation of the fibre optic hybrid cable.

Figure 3.4: ERGT with measure device and data logger.

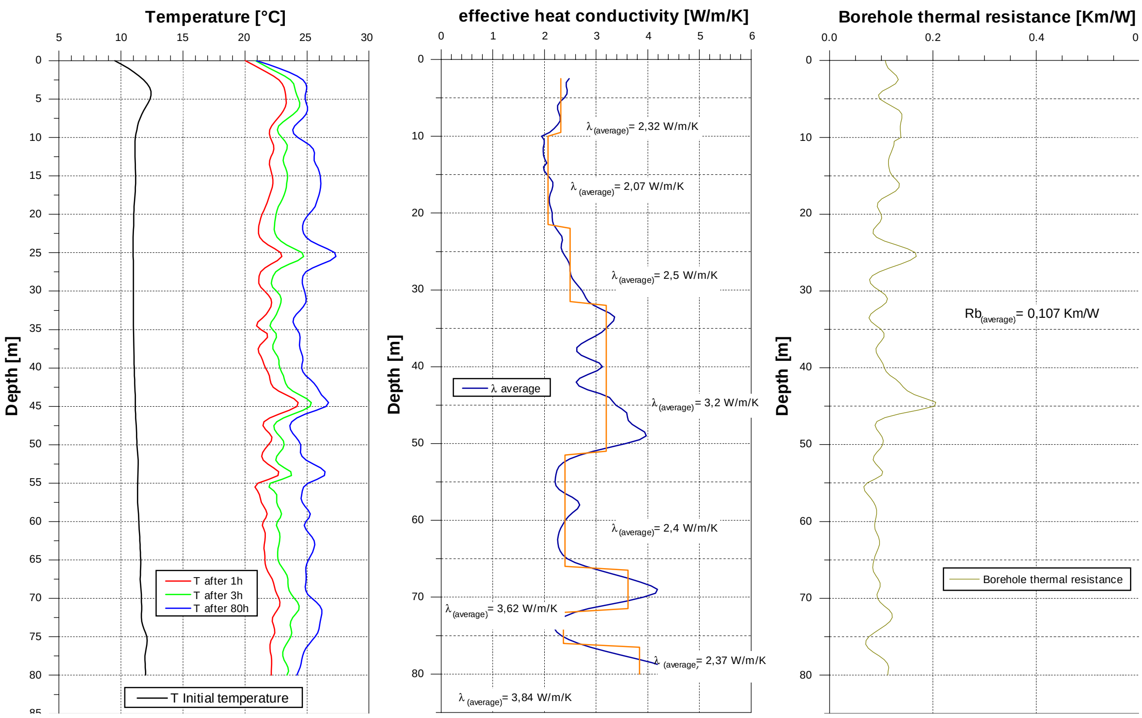


Figure 3.5: Results of an ERGT (Temperature, □eff, Rb).

The heating load qL is given by:

qL=RI²/L (3.3)

where R is the resistance [Ω], I the current [A] and L the length of the wires.

The calculation of the effective thermal conductivity and the borehole thermal resistance from the results of an ERGT is according to the calculation of a normal TRT by using the line source approximation respectively the cylinder source approximation (Subtask 3).

A further benefit of the ERGT is the possibility to calculate the Darcy velocity vf[m/s] of the groundwater flow, which has a significant influence on the effective heat conductivity. The calculation bases upon the application of Péclet number analysis. The Péclet number Pe[-] is defined as the ratio of the convective and conductive heat transport.

$$P_e = \frac{q_{conv.}}{q_{cond.}} = \frac{\lambda_{cond.+conv.} - \lambda_{cond.}}{\lambda_{cond.}} = \frac{l \rho c_p v_f}{\lambda_{cond.}} \qquad (3.4)$$

$$v_f = \frac{\lambda_{cond.+conv.} - \lambda_{cond.}}{l \rho c_p} \qquad (3.5)$$

qconv.	convective heat flow	[W/m²]
qcond.	conductive heat flow	[W/m²]
λconv	convective heat conductivity	[W/mK]
λ cond.	conductive heat conductivity	[W/mK]

l	characteristic length	[m]
ρ	density of the fluid	[kg/m³]
cp	specific heat capacity	[J/kg/K]

An imported condition of this method is the knowledge of the geological situation.

2.3 Advantages and benefits

1) Light weight and easy handle.

2) Fast set up and low cost.

3) It's possible to repeat the ERGT under the same conditions.

4) Distribution of effective thermal conductivity can be estimated.

5) Calculation of the borehole resistance (cable).

6) Darcy velocity.

7) Temperature measurements during the operation of the BHEX.

2.4 Problems

1) Free convection of the filled water (if the cable is installed in the tubes).

2) Accuracy of the fibre optic sensor.

3) Strong groundwater flow.

4) The estimated Rb is from the cable and not from the BHEX

5) Accurate knowledge about the geological situation (Aquifer and so on).

2.5 References

1) K. Nagano (2009): TRT by using a hot wire cable.- Presentation in 6th Meeting of ANNEX21, Bologna (2009).

2) Heidinger P. (1998): Bestimmung der Sickerwasserfliessgeschwindigkeit durch Wärmezufuhr Diplomarbeit am Geophysikalischen Institut der Universität Karlsruhe, Juni 1998.

3) Heidinger P., Dornstädter J., Fabritius A., Welter M., Wahl G., Zurek K., (2004): EGRT - Enhanced Geothermal Response Tests.- Die neue Rolle der Geothermie, Tagungsband 10.-12. November 2004 Landau in der Pfalz, Geothermische Vereinigung e.V.

4) Dornstädter J., Heidinger P., Heinemann-Glutsch B. (2008): Erfahrungen aus der Praxis mit dem Enhanced Geothermal Response Test (EGRT).- Tagungsband des Geothermiekongresses 2008 (11. bis 13.11.2008) in Karlsruhe, Deutschland.

5) Heidinger P., Dornstädter J. (2009): Qualitätskontrolle der Bohrlochverfüllung bei Erdwärmesonden - ein hilfreiches Nebenergebnis des Enhanced Geothermal Response Tests (EGRT).- Symposium 10 Jahre Thermal Response Test in Deutschland, Göttingen 16. September 2009.

6) Heske C., Kohlsch O., Dornstädter J., Heidinger P. (2010): Der Enhanced-Geothermal-Response-Test als Auslegungsgrundlage und Optimierungstool.- bbr (Fachmagazin für Brunnen- und Leitungsbau) Sonderheft Oberflächennahe Geothermie 2011, wvgw Wirtschafts- und Verlagsgesellschaft Gas und Wasser mbH, Bonn, Deutschland.

3. TRT while drilling

3.1 Developers

In this section we list, per development, the different people and organizations involved in the development.

Name	Organisation	Email
Bo Nordell	LTU	bon@ltu.se
Göran Tuomas	Atlas Copco	
Anna-Maria Gustafsson	LTU	amg@ltu.se
Johan Claesson	CTH/LTH	
Halime Paksoy	Çukurova University	hopaksoy@mail.cu.edu.tr

3.2 Summary and examples

Figure4.1 demonstrates concept diagram of Thermal response test while drilling (TRTWD). TRTWD uses the same basic principle as standard TRT measurement. A constant heat power is injected into the borehole and the thermal response of circulating fluid is measured. Instead of heating the circulating fluid, energy is in the form of heat dissipation from drilling work, i.e. from pressurised fluid, mechanical torque and mechanical force-feed. Part of this heat leaves with the drilling fluid, but the rest is transferred into the bedrock. The energy flow depends on the circulating drilling fluid, drilling process and bedrock properties.

Figure 4.2 shows the model when the drill has reached the depth z = zd. The drilling fluid flows inside the drill string, qf [m3/s], changes direction at the bottom and flows upwards outside the drill string in direct contact with the bedrock. As the fluid passes the hammer tool in the bottom a constant heat power Qd [W] raises the fluid temperature. Heat is transferred between inner and outer channel, Q', and between outer channel and bedrock wall.

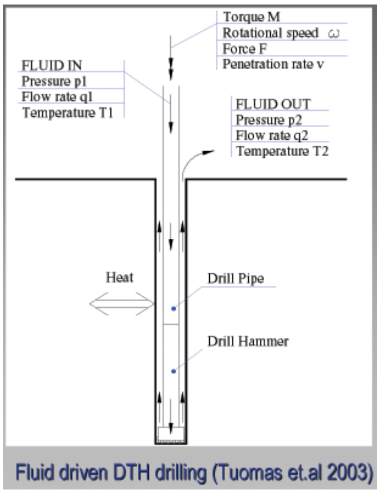


Figure 4.1: Concept diagram of TRTWD.

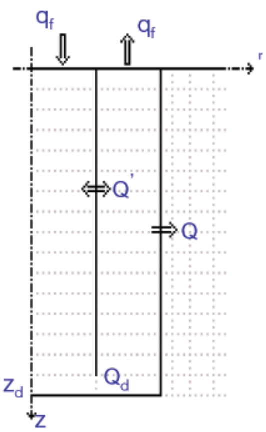


Figure 4.2: Calculation model of TRTWD.

3.3 Advantages and benefits

1) Continuous thermal conductivity along the borehole instead of a mean value.

2) The thermal conductivity can be measured on making boreholes.

3.4 Problems

Measurements at high accuracy are required. It may be difficult to measure in the borehole without damaging the sensor.

3.5 References

1)Tuomas G, Gustafsson A-M, Nordell B (2003): Thermal Response Test Integrated to Drilling.- Futurestock, 9th Int. Conf. on Thermal Energy System 2003; Part I, pp 411-15.Warsaw, Poland.

2) Tuomas G. (2004): Water Powered Percussive Rock Drilling - Process Analysis, Modelling and Numerical Simulation. Doctoral Thesis 2004:58. Luleå University of Technology..

3) Gustafsson A-M, Claesson J, Nordell B. (2005): Technical report: Thermal Response Test While Drilling - Description of numerical model.- Luleå University of Technology.

4. Step pulse

4.1 Developers

In this section we list, per development, the different people and organisations involved in the development.

Name	Organisation	Email
Henk Witte	Groenholland BV	henk.witte@groenholland.nl

4.2 Summary and examples

In the step pulse test, sequential pulses of different heat flux (injecting and extracting heat) are used as shown in Figure 5.1. The test results can be used to calibrate the heat transfer of the model used for the final design (EED, SBM, DST or others).

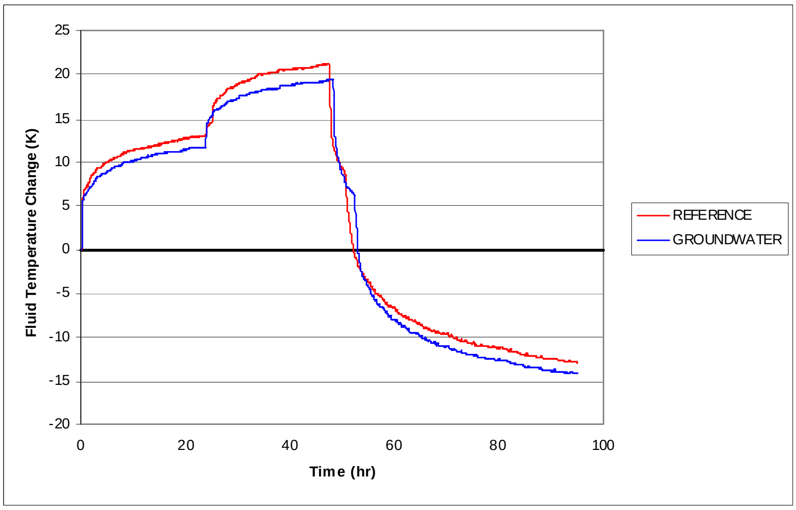


Figure 5.1: Example of step pulse test.

4.3 Advantages and benefits

1) This test minimizes effect of ambient temperature because it is possible to either start with a heating or cooling pulse.

2) More precise effective thermal conductivity and borehole thermal resistance are obtained.

4.4 Problems

1) This test requires lager test apparatus because of cooling test.

2) This test needs a model that includes all these processes, includes a detailed borehole heat exchanger model and allows for a short time step.

4.5 References

1) Witte, H.J.L. & van Gelder, A.J. (2006): Geothermal Response Tests using controlled multi-power level heating and cooling pulses (MPL-HCP): Quantifying ground water effects on heat transport around a borehole heat exchanger. In: Stiles (ed). The Tenth International Conference on Thermal Energy Storage, Ecostock 2006 Proceedings. May 31 - June 2, 2006, Stockton College New Jersey (USA)

2) Witte, H.J.L. (2006): Advances in Geothermal Response Testing. In: Paksoy (ed), Nato Advanced Study Institute on Thermal Energy Storage for Sustainable Energy Consumption (TESSEC), Fundamentals Case Studies and Design. June 6 - 17 2005. Izmir-Cesme/Turkey

3) Witte, H.J.L. (2002): Ground thermal conductivity testing: Effects of groundwater on the estimate. Wärmetransport in der Kruste - Beiträge zur allgemeinen und angewandten 3. Kolloquium des AK Geothermik der DGG 3-4 October 2002, Aachen, Germany.

4) Witte, H.J.L., Gelder, A.J, van & Spitler, J.D. (2002): In-situ measurement of ground thermal conductivity: The dutch perspepctive. ASHRAE Transactions, Volume 108, No. 1.

5) Witte, H.J.L. (2001): Geothermal response tests: The design and engineering of geothermal energy systems. Europäischer workshop über Geothermische Response Tests, EPFL, Lausanne, 25th and 26th of October 2001.

5. Nimo-T (Non-wired Immersible Measuring Object for Temperature)

5.1 Developers

In this section we list, per development, the different people and organisations involved in the development.

Name	Organisation	Email
Roland Wanger	Geowatt	info@geowatt.ch
Thomas Kohl	KIT	thomas.kohl@kit.edu
Ernst Rohner	Geowatt	info@geowatt.ch

5.2 Summary and examples

The miniature data logger "Nimo-T" shown in Figure 6.1 is a temperature measurement device for vertical profiles. The Nimo-T is inserted in the heat exchanger pipe and sinks down slowly under its adjustable weight, which is close to the density of water(Figure 6.2). During the sinking process the wireless NIMO-T records pressure and temperature at preselected time intervals. By this method, temperature profiles in the heat exchanger pipes can be measured prior to a TRT with heat injection or extraction, or afterwards.

The thermal conductivity calculation is based on undisturbed conduction. Therefore, disturbing effects like the influence of ground temperature changes (due to paleoclimatic variations), groundwater flow effects must be eliminated from the measured values beforehand. From the measured temperature profile the local geothermal gradient is then calculated for each layer (1st derivative; ∇Ti: temperature gradient of depth section i)

$$\nabla T_i = \frac{T_u - T_1}{Z_u - Z_1} \qquad (6.1)$$

where Tu is the temperature measured at the top (z = zu) and T1 at the bottom (z = z1) of interval i.

Finally, with the local terrestrial heat flow value qloc (obtainable from regional heat flow maps; e.g. Medici & Rybach 1995), the thermal conductivity of each individual depth section can be calculated:

$$\lambda_i = \frac{q_{loc}}{\nabla T_i} \qquad (6.2)$$

Figure 6.3 are an example of distribution of water temperature in the BHEX and distribution of effective thermal conductivity.

Figure 6.1: Appearance of miniature data logger "Nimo-T".

Figure 6.2: Example of temperature logging in BHEX using "Nimo-T".

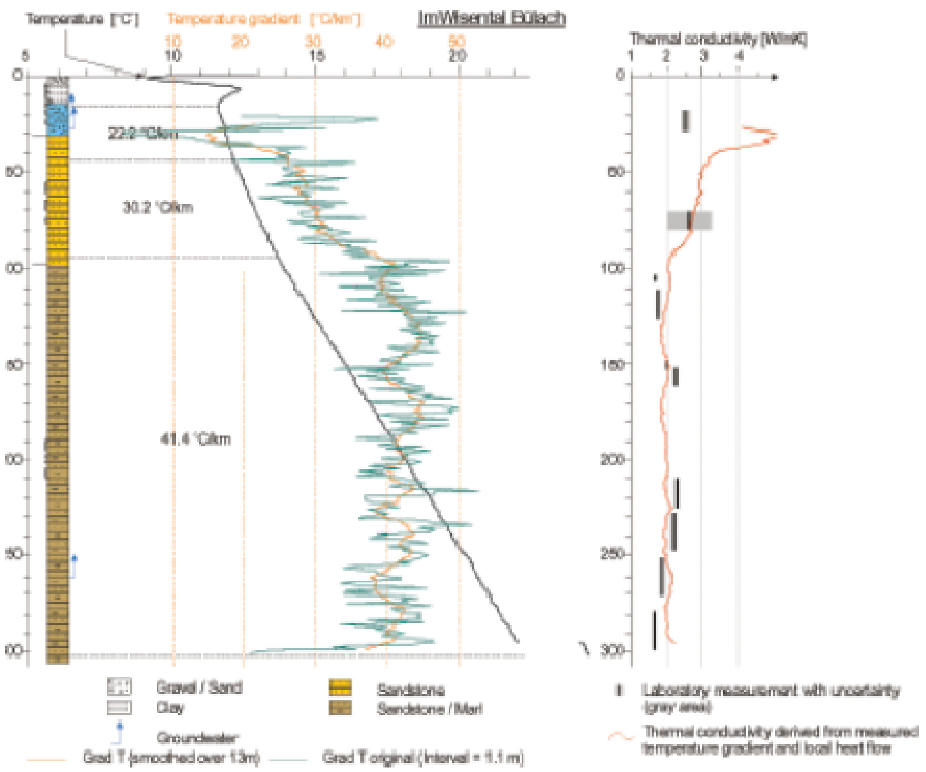


Figure 6.3: Distribution of temperature and effective thermal conductivity

5.3 Advantages and benefits

1) Ground temperature distribution can be measured.

2) Distribution of effective thermal conductivity can be estimated.

3) Pressure in the BHEX can also be measured. This makes it possible to confirm leaks of thermal medium in the BHEX and to determinate the accurate length of the BHEX.

5.4 Problems

It is difficult to measure temperature distribution during heating.

5.5 References

1) Rohner, E. Rybach, L., Mégel, T. & Forrer, S. (2008): New measurement techniques for geothermal heat pump – borehole heat exchanger quality control, 9th IEA International Heat Pump Conference in Zurich, s4-p22 (2008).

2) Medici F., Rybach L., (1995): Geothermal Map of Switzerland 1995 (Heat Flow Density), Matériaux pour la Géologie de la Suisse, Géophysique Nr. 30. Schweizerische Geophysikalische Kommission.

6. Energy Pile

6.1 Developers

In this section we list, per development, the different people and organisations involved in the development.

Name	Organisation	Email
Takao Katsura	The University of Kita-kyushu	t-katsura@env.kitakyu-u.ac.jp

6.2 Summary and examples

In the energy pile system, the foundation piles of building are used as ground heat exchangers. Three types of foundation piles are classified broadly. The first is the cast-in-place concrete pile, the second is the pre-casting concrete pile with a hole in the center and the last one is the steel foundation pile. When the cast-in-place concrete pile is used as the ground heat exchanger, the U-tubes are bound on the reinforced frame as shown Figure 7.1. The U-tubes are inserted in the hollow of pile as shown in Figure 7.2 or Figure 7.3 in the case where the pre-casting concrete pile or steel foundation piles are used as the ground heat exchanger. The advantage of the energy pile systems is the lower installation cost compared to the BHEX system, because there is no additional drilling cost required.

The diameter of foundation piles are 400~2000 mm for large buildings. This is about 3~16 times bigger than the diameter of boreholes of BHEX, which are about 120 mm. Hence, for the calculation of the effective thermal conductivity by applying the line source approximation method, a test time of 500~1500 h is required to satisfy Equation 7.1.

$$\frac{at}{r^2} \geq 20 \qquad (7.1)$$

a Thermal diffusivity of the ground [m2/s]

t TRT test time [s]

r Borehole or pile radius [m]

As an example of TRT at a steel foundation pile with large diameter, Figure 7.4 shows the TRT equipment and a schematic overview of a TRT experiment at a steel pile with a diameter of 600 mm. The TRT was carried out for about 3,000 h. The developments of the different temperatures Tpin, Tpout, Tpm and flow rate Gf during the TRT experiment are shown in

Figure 7.5. In the TRT, flow rate and number of U-tubes were changed several times. Table 7.1 shows the conditions of flow rate and number of U-tubes according to elapsed time.

Furthermore, the development of the apparent effective thermal conductivity of the ground is calculated by Equation 7.2.

$$\lambda(t) = {q_p}/{4\pi k(t)} \quad (7.2)$$

λ Apparent effective thermal conductivity of the ground [W/m/K]

qp Heat injection rate to the ground [W/m]

t Elapsed time [s]

with,

$$k(t) = \frac{T_{pm}(t) - T_{pm}(t/m)}{\ln(m)} \quad (7.3)$$

k Gradient of temperature variation

Tpm Mean temperature between inlet and outlet temperature of the ground heat exchanger (=(Tpin+Tpout)/2) [K]

Tpin Inlet temperature of the ground heat exchanger [K]

Tpout Outlet temperature of the ground heat exchanger [K]

m Arbitrary constant value (=5)

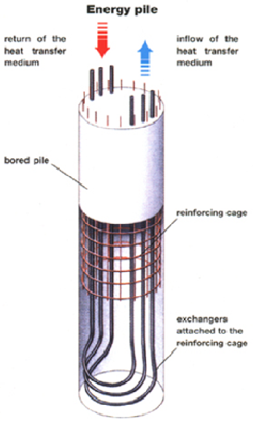
Here, the Equation 7.3 can be derived by the following equations.

$$T_{pm}(t) = k \ln(t) + l \quad (7.4)$$

$$T_{pm}(t/m) = k \ln(t/m) + l \quad (7.5)$$

The calculated effective thermal conductivities are shown in Figure 7.6. It is 3.0 W/m/K at test duration of 60 h. This value is about two times higher than the result which was obtained by a standard TRT which was carried out at a double pipe ground heat exchanger at the same area and with the same depth. On the other hand, the effective thermal conductivity after a runtime of 2,000 h is less than 2.0 W/m/K and close to the 1.72 W/m/K which was measured at the double pipe ground heat exchanger (The detail is described below). This result suggests that the estimated effective thermal conductivity might be higher than the value obtained by using the TRT result with the double pipe ground heat exchanger. Another evaluation method for the short-term TRT is necessary.

A standard TRT was also carried out at a double pipe ground heat exchanger at the same area and with the same depth. Figure 7.7 shows the appearance of the TRT at a double pipe with a diameter of 60 mm. As the result, the variation of temperatures Tpin, Tpm and flow rate Gf during the TRT experiment are shown in Figure 7.8. In addition, the variation of mean temperature Tpm (=Tpin + Tpout) is shown in Figure 7.9. Using the temperature variation, the estimated effective thermal conductivity at the area is 1.72 W/m/K.



(a)U-tubes inside reinforced frame (b) U-tubes outside reinforced frame

Figure7.1: Energy piles using cast-in-place concrete piles.

Figure7.2: Energy pile using pre-casting concrete pile.

Figure7.3: Energy pile using steel pile.

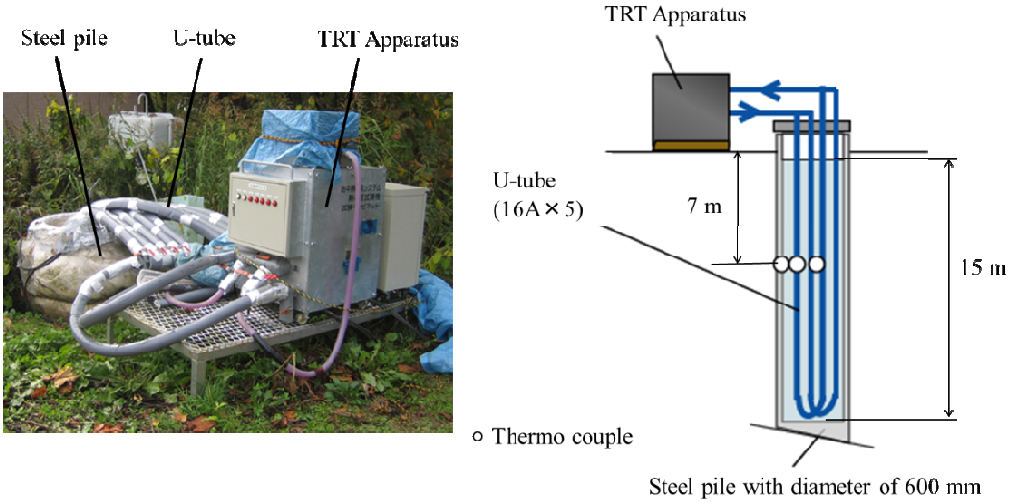


Figure7.4: TRT using steel pile with diameter of 600 mm.

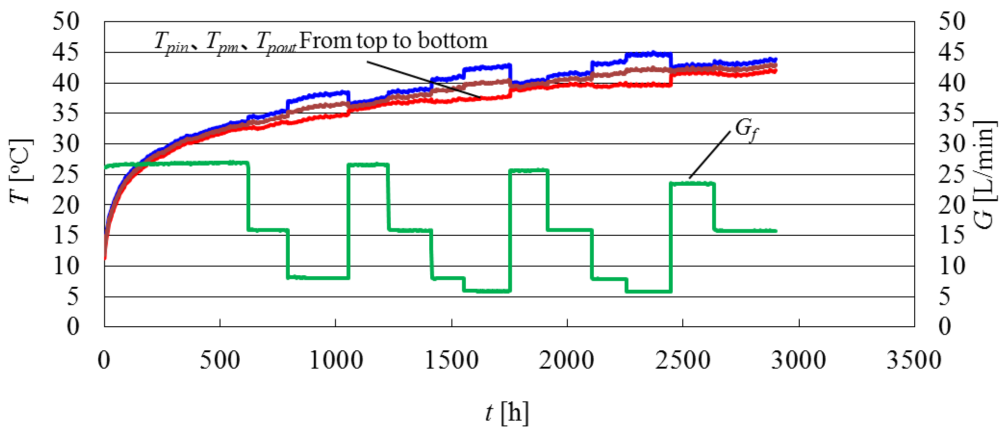


Figure7.5: Variation of Tpin, Tpout, Tpm and Gf..

Table 7.1: Conditions of flow rate and number of U-tubes according to elapsed time.

	U-tube	G_f [L/min]	Start date	Elapsed time from start
L2-1	25A×5U-tubes	26	2008/5/7	0
L2-2		16	2008/5/28	622
L2-3		8	2008/6/4	793
L2-4	25A×4U-tubes	26	2008/6/11	1055
L2-5		16	2008/6/18	1228
L2-6		8	2008/6/25	1414
L2-7		6	2008/7/2	1553
L2-8	25A×3U-tubes	26	2008/7/9	1754
L2-9		16	2008/7/16	1915
L2-10		8	2008/7/23	2107
L2-11		6	2008/7/30	2255
L2-12	25A×2U-tubes	26	2008/8/6	2447
L2-13		16	2008/8/13	2635

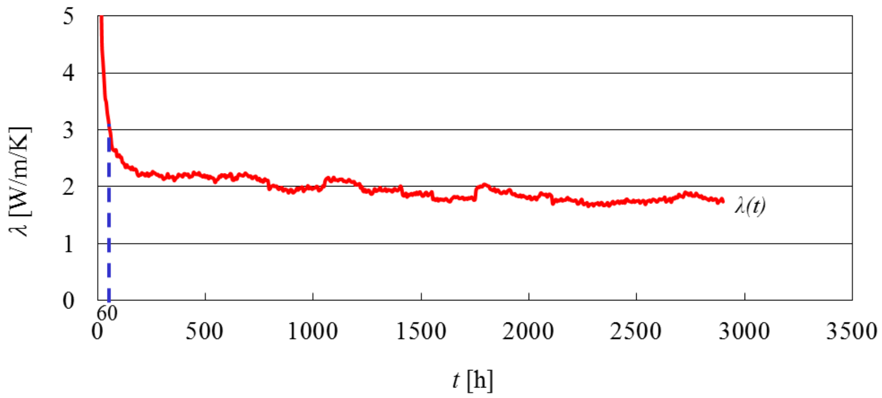


Figure7.6: Variation of apparent effective thermal conductivity.

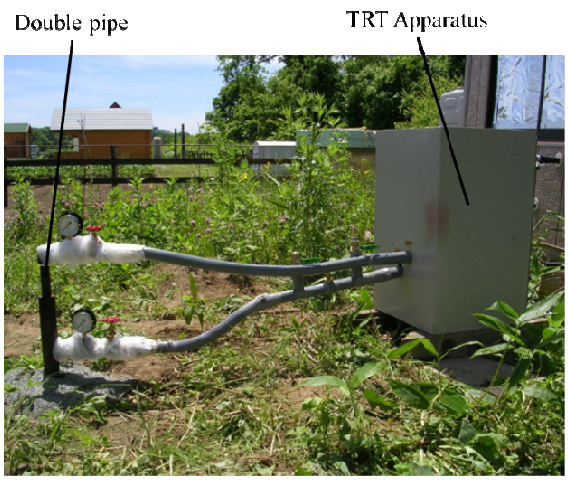


Figure7.7: TRT using double pipe ground heat exchanger of 60 mm.

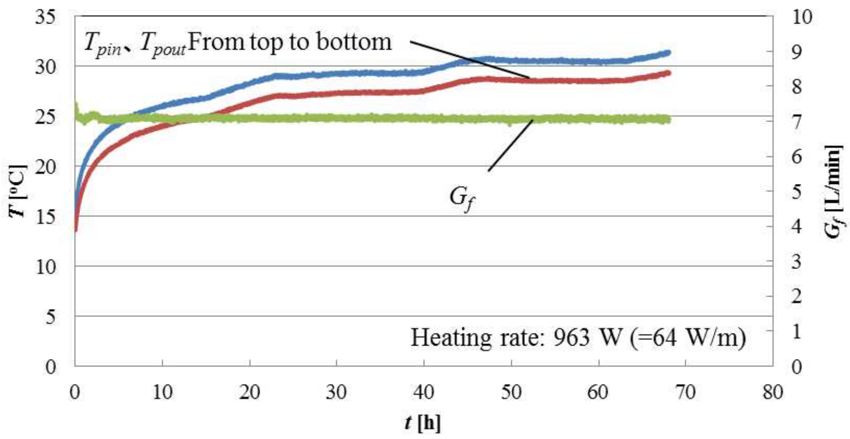


Figure7.8: Variation of Tpin, Tpout and Gf..

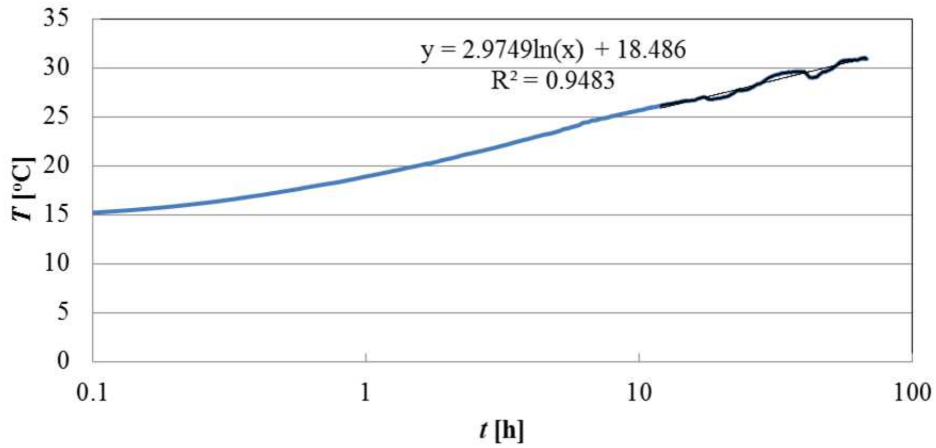


Figure7.9: Variation of Tpm.

6.3 Advantages and benefits

1) The drilling cost for a conventional TRT can be reduced by using the short-term TRT.

2) With the thermal parameter from these TRT is the design of a geothermal energy pile system assured.

6.4 Problems

1) The evaluation method for the short-term TRT on energy piles is not established until now.

2) There is the possibility that the estimated effective thermal conductivity is higher (Depends on the evaluation method).

6.5 References

1) Japanese text of the ground source heat pump system

7. TRT for special geometries

7.1 Developers

In this section we list, per development, the different people and organisations involved in the development.

Name	Organisation	Email
Jim Bererton	Stantec Consulting Ltd.	mannasol@shaw.ca

7.2 Summary and examples

Traditional TRT methods apply primarily to vertically oriented borehole heat exchangers. Differences in geometries create a number of problems. The different geometries are vertical ground heat exchanger with short length (include Energy piles) and horizontal ground heat exchanger.

Uniform temperature profile assumptions may only be applied for depths > 60m. Shallower designs do not have a uniform temperature profile in the initial condition. Edge effect can be considered by applying the finite line source theory. It is possible to apply the infinite line source theory to the ground heat exchanger with short length by calculating error between the finite line source theory and the infinite line source theory.

Figure 8.1 shows the finite line source model with a condition that temperature on the ground surface is kept at initial ground temperature Ts0 constant. As shown in Figure 8.1, a finite line source, whose length is Lp and heating rate is q' = -q, is placed from z = 0. The calculation result is demonstrated in Figure 8.2. Edge effect is lager when the length of the ground heat exchanger is short.

Horizontal geometries do not have the same surface boundary conditions. For vertical geometries the surface energy balance has a negligible effect, but this must be accounted for in shallow designs. This includes solar radiation, snow cover, wind, evaporation, rain fall, etc. In the recent research, numerical model of horizontal ground heat exchanger shown in Figure 8.3 is developed and the ground property is analyzed. The model is validated by comparing to the TRT result using horizontal ground heat exchanger. In addition, there is a possibility that the TRT using the hot wire cable (Chapter 3) can be applied to design the horizontal ground heat exchanger.

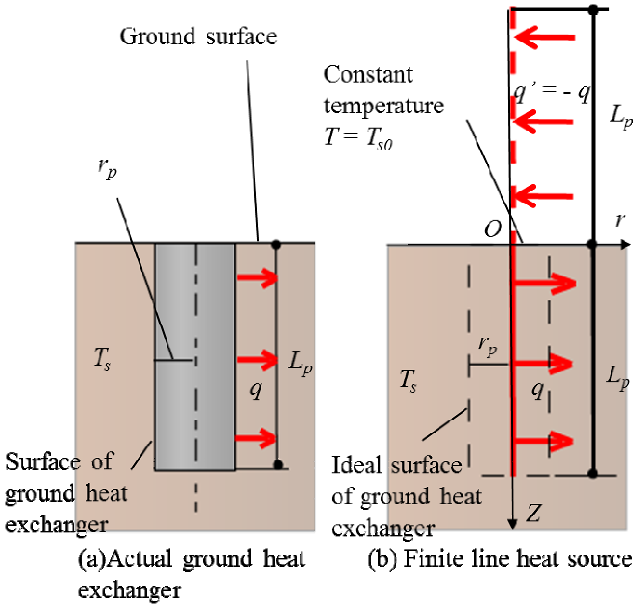


Figure 8.1: Finite line heat source model with ground surface temperature T (z = 0) = Ts0.

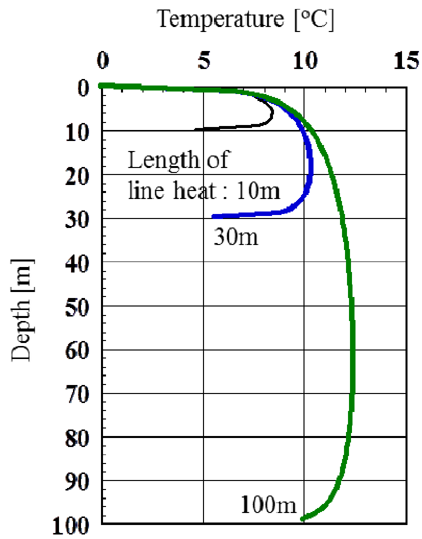


Figure 8.2: Vertical temperature distributions for length of line heat source at steady state.

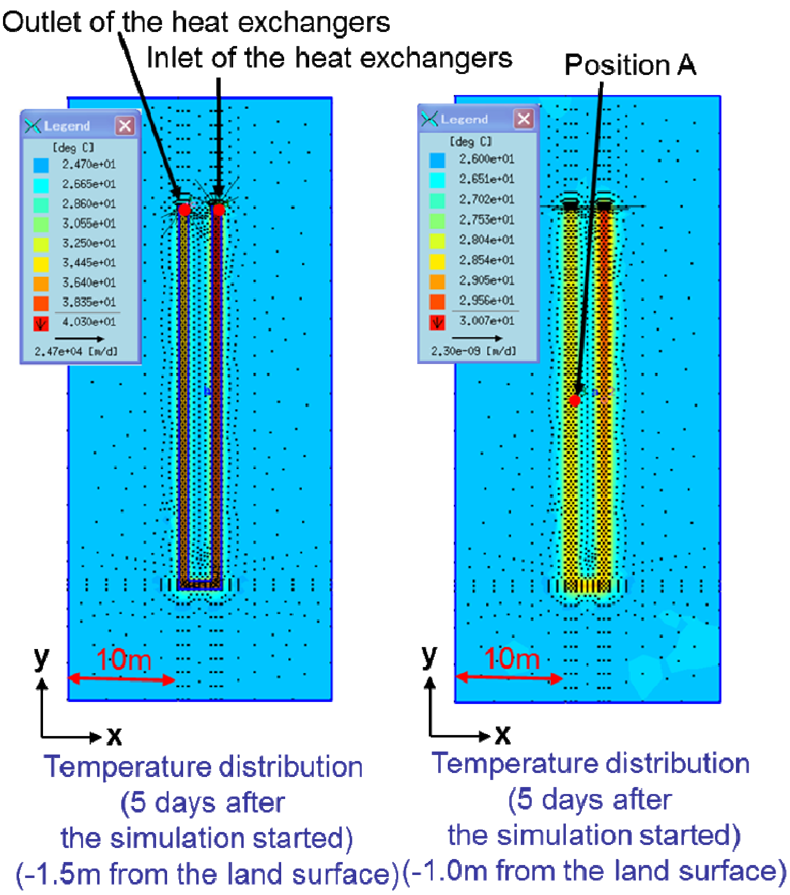


Figure 8.3: Example of numerical model of horizontal ground heat exchanger

7.3 Advantages and benefits

New knowledge is obtained because there are few case examples of TRT with different geometries.

7.4 Problems

Boundary condition of ground surface also differs when there is a building on the surface.

7.5 References

1) Nagasaka, S.,. Ochifuji, K., Nagano, K., Yokoyama, S., Nakamura, M. & Hamada, Y. (1995): An Estimate of the Surface Temperature at a Vertical Ground Pipe by Line Source

Theory," The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan 59 (1995) 143-151 (In Japanese).

2) Katsura, T., Nagano, K. & Takeda, S. (2008) : Method of Calculation of the Ground Temperature for Multiple Ground Heat Exchangers, Applied Thermal Engineering, Volume 28, pp.1995-2004.

3) Nishi, K. & Fujii, H. (2009) : Numerical modeling of horizontal ground heat exchangers, Presentation in 6th Meeting of ANNEX21, Bologna.

8. Groundwater influence

8.1 Developers

In this section we list, per development, the different people and organisations involved in the development.

Name	Organisation	Email
Henk Witte	Groenholland BV	henk.witte@groenholland.nl
Takao Katsura	The University of Kita-kyushu	t-katsura@env.kitakyu-u.ac.jp

8.2 Summary and examples

Groundwater flow is categorized as shown in Figure 9.1.

A. Darcy flow through the porous media

B. Water flow through the fracture

C. Natural convection in the aquifer

D. Vertical water flow caused by rainfall or thermo-syphon effect

Groundwater flow prevents the temperature rise in the TRT and the effect becomes lager when the groundwater velocity increases. With respect to groundwater type A, the relation between the groundwater velocity and effect is revealed by using the TRT result with a large underground tank shown in Figure 9.2. During the TRT, the thermal medium is supplied to the GHEX at constant flow and heating rates. Table 1 shows the experimental conditions during the test. The TRT is performed four times at different imitated groundwater velocities. Figure 9.3 shows the temperature variations on the surface of the GHEX with respect to the logarithmic elapsed time. At the elapsed time of 80 h, the temperature variation in CASE3 (vgw=193 m/year) is 4 oC smaller than the one in CASE1 (vgw=0 m/year).

In addition, groundwater effects of type A and type B are investigated by numerical simulation as shown in Figure 9.4. Groundwater effect caused by thermo-syphon effect is also analyzed by numerical simulation.

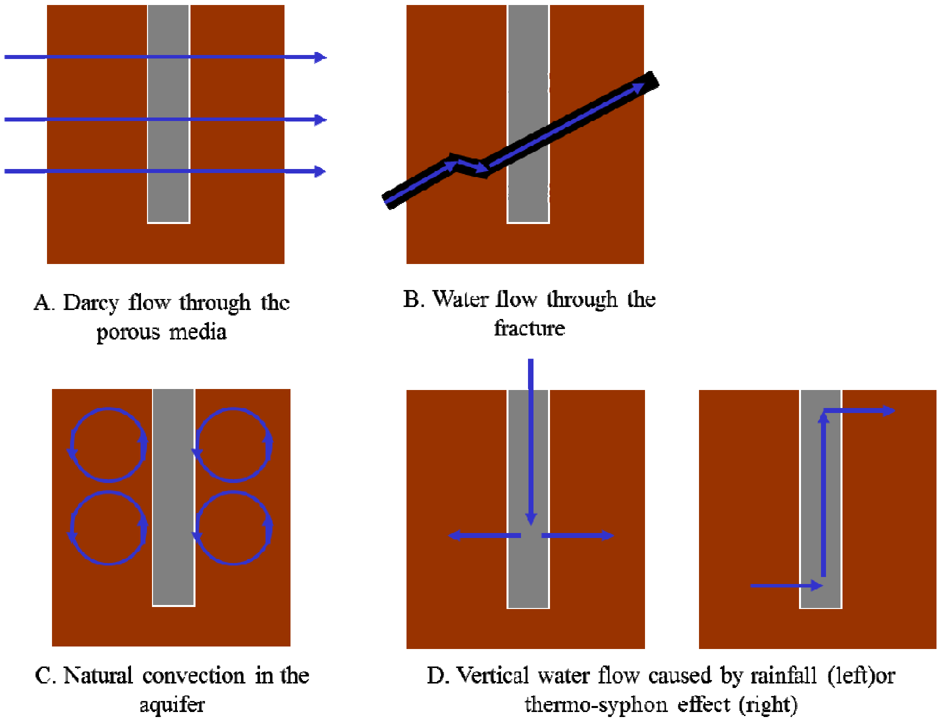


Figure 9.1: Types of groundwater flow.

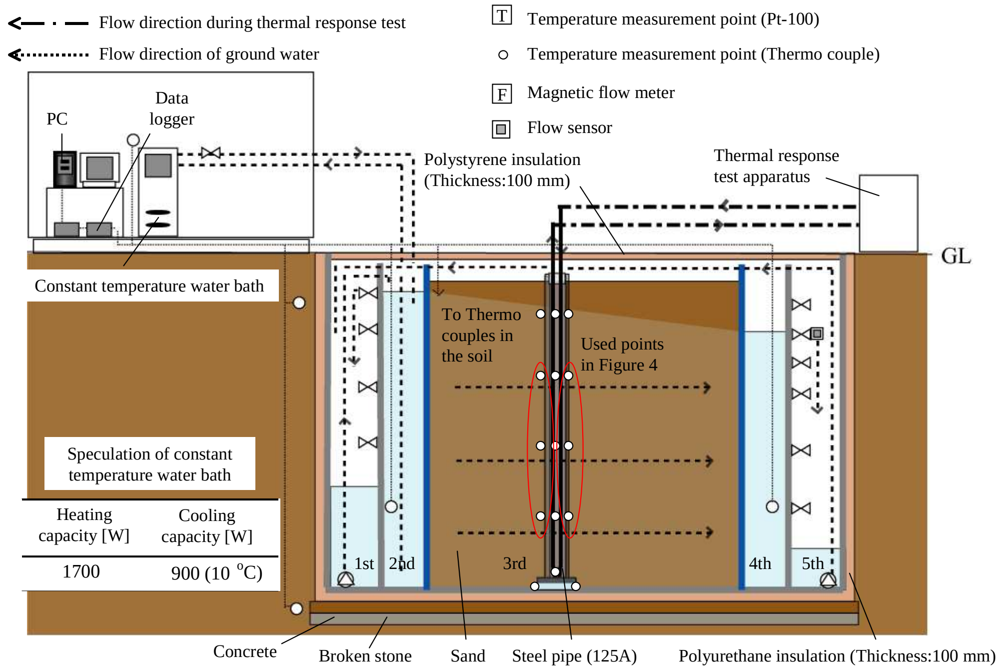


Figure 9.2: Schematic diagram of experiment with underground tank.

Table 9.1: Experimental conditions.

	q_p [W/m]	u_{gw} [m/year]	T_{pm} [ºC]	T_{gw} [ºC]
CASE1	50.50	0	30.83	15.00
CASE2	49.72	29	32.21	16.37
CASE3	54.10	193	30.58	15.77
CASE4	50.20	550	29.12	16.29

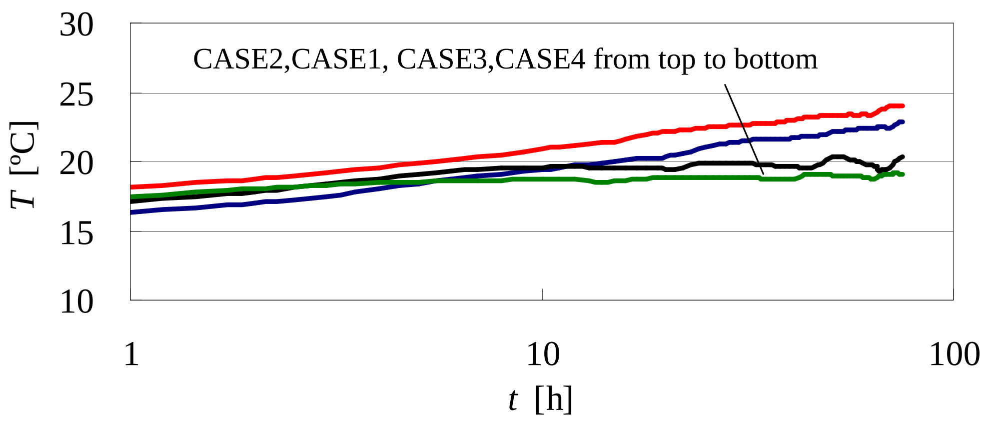


Figure 9.3: Temperature variations in TRT.

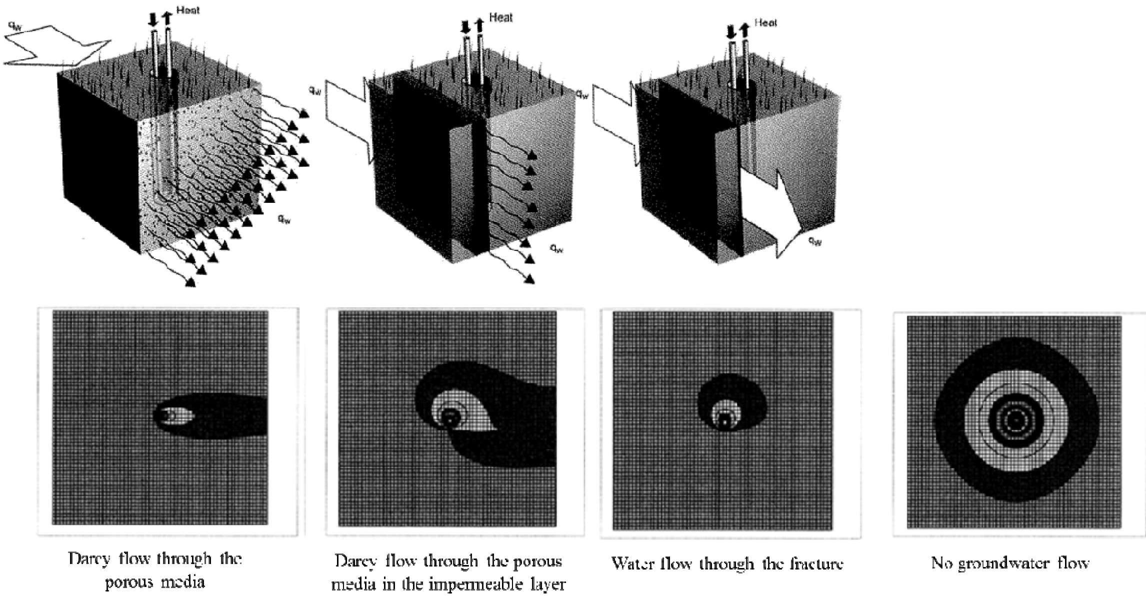


Figure 9.4: Numerical model of groundwater flow and calculation result of temperature distribution surround borehole heat exchanger.

8.3 Advantages and benefits

Considering the groundwater flow for design of GSHP system can reduce length of the ground heat exchanger and the installation cost.

8.4 Problems

1) It is difficult to determine the sort of groundwater flow from the TRT result. Also, estimating the groundwater velocity and thickness of aquifer are also difficult (the thickness can be estimated from the cuttings).

2) Effect of groundwater type C has not been indicated yet.

8.5 References

1) Henk W. (2009): TRT and Groundwater flow, Presentation in 6th Meeting of ANNEX21, Bologna .

2) Katsura, T. Nagano, K. Okawada, T. & Hori S. (2009): Investigation of Ground Water Flow Effect on the Thermal Response Test Result.- Proceedings of 11th Energy Conservation Thermal Energy Storage Conference Effstock 2009, Stockholm.

3) Gehlin, S. (2002): Thermal Response Test-Method Development and Evaluation.- Ph.D. Dissertation, Luleå University of Technology.

4) Gehlin. S. & Hellström, G. (2003) : Influence on Thermal Response Test by Groundwater Flow in Vertical Fractures in Hard Rock.- Renewable Energy 28, pp.2221-2238.

E. SUBTASK 3
Evaluation Methods and Developments

Contents of Subtask

Nomenclature

t	=	time [s]
a	=	thermal diffusity (a = λ / c_s) [m²/s]
λ, λ_s	=	heat conductance ground/soil [W/(mK)]
λ_g	=	heat conductance grouting/filling [W/(mK)]
c_s	=	specific heat capacity of the ground (soil) [J/m3/K]
c_g	=	specific heat capacity of the grouting / borehole filling [J/m3/K]
R_b	=	effective borehole thermal resistance [mK/W]
Tb	=	undisturbed (far field) underground temperature [°C]
Tave	=	average fluid temperature on ground surface
$\dot{q}$	=	specific heat extraction/injection [W/m]
$\dot{Q}$	=	total heat extraction/injection [W]
H	=	thermal active depth of the vertical ground heat exchanger [m]
r	=	radial distance from center of the drilling [m]
r_b	=	borehole radius [m]
γ	=	Euler constant (0.57722)

1. Introduction

One of the reasons why Thermal Response Testing got popular is the simple evaluation of the temperature response. But the process of evaluating also includes the determination of the correct evaluation period of the measurement due to borehole effects at the beginning of the test, as well as a minimum measurement duration to ensure a reliable result. Therefore some enhanced methods of evaluating the temperature response will be shown.

Further, numerical models can permit to evaluate tests with a non-constant power pulse. Also one has to ensure that other heat transfer effects than heat conductance in the ground can be neglected. Methods will be given how to identify those effects.

Last, a comparison of numerical models and evaluations of different testers will be given.

1.1 Objectives

- Comparison of evaluation methods
- software for automatic evaluations
- Comparative evaluation of reference test data
- Inclusion of c_s in the evaluation

  Evaluation during testing e.g. to determine duration

2. Evaluation methods

2.1 Terminology

The *average fluid temperature* shall be the arithmetic average of in- and outlet fluid temperature at ground surface level (GSL).

The *thermal power* means the effectively injected power in the borehole heat exchanger and is calculated out of the in- and outlet fluid temperatures at GSL and the mass flow rate, considering the temperature dependency of the density and the heat capacity of the heat carrier fluid. A constant thermal power rate over a certain period shall be called *thermal power pulse* and can be positive, negative or equal zero.

The *line source approximation LSA* shall mean the simplification of the borehole heat exchanger to an infinite line source with a specific power rate (W/m) and heat transfer by heat conduction. The LSA can be described by analytical or numerical solutions. LSA does not necessarily mean the simplified analytical solution in chapter 2.2.1, where the heat conductance can be determined directly out of the slope on semi logarithmic scale.

Speaking of the *minimum time criterion MTC* one has to differentiate between the theoretical and the physical MTC. The theoretical shall mean the validity of the model assumption after a certain time scale. The physical or experimental MTC describes the point in time, when evaluation can be started due to negligible borehole thermal effects.

2.2 Analytical methods

2.2.1 Line source approximation (LSA)

The Line source approximation reduces the geometry of a vertical ground heat exchanger drilling to an infinite line source. As heat transport, only heat conduction is considered. Therefore Fourier's law is applied:

$$\vec{q} = -\lambda \nabla T$$

Eqn. 1

For the case of a constant heat injection (or extraction) $\dot{q}$, the temperature increase in radial direction can be described as

$$T(r,t) = \frac{\dot{q}}{4\pi\lambda}\int_0^t e^{-r^2/4a(t-t')}\frac{dt'}{t-t'}$$
$$= \frac{\dot{q}}{4\pi\lambda}\int_{r2/4at}^{\infty}\frac{e^{-u}}{u}du$$
$$= \frac{\dot{q}}{4\pi\lambda}E_1(r^2/4at)$$

Eqn. 2

Usually the temperature response of the soil is evaluated at the radius of the borehole wall r_b. To evaluate the temperature response of the fluid in the heat exchanger, the effective borehole thermal resistance R_b is introduced. R_b describes the temperature difference between the soil temperature at the borehole wall (Eqn. 3) and the arithmetic average fluid temperature and the ground surface level T_{ave}. With the assumption of a steady state flux in the borehole follows:

$$\dot{q}R_b = \Delta T = T_{ave} - T(r_b)$$

Eqn. 3

with

$$T_{ave} = (T_{in} + T_{out})/2$$

Eqn. 4

With Eqn. 2, Eqn. 3 and Eqn. 4 follows

$$T_{ave}(r_b,t) = \frac{\dot{q}}{4\pi\lambda}E_1(r_b^2/4at) + \dot{q}R_b + T_g$$

Eqn. 5

For larger times, the so-called exponential integral can be approximated by

$$E_1(r^2/4at) = \ln(\frac{4at}{r^2}) - \gamma - \frac{1}{4}\left[\frac{r^2}{at} - \left(\frac{r^2}{4at}\right)^2\right]$$

Eqn. 6

With a maximum error of 1% if:

$$\frac{at}{r^2} \geq 0.5$$ **Eqn. 7**

For even larger times of at / r2 ≥ m Eqn. 6 can be simplified to

$$E_1(r^2/4at) = \ln(\frac{4at}{r^2}) - \gamma$$ **Eqn. 8**

while the error of this approximation is

m	5	10	20	40	50	100
error (%)	10.5	5.3	2.5	1.5	1.0	0.5

⚐ Please note that the given time scales refer only to the validity of the approximated solutions. They must not be taken to choose the evaluation time period. Using the approximated solutions, the given time scales have to be respected in order to reach the intended precision of the solution.

Note:

The exponential integral can also be expressed as:

$$E_1(1,x) = \ln(\frac{1}{y}) - \gamma + \sum_{n=1}^{\infty} \frac{(-1)^{n+1} y^n}{n \cdot n!}$$ **Eqn. 9**

which results in following approximation error of the ground temperature:

$$\Delta T = \frac{\dot{q}}{4\pi\lambda} \sum_{n=1}^{\infty} \frac{(-1)^{n+1} (r^2/4at)^n}{n \cdot n!}$$ **Eqn. 10**

Using the approximated solution of Eqn. 8 and including the undisturbed (or far field) temperature T_g and the effective thermal borehole resistance R_b, one obtains the most common expression of the temperature increase/decrease of the average fluid temperature:

$$T_{ave}(r_b,t)=\frac{\dot{q}}{4\pi\lambda}\left[\ln(\frac{4at}{r_b^2})-\gamma\right]+\dot{q}R_b+T_g$$ **Eqn. 11**

Using this equation, one can separate the time dependency:

$$T_{ave}(r_b,t)=\frac{\dot{q}}{4\pi\lambda}\ln(t)+\dot{q}\left[\frac{1}{4\pi\lambda}\left[\ln(\frac{4a}{r_b^2})-\gamma\right]+R_b\right]+T_g$$ **Eqn. 12**

For the application of the above described solutions in order to evaluate the measured temperature response, see chapter 2.2.5.

References:

[1] H.S. Carslaw, J.C. Jaeger, Conduction of Heat in Solid, Oxford University Press, Oxford, 1959

[2] Gehlin, S., 1998. Thermal Response Test, In-Situ Measurements of Thermal Properties in Hard Rock. Licentiate Thesis, Luleå University of Technology, Department of Environmental Engineering, Division of Water Resources Engineering. 1998:37. 41 pp.

[3] Hellström, G. 1991. Ground Heat Storage. Thermal Analysis of Duct Storage Systems: Part I Theory. University of Lund, Department of Mathematical Physics. Lund, Sweden

2.2.2 Cylinder source approximation (CSA)

A further way to describe the temperature response of a single vertical ground heat exchanger is cylinder source approximation. The temperature response is solved by using Bessel functions.

It can be written using Hellström [3], Carslaw and Jaeger [1]:

$$T(r,t)=\frac{q}{2\pi\lambda r_b}\left\{\frac{r_b r_1}{r_1^2-r_b^2}\cdot[\frac{2a}{r_1}t+\frac{2r^2-3r_1^2-r_b^2}{4r^1}+\frac{r_b^2 r_1}{r_1^2-r_b}\ln(\frac{r_1}{r_b})+r_1\ln(\frac{r_1}{r})]-\right.$$
$$\left.-\pi\sum_{n=1}^{\infty}\frac{e^{-a\alpha_n^2 t}J_1(\alpha_n r_b)J1(\alpha_n r_1)[Y1(\alpha_n r_1)J_0(\alpha_n r)-Y_0(\alpha_n r)J_1(\alpha_n r_1)]}{\alpha_n[J_1(\alpha_n r_1)^2-J_1(\alpha_n r_b)^2]}\right\}$$ **Eqn. 13**

where α_n the positive roots of the equation

$$J_1(a_n r_b)\cdot Y_1(a_n r_1) - J_1(a_n r_1)\cdot Y_1(a_n r_b) = 0$$

Eqn. 14

Or as described in Gehlin [4]

$$T(r,t) = \frac{q}{\lambda}\cdot G(z,p) \qquad \begin{cases} z = \dfrac{a\cdot t}{r^2} \\ p = \dfrac{r}{r_0} \end{cases}$$

Eqn. 15

Where G is

$$G(z,p) = \frac{1}{\pi^2}\int_0^{\infty} f(\beta)d\beta$$

Eqn. 16

and

$$f(\beta) = (e^{-\beta^2 z} - 1)\cdot \frac{[J_0(p\beta)\,Y_1(\beta) - Y_0(p\beta)\,J_1(\beta)]}{\beta^2[J_1^2(\beta) + Y_1^2(\beta)]}$$

Eqn. 17

Where J_0, J_1 ,Y_0 ,$Y_1$are Bessel functions of the first and second kind.

References:

[1] H.S. Carslaw, J.C. Jaeger, Conduction of Heat in Solid, Oxford University Press, Oxford, 1959

[2] Ingersoll, L.R. and H.J. Plass. 1948. Theory of the Ground Pipe Heat Source for the Heat Pump. Heating, Piping & Air Conditioning. July. pp. 119-122.

[3] Hellström, G. 1991. Ground Heat Storage. Thermal Analysis of Duct Storage Systems: Part I Theory. University of Lund, Department of Mathematical Physics. Lund, Sweden

[4] Gehlin, S., 1998. Thermal Response Test, In-Situ Measurements of Thermal Properties in Hard Rock. Licentiate Thesis, Luleå University of Technology, Department of

Environmental Engineering, Division of Water Resources Engineering. 1998:37. 41 pp.
[5] Deerman, J. D., Kavanaugh, S. P. 1991. “Simulation of Vertical U-Tube Ground Coupled Heat Pump Systems Using the Cylindrical Heat Source Solution”. ASHRAE Transactions 97(1): 287-295.
[6] Kavanaugh, S.P. 1985. Simulation and experimental verification of vertical ground coupled heat pump systems. Ph.D. dissertation. Stillwater, Oklahoma: Oklahoma State University.
[7] Kavanaugh, S. P., K. Rafferty. 1997. Ground Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

2.2.3 Finite line-source model for borehole heat exchangers

In the surroundings of the borehole, the infinite line source model for sufficiently large times predicts the following dependence for the ground temperature as a function of time and radial distance to the line-source:

$$T(r,t) = T_0 - \frac{Q_z}{4\pi\lambda} Ei\left(-\frac{r^2}{4\alpha t}\right)$$
$$\approx \frac{Q_z}{4\pi\lambda}\left\{\ln\frac{4\alpha t}{r^2} - \gamma + O\left(\frac{r^2}{4\alpha t}\right)\right\} + T_0, \qquad for\ \frac{4\alpha t}{r^2} >> 1, \qquad \textbf{Eqn. 18}$$

The function Ei(u) denotes the exponential integral, γ is Euler’s constant, and T_0 is the undisturbed ground temperature.

The Finite Line-Source model considers heat flow along the vertical z axis with a constant temperature gradient k_{geo} in the semi-infinite region, and a variable ground surface temperature, $\Psi(t)$ .The heat is released at a constant rate along the Borehole Heat Exchanger (BHE), and is transferred by thermal conduction. The equation of heat diffusion is invariant under spatial rotation about the z-axis of the vertical BHE. The subsurface temperature, T, is governed by the heat conduction equation

$$C\frac{\partial T(\vec{r}_\perp, z, t)}{\partial t} = \lambda \Delta T(\vec{r}_\perp, z, t) + Q_z \delta(\vec{r}_\perp)(\theta(z) - \theta(z-H)), \quad for\ t \geq 0,\ z$$

Eqn. 19

where coordinate vector $\vec{r}_\perp$ is orthogonal to z axis, Q_z is the heat flux density per length of the BHE of radius r_b, and $\Theta(z)$ is the unit step function; that is zero for $z<0$, unit for $z>0$. The initial condition,

$$T(z, t=0) = T_0 + \nabla_z T_{geo} z$$

Eqn. 20

reflects natural heat flow; the constant $k_{geo} = \nabla_z T_{geo}$ denotes the geothermal gradient. The boundary condition on the surface,

$$T(z=0, t) = \psi(t)$$

Eqn. 21

accounts for the ambient temperature variation with time on the upper part of the BHE.

The solution of this equation for the ground temperature shows dependence with z coordinate. Then, as only two measures are available from a thermal response test (the inlet and outlet temperature of the heat-carrier fluid as a function of time), the analysis procedure arrives at the question of what is the right comparison between these two measures of fluid temperatures and ground modelled temperatures which depend on spatial coordinates. Different approaches are followed in the literature, as comparing the average fluid temperature with the ground temperature at the mid-depth of the borehole heat exchanger, or comparing it with the average ground temperature in the neighbourhood of the heat exchangers.

The comparison with the average ground temperature seems to be the most appropriate one. The approximate expressions for this quantity for the intermediate and long-time intervals for the heat conduction problem $r \geq r_b$, are the following ones:

$$T(r,t) = T_0 + \frac{Q_z}{4\pi\lambda}\frac{1}{2}\begin{cases} -\gamma + \ln\dfrac{4\alpha t}{r^2} - \dfrac{3}{\sqrt{\pi}}\dfrac{\sqrt{4t}}{\sqrt{t_z}} + \dfrac{3r}{H} - \dfrac{3}{\sqrt{\pi}}\dfrac{r^2}{H^2}\dfrac{\sqrt{t_z}}{\sqrt{4t}} & (a) \\ -2 - 2\ln\dfrac{r}{H} + 3\dfrac{r}{H} - \dfrac{t_z^{3/2}}{12\sqrt{\pi}\, t^{3/2}} & (b) \end{cases}$$

Eqn. 22

where equation. Eqn. 22a is valid for time values $5r^2/\alpha \leq t \leq H^2/(\alpha m)$ (in the range of the duration of standard test in situ proofs) and equation Eqn. 22b for time values $t > H^2/m\alpha$.

An estimation of the ground heat capacity can be given in both cases (infinite line-source model and finite line-source model) with an appropriate fitting of ground temperature predictions to experimental temperature measurements. Both predictions have as parameters to be determined the undisturbed ground temperature, ground thermal conductance and thermal diffusivity. In addition, borehole thermal resistance is also a parameter to be determined when relating ground temperature with average fluid temperature.

	Description
B	Inter-borehole distance [m]
C	Volumetric heat capacity of ground, [Jm-3K-1]
$d_p \left(=\sqrt{2\alpha/\omega}\right)$	Depth of thermal penetration [m]
Ei	Exponential integral
$g(t)=\frac{2\pi\lambda}{Q_z}v(r_b,z,t)$	Extended thermal response function
H	Depth of the borehole heat exchanger [m]
$k_{geo}=\nabla_z T_{geo}$	Geothermal gradient [ºC/m]
m	Constant
r	Radial coordinate [m]
r_b	Radius of the borehole heat exchanger [m]
R_b	Borehole thermal resistance [K m/W]
$\vec{r}_\perp$	Coordinate vector orthogonal to z axis
Q_z	Heat flow per length unit [W/m]
t	Time [s]
$t_r = r_b^2/\alpha$	Short time scale for the borehole heat exchanger [s]
$t_s = H^2/9\alpha$	Eskilson steady state time scale [s]
$t_z = H^2/\alpha$	Large time scale for the borehole heat exchanger [s]
T	Temperature of ground [K or °C]
T_f	Temperature of heat carrier fluid [K or ºC]
T_0	Undisturbed ground temperature [K or ºC]
T_{in}	Inlet temperature of borehole heat exchanger [K or ºC]
T_{out}	Outlet temperature of borehole heat exchanger [K or ºC]
T_s	Amplitude of the ground temperature oscillations [K or ºC]
v_d	Contribution to temperature by the heat source [K or ºC]
v_0	Contribution to temperature by the initial conditions [K or ºC]
v_s	Contribution to temperature induced by the ground surface [K or ºC]

z	Vertical axial coordinate [m]
Greek Letters	**Description**
$\alpha = \lambda / C$	Ground thermal diffusity [m2/s]
δ	Two dimensional delta function [m-2]
γ	Euler's constant
λ	Ground thermal conductance [W/m.K]
$\psi(t)$	Ground surface temperature
$\theta(z)$	Unit step function
ω	Frequency of ambient temperature change
Superscripts	**Description**
$-$	Arithmetic mean
$< ... > (= \frac{1}{H} \int_0^H ... dz)$	Integral mean

Reference:

[1] Tatyana V. Bandos, Álvaro Montero, Esther Fernández, Juan Luis G. Santander, José María Isidro, Jezábel Pérez, Pedro J. Fernández de Córdoba, Javier Urchueguía, Finite line-source model for borehole heat exchangers: Effect of vertical temperature variations, Geothermics 38 (2009) 263-270.

[2] L. Lamarche, B. Beauchamp, A new contribution to the finite line-source model for geothermal boreholes, Energy and Buildings 39 (2007) 188-198.

2.2.4 Step pulse temperature response

So far, only the description of a single constant heat pulse of injection or extraction has been described. The following chapter shall also describe the analytical solution of the temperature response, when using several serial heat pulses. Those can be of different quantity, positive, negative or zero (injection, extraction or recovery). The total heat pulse function in time can thereby be described by a Heaviside function:

$$\dot{q}(t) = \sum_{n=1}^{N} (q_n - q_{n-1}) \cdot He(t - t_n) \qquad \textbf{Eqn. 23}$$

with $\dot{q}_0 = 0$

2.2.4.1 Estimation of the effective thermal conductance from the temperature response in the recovery period

After the execution of a regular TRT with one constant heat in- or extraction pulse the underground will regenerate. By measuring this recovery temperature response, a second result for the heat conductance can be evaluated by using Eqn. 23, where $\dot{q}_2 = -\dot{q}_1$.

$$T_{ave} - T_g \cong \frac{q}{4\pi\lambda}\left(\ln\frac{4at}{r_b^2} - \ln\frac{4a(t-t')}{r_b^2}\right) = \frac{q}{4\pi\lambda}\ln\frac{t}{(t-t')} \qquad \text{Eqn. 24}$$

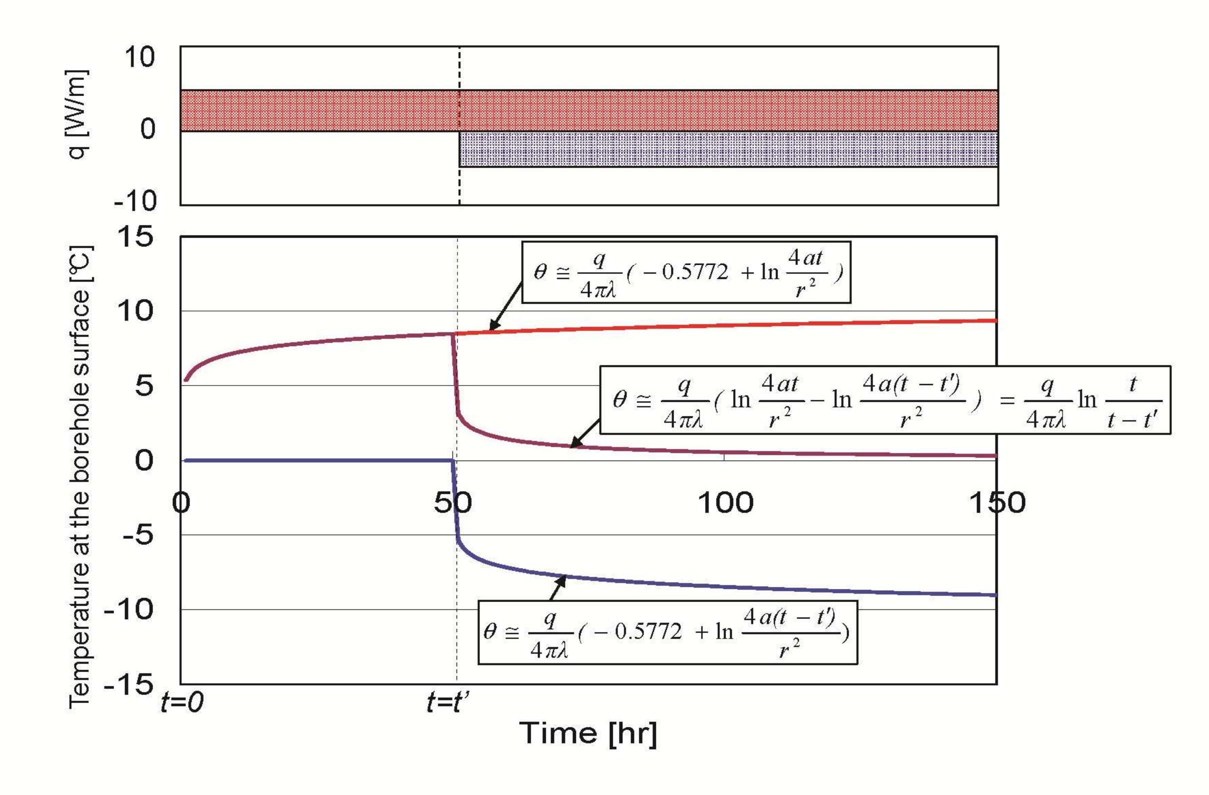


Figure 1: Illustration of the superposition of heat pulse and recovery analytical solution. (©Nagano 2010)

2.2.4.2 *Estimation of the effective thermal conductance from the temperature response of several heat pulses*

This method can generally be applied on every kind of serial constant heat pulses. Applications can be the testing of eventual differences of heat conductance for heat in- and extraction pulses of simply a higher reliability of the result for different heat pulse values.

Also, this method was already applied to evaluate test with an invalid temperature response of the first heat pulse due to incorrect test conditions (e.g. non-constant flow rate, ambience coupling, etc.). After a recovery period, a second heat injection pulse has been applied and the temperature response evaluated. This is only possible, if the heat pulses of all steps are correctly measured.

References:

[1] Eskilson, P. 1987. Thermal analysis of heat extraction boreholes. Doctoral Thesis, Lund University, Sweden.

2.2.5 *Evaluation of the temperature response*

In general, there are two ways of evaluating the temperature response of the TRT experiment. In this chapter we only refer to TRTs with one constant heat pulse of either extraction or injection. In both cases the task is to fit the analytical solution of the line source approximation to the temperature response of the measurement. As the heat capacity of the borehole components are not considered in the LSA, the free parameters are the heat conductance of the soil λs, the effective thermal borehole resistance R_b and the heat capacity of the soil c_s. As shown in chapter 2.2.6 and chapter 2.9 R_b and c_s cannot be determined at the same time. As c_s has the smaller influence on the ground temperature response, it shall be guessed.

The most common, because also the easiest, method is using the approximated solution in Eqn. 12. As can be seen, it allows separating the logarithmic time dependency in the form:

$$T_f(t) = k \cdot \ln(t) + m \qquad \textbf{Eqn. 25}$$

With

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

Eqn. 26

So the soil heat conductance λ_s can be directly determined out of the slope of the logarithm time dependency in Eqn. 25. Plotting the measured temperature response on a semi logarithmic scale (temperature vs. logarithmic of time) means doing a simple linear regression on the measurement curve.

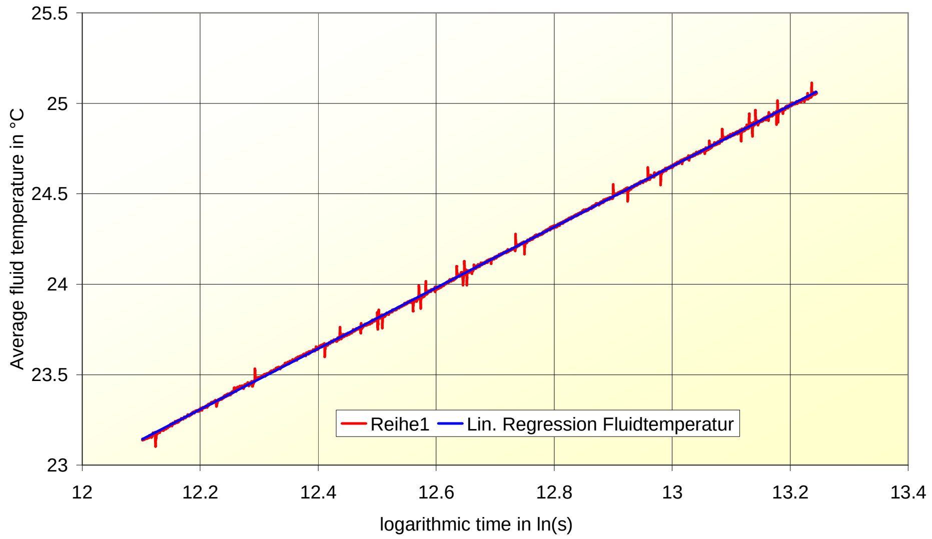


Figure 2: Linear Regression (blue) of the average fluid temperature (red) on semi logarithmic scale

Knowing the heat conductance, means the slope of the analytical solution of the LSA, one has to determine the effective thermal borehole resistance. As mentioned in chapter 2.2.1, R_b describes the temperature difference between the theoretical prediction of the analytical solution at the borehole wall, which now can be calculated using λ_s, and the mean fluid temperature.

$$T_{ave}(r_b,t) = \frac{\dot{q}}{4\pi\lambda}\left[\ln\left(\frac{4at}{r^2}\right) - \gamma\right] + \dot{q}R_b + T_g$$

Eqn. 27

$$R_b = \frac{T_{ave}(t) - T(r_b,t)}{\dot{q}} = \frac{1}{\dot{q}}\left(T_{ave}(r_b,t) - T_g\right) - \frac{1}{4\pi\lambda}\left[\ln\left(\frac{4at}{r^2}\right) - \gamma\right]$$

Eqn. 28

Or one can use the axis intercept m out of Eqn. 25:

$$m = \dot{q}\left[\frac{1}{4\pi\lambda}\left[\ln\left(\frac{4a}{r_b^2}\right) - \gamma\right] + R_b\right] + T_g$$ **Eqn. 29**

The evaluation of R_b is valid for the time period, when the measured fluid temperature response follows Eqn. 25. The definition of R_b via

$$\dot{q}R_b = \Delta T = T_{ave}(t) - T(r_b, t)$$ **Eqn. 30**

assumes a steady state with constant flow dq/dt. The heat capacity of the borehole filling and its components is neglected.

A second method to evaluate the temperature response is fitting one of the analytical solutions of the LSA, CSA or FLSA to the measured data. As with the method above, the free parameters are the undisturbed ground temperature T_g, the ground heat conductance λ_s, the specific ground heat capacity c_s and the effective thermal borehole resistance R_b. As described in chapter 2.2.6 R_b and c_s cannot be used as free parameters at the same time when evaluating a single step heat pulse, because they result both in temperature shift. For further information on parameter estimation, please also see chapter 2.3.3.

For both evaluation techniques (parameter estimation and slope determination) the choice of the correct time period for evaluation is essential. First, the chosen approximation of the solution of the heat transport must be valid, respectively the error compared to the exact LSA must be small. Further, the heat transport must reach a state, when it behaves like the approximated model (LSA, FLSA, CSA etc.). This point in time, also called "minimum time criteria", cannot be predicted analytically. The determination of the evaluation period, and thereby the needed test duration is described in chapter 2.4.

Advanced methods to this chapter can also be found at chapter 2.4 “Convergence of the result” and chapter 2.8.6 “Drift and Conditional Estimation”.

2.2.6 Sensitivity analyses of input parameters

All evaluation methods have in common that they need different input values. There are used measurement values as well as guessed values to fit the free parameters to the temperature response. The following chapter should discuss the importance of each of these values and their influence on the precision of the evaluation.

A detailed discussion of the measurement and evaluation accuracies and the effect on the final result can be found at Witte (see Appendix I).

This chapter shall outline the influence and the importance of measured and guessed values, and should show the connection between result values.

2.2.6.1 Measured values

Undisturbed ground temperature

Is measured prior to the test by purging the heat exchanger fluid or by data loggers lowered in the pipes. The vertical profile of the undisturbed ground temperature, and thereby its average, is dependent from the season of the year. As the numerical and analytical solutions of the temperature response is added to the undisturbed ground temperature, the influence of an error in the temperature response results in a temperature shift. Thereby, it has the same kind influence as the borehole thermal resistance R_b, discussed below (see chapter 2.2.6.3). This means, a too high undisturbed ground temperature will result in a smaller R_b, and vice versa.

Power input and effective borehole lengths

The effective power input must be calculated for the in- and output of the fluid in the vertical heat exchanger at the ground surface level to exclude thermal coupling to the ambience, following the equation

$$\dot{Q} = \frac{\dot{m}}{\rho} \cdot c_p \cdot (T_{in} - T_{out})$$

Eqn. 31

The power input dQ/dt results, together with the thermally active borehole lengths H, in the specific injection/extraction power dq/dt. As can be seen in Eqn. 12, die evaluation of λ_s is directly proportional to dq/dt.

$$\lambda \propto \dot{q}$$

Eqn. 32

Thereby, the error of dq/dt is dependent of the precision of the mass flow measurement dm/dt and the relative precision of the fluid temperature measurement. As shown in Appendix I, density and specific heat capacity of the heat carrier fluid must be considered as a function of the fluid temperature.

Bandos and Montero showed a method to take ambient couplings into account [2] (see also chapter 2.8.5)

For the input of a correct value of H, one must determine thermally active lengths of the heat exchanger. This is not identical with the depth of the borehole or the lengths of the heat exchanger pipes. Also an eventually built in weight at the bottom of the heat exchanger should be considered. For open boreholes one has also to consider the ground water level and the position of the injection pipes.

Borehole radius r_b

R_b and r_b should be considered as a pair. As R_b is defined as the temperature difference between average fluid temperature and the calculated temperature at the borehole wall, the borehole radius r_b will influence R_b, according to the solution of the LSA (bzw. Description of the heat transport in the ground)

Average fluid temperature

Using the arithmetic average of the fluid inlet and outlet temperature at the ground surface level is a rather rough estimate of the complex development of the fluid temperature along the borehole length. Considering the influence on the λ value, this estimate is valid if the temperature change in time is behaving like the actual in-depth average of the fluid temperature insides the pipes. Marcotte and Pasquier [1] suggest a method how to give a better estimate of the average fluid temperature.

References:

[1] D. Marcotte, P. Pasquier, On the estimation of thermal resistance in borehole thermal conductance test, Renewable Energy 33 (2008) 2407-2415.

[2] Tatyana V. Bandos, Álvaro Montero, Pedro Fernández de Córdoba, Javier Urchueguía, Improving parameter estimates obtained from thermal response tests: effect of ambient temperature variations, Geothermics 40 (2011) 136-143.

[3] Henk J.L. Witte - "Error Analysis of Thermal Response Tests (Extended Version)", INNOSTOCK 2012 conference, Groenholland Geo-Energysystems, Valschermkade 26, 1059CD Amsterdam, Netherlands, Phone: 31-20-6159050, e-mail: henk.witte@groenholland.nl

2.2.6.2 Guess values

Some values used for the evaluation can hardly be measured and must thereby be guessed. The *specific heat capacity* c_s of the surrounding underground usually is determined by taking a look the drilling log and using table values. The value c_s is used, together with T_g, to determine the effective thermal borehole resistance R_b. That means, that for a later use of the R_b value, e.g. in a simulation, all three values c_g, T_g, and R_b should be used as a bundle, as a different guess value of c_s would also influence the R_b value.

Another guess value, that occurs usually when evaluation with numerical models is the specific heat capacity c_g. This value too, influences the R_b value as well as the ground heat conductance λ_g.

For this reason all guess values shall be mentioned the documentation of the test and its evaluation.

To get a better understanding of the intensity of the influence of the guess values, a sensitivity analyses is being showed in chapter 2.2.6.3 below, as well as in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

2.2.6.3 Free parameters (results)

For a better understanding of the influence of the resulting parameters on the temperature response is shown. The following figures show the change of the temperature curve by varying the free parameter λ_s, c_s and R_b by +-10%.

One can see, that the variation of λ_s in Figure 3 leads to a change in the slope of the logarithmic temperature response (also Figure 4), whereas the change of R_b leads to a parallel shift of the curve (see Figure 5) for bigger times. This makes clear why these two parameters can be determined out of the temperature response of a single heat pulse. Further it shows that the evaluation of R_b is directly coupled with the correct measurement of the undisturbed ground temperature T_g.

Figure 7 shows the temperature response under variation of c_s. Here too, a parallel shift temperature curve can be seen, but on a smaller scale compared to the variation of R_b. This makes clear, that R_b and c_s cannot be determined out of the temperature response of a single heat pulse. The fact that the influence of c_s is usually much smaller than the influence of R_b (depending on the power input) is the reason why c_s is used as a guess value.

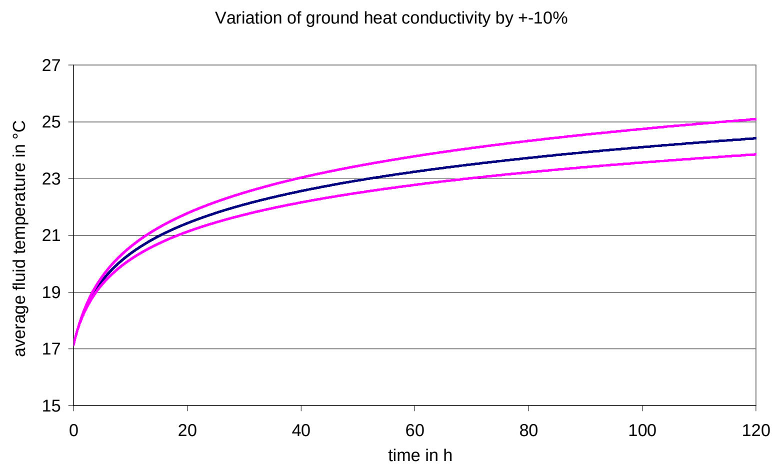


Figure 3: Change of temperature response under variation of λ_s

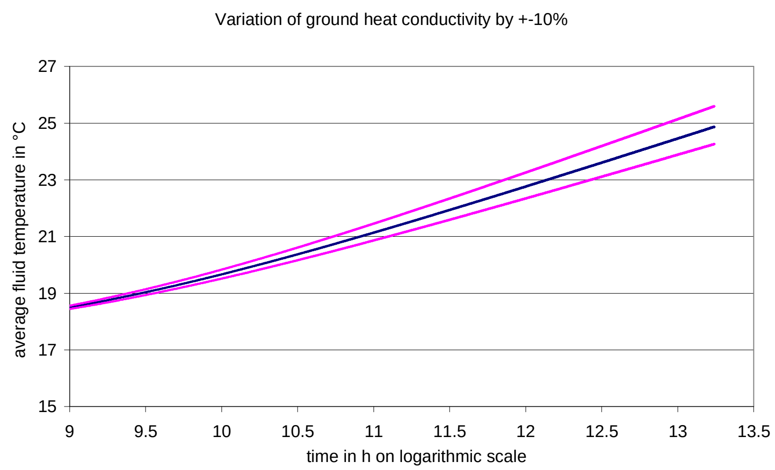


Figure 4: Change of temperature response under variation of λ_s on semi logarithmic time scale.

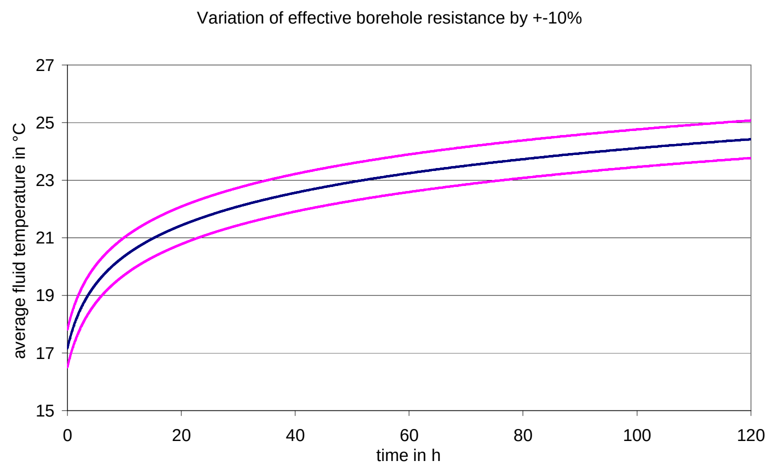


Figure 5: Change of temperature response under variation of the borehole thermal resistance R_b.

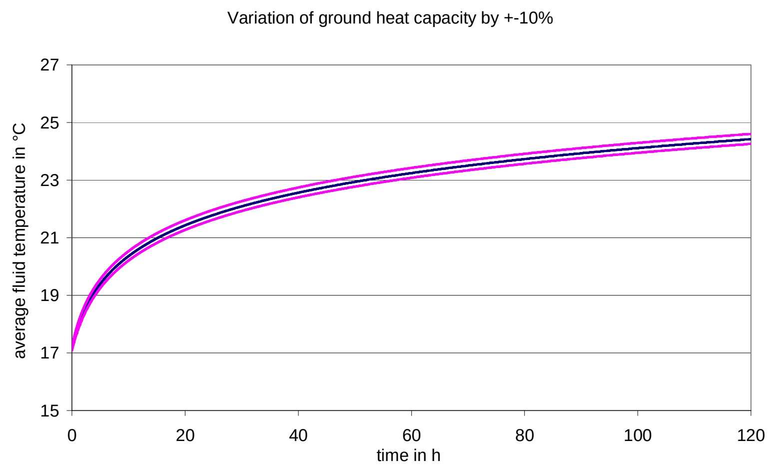


Figure 6: Change of temperature response under variation of the soil heat capacity c_g.

Another way of showing the R_b-c_g-dependency is plotting the heat capacity c_g as function of R_b or vice versa (Figure 7). The minimum and maximum are the guessed boundaries, where c_g and R_b are susbected.

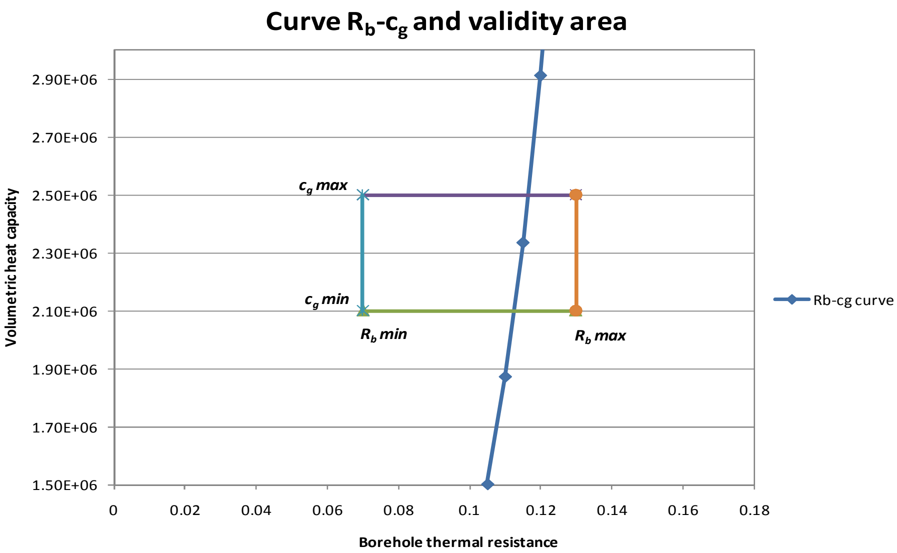


Figure 7: Influence of the correlation between heat capacity c_s and the borehole resistance R_b

2.2.7 Mathematical references

References:

[1] Carslaw, H. S. and J. C. Jaeger. 1947. Conduction of Heat in Solid. Oxford, U.K: Claremore Press.

[2] Ingersoll, L. R., O. J. Zobel, and A. C. Ingersoll. 1954. Heat conduction with engineering, geological, and other applications. New York: McGraw-Hill.

[3] Hellström, G. 1991. Ground heat storage. Thermal analysis of duct storage systems: Part I Theory. Lund, Sweden: University of Lund, Department of Mathematical Physics.

[4] GEHLIN, S. (2002). Thermal response test: method development and evaluation. Doctoral thesis / Lulea° University of Technology, 2002:39.

[5] Tatyana V. Bandos, Alvaro Montero, Esther Fernandez, Juan Luis G. Santander, Jose Maria Isidro, Jezabel Perez, Pedro J. Fernandez de Cordoba, Javier F. Urchueguia, Finite line-source model for borehole heat exchangers: effect of vertical temperature variations, Geothermics, Volume 38, Issue 2, June 2009, Pages 263-270, ISSN 0375-6505

[6] Morgensen, P, 1983: Fluid to duct wall heat transfer in duct system heat storage. Proc. Int. Conf. on Surface Heat Storage in Theory and Practice. Stockholm, Sweden, June 6 - 8 1983, 652 – 657.

[7] H. Y. Zeng, N. R. Diao, and Z. H. Fang - “A Finite Line-Source Model for Boreholes in Geothermal Heat Exchangers”, Heat Transfer - Asian Research, 31 (7), 2002

2.3 Numerical methods

The usage of numerical models for the evaluations of TRTs can have many advantages. Generally they handle any kind of power input, which allows evaluating TRTs with a more complicated test design. A more detailed modelling of the borehole and its components allows the evaluation of effects on smaller time scales and lowers the time minimum criterion. Numerical models exist, which consider heat transfer in two or three dimensions, which increases the precision compared to the infinite LSA and allows the evaluation of temperature profiles. Also the heat transfer consider in the ground is not restricted to heat conductance, but include for example ground water flow.

This chapter gives an outline how to specify the potential of numerical models by introducing "key features" in order to choose the right model for a special application. A listing of numerical models including their key features will be for download on the IEA ECES Annex21 website (**www.thermalresponsetest.org**).

For model authors there will also be the questionnaire for download. Authors of numerical models appropriate for TRT evaluation are kindly asked to provide information to the users of the website.

The key features are as follows:

FV, FE, FD:	finite volume/elements/difference
1D, 2D, 3D:	Dimensions
Ground layers:	Yes/No
CS, FLSA, ILSA:	Cylinder source, finite source, infinite source
Rec, PL, HEX:	Handling of underground recovery, power loss, (heat extraction)
STS:	short time step; with specification of the allowed minimum
GWF:	handling of ground water flow
Availability:	free/buy/none

Description of key features

a) FV, FE, FD: Gives information which kind of numerical method was chosen to describe the heat transfer

b) 1D, 2D, 3D: A two dimensional description of the processes in the borehole allow the evaluation of temperature responses within small time scales, and decrease thereby the minimum time criterion. This can shorten the test duration and give more precision to test design with non-constant power input. Three dimensional models can also consider the finite length of the borehole heat exchanger or couplings to the ambiance.

c) Ground layers: The model considers also the presence of several ground layers with different thermal properties. This is of special interest if an in-depth evaluation is wanted.

d) CS, FLSA, ILSA: For a shallow borehole depth, the usage of the infinite LSA might be impropriate or will lead to smaller precisions.

e) Rec, PL, HEX: The handling of non-constant power pulses should be self-evident for numerical models. Nevertheless, because of programming issues negative or zero power pulses might be a problem.

f) STS: Is resulting out of a), b) and d). As a rough guide one can say that a model with higher precision, especially near and inside the borehole, allow the correct evaluation of changes on a smaller time scale.

g) GWF: Very important feature if natural ground water flow is too high to handle as an effective conductive value. Correlates with c).

2.3.1 Model reference and key features

[1] Allen, J.R. (1920): Theory of Heat Loss from Pipe Buried in the Ground. - Journal ASHVE 26, 455-469 and 588-596

[2] Brehm, D.R. (1989): Entwicklung, Validierung und Anwendung eines dreidimensionalen, strömungsgekoppelten finite Differenzen Wärmetransportmodells. - Giessener Geologische Schriften 43, 120 p.

[3] Claesson, J. & Eskilson, P. (1988): PC Design Model for Heat Extraction Boreholes. - Proc. 4th Int. Conf. Energy Storage JIGASTOCK 88, 135-137

[4] Claesson, J., Eskilson, P. & Hellström, G. (1990): PC Design Model for Heat Extraction Boreholes. - Proc. 3rd WS on SAHPGCS Göteborg, CIT. 1990:3, 99-102

[5] Claesson, J. (1991): PC Design Model for Thermally Interacting Deep Ground Heat Exchang-ers. - IEA Heat Pump Centre report HPC-WR-8, 95-104

[6] Eskilson, P. (1987): Thermal Analysis of Heat Extraction Boreholes. - 264 p., PhD-thesis Lund-MPh-87/13, Lund University of Technology

[7] Eskilson, P. & Claesson, J. (1988): Simulation Model for thermally interacting heat extraction boreholes. - Numerical Heat Transfer 13, 149-165

[8] Eugster, W.J. (1991): Erdwärmesonden - Funktionsweise und Wechselwirkungen mit dem geologischen Untergrund, Feldmessungen und Modellsimulation. - PhD-thesis ETH-9524, Zürich University of Technology

[9] Gilby, D.J. & Hopkirk, R.J. (1985): McTrad-2D, a multiple coordinate computer code for calculation of transport by diffusion in two dimensions. - Nagra Technische Berichte NTB 85-37, Nagra, Baden

[10] Guernsey, E.N., Betz, P.L. & Skan, N.H. (1949): Earth as a heat source and storage medium for the heat pump. - ASHVE Trans. 55,321-344

[11] Hellström, G. (1991): PC-Modelle zur Erdsondenauslegung. - IZW Bericht 3/91, 229-238

[12] Hellström, G. & Sanner, B. (1994): Software for dimensioning of deep boreholes for heat extraction. - Proc. 6th Int. Conf. Energy Storage CALORSTOCK 94, 195-202

[13] Hellström, G., Sanner, B., Klugescheid, M., Gonka, T. & Mårtensson, S. (1997): Experiences with the borehole heat exchanger software EED. - Proc. 7th Int. Conf. Energy Storage MEGASTOCK 97, 247-252

[14] Huber, A. & Schuler, O. (1997): Programm-Modul EWS. - IZW-Bericht 2/97, 213-218

[15] Ingersoll, L.R., Zobel, O.J. & Ingersoll, A.C. (1948): Heat conduction with engineering and geological application. - 278 p., McGraw-Hill, New York

[16] Ingersoll, L.R. & Plass, H.J. (1948): Theory of the ground pipe source for the heat pump. -ASHVE Trans. 54, 339-348

[17] Ingersoll, L. R., Adler, F.T., Plass, H.J. & Ingersoll, A.C. (1950): Theory of earth heat exchangers for the heat pump. - ASHVE Trans. 56, 167-188

[18] Kavanaugh, S.P. (1984): Simulation and experimental verification of vertical ground-couple heat pump systems - Ph.D. Dissertation, Oklahoma State University, Stillwater, Oklahoma.

[19] Kavanaugh, S.P. & Rafferty, K. (1997): Ground-Source Heat Pumps - Design of Geothermal Systems for Commercial and Institutional Buildings - American Society of Heating, Refriger-ating, and Air-Conditioning Engineers (ASHRAE), Atlanta GA.

[20] Morrison, A. (2000): GS2000 Software TM. - Proceedings of the Fourth International Heat Pumps in Cold Climates Conference, Aylmer, Québec. August 17-18, 2000

[21] Pahud, D. & Hellström, G. (1996): The New Duct Ground Heat Model for TRNSYS. - Proc. Eurotherm Seminar 49, Eindhoven, 127-136

[22] Penrod, E.B. (1954): Sizing Earth Heat Pumps. - Refrigerating Engineering 62/4, 57-61+108

[23] Phetteplace, G. & Sullivan, W. (1998). Performance of a Hybrid Ground-Coupled Heat Pump System. -Transactions of the American Society of Heating, Refrigerating, and Air-Condi-tioning Engineers (ASHRAE), V. 104, Part 1, paper SF-98-1-1, Winter 1998 ASHRAE meeting, 17-21 January 1998, San Francisco, CA

[24] Sanner, B., Hellström, G. (1996): "Earth Energy Designer", eine Software zur Berechnung von Erdwärmesondenanlagen. - Proc. 4. Geothermische Fachtagung Konstanz, GtV, 326-333

[25] Sanner, B., Klugescheid, M. & Knoblich, K. (1996a): Numerical Modelling of Conductive and Convective Heat Transport in the Ground for UTES, with example. -Proc. Eurotherm Seminar 49, Eindhoven, 137-146

[26] Sanner, B., Klugescheid, M., Knoblich, K. & Gonka, T. (1996b): Saisonale Kältespeicherung im Erdreich. - Giessener Geologische Schriften 59, 181 p.

[27] Sanner, B., Phetteplace, G. & Hellström, G. (1999): Introduction to computer models for geothermal heat pumps. - in: Popovski, K., Lund, J.W., Gibson, D.J. & Boyd, T.L. (eds.), Small-scale electric power generation and geothermal heat pumps, S. 175-182, GHC-OIT, Klamath Falls

[28] Shonder, J.A. & Hughes, P.J. (1998): Increasing confidence in geothermal heat pump design methods. - Proc. 2nd Stockton Geothermal Conference, www.geo-journal.stockton.edu

[29] Shonder, J.A., Baxter, V., Thornton, J., & Hughes, P.J. (1999): A new comparison of vertical ground heat exchanger design methods for residential applications. -American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), SE-99-20-01, 1999 Annual meeting, Seattle WA.

[30] Shonder, J.A. (2000): Comparison of commercially available design software for closed-loop vertical ground heat exchangers. - Proceedings of the Fourth International Heat Pumps in Cold Climates Conference, Aylmer, Québec. August 17-18, 2000.

[31] Smolen, S. & Szaflik, W. (1997): Analytische Berechnungsverfahren zur Bestimmung der Temperaturverteilung im Boden für Wärmepumpen mit vertikalen Erdwärmesonden. - IZW-Bericht 2/97, 219-224

[32] Spitler, J.D. (2000): GLHEPRO - A Design Tool For Commercial Building Ground Loop Heat Exchangers. -Proceedings of the Fourth International Heat Pumps in Cold Climates Conference, Aylmer, Québec. August 17-18, 2000.

[33] Szauter, S. (1998): Untersuchungen der gegenseitigen Beeinflussung von EW-Sonden durch Grundwasserfluß bei dichter Bebauung. - 92 p., Dipl. thesis, Giessen University

[34] W. Yang, M. Shi, G. Liu, Z. Chen - "A two-region simulation model of vertical U-tube ground heat exchanger and its experimental verification" - Applied Energy 86 (2009) 2005–2012

[35] B. Beauchamp, L. Lamarche and S. Kajl - "A dynamic model of a vertical direct expansion ground heat exchanger", Department of mechanical engineering École de technologie supérieureMontréal, (Quebec), CANADA.

[36] Byoung Ohan Shim, Hikari Fujii, Cholwoo Lee - "Numerical model development to predict the performance of a borehole heat exchanger system", Korea Institute of Geoscience & Mineral Resources (KIGAM) (Republic of Korea), Kyushu University (Japan),Korea Institute of Geoscience & Mineral Resources (KIGAM) (Republic of Korea), INTERNATIONAL GEOLOGICAL CONGRESS OSLO 2008

[37] D. Mottaghy (1) and L. Dijkshoorn (2) - Implementing a new effective finite difference formulation for borehole heat exchangers into a heat transport code; (1) Geophysica Beratungsgesellschaft mbH (d.mottaghy@geophysica.de), (2) Applied Geophysics & Geothermal Energy, RWTH Aachen Geophysical Research Abstracts, Vol. 10, EGU2008-A-02169, 2008: SRef-ID: 1607-7962/gra/EGU2008-A-02169: EGU General Assembly 2008 PROCEEDINGS, Thirty-Third Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 28-30, 2008. SGP-TR-185

[38] Heyi Zeng, Nairen Diao, Zhaohong Fang * - Heat transfer analysis of boreholes in vertical ground heat exchangers The Ground Source Heat Pump Research Center, Shandong Institute of Architecture and Engineering, 47 Heping Road,Jinan 250014, ChinaInternational Journal of Heat and Mass Transfer 46 (2003) 4467–4481

[39] Zhongjian Li, Maoyu Zheng, Development of a numerical model for the simulation of vertical U-tube ground heat exchangers, Applied Thermal Engineering, Volume 29, Issues 5-6, April 2009, Pages 920-924, ISSN 1359-4311, DOI: 10.1016/j.applthermaleng.2008.04.024.

[40] P. Cui, H. Yang, Z. Fang, Numerical analysis and experimental validation of heat transfer in ground heat exchangers in alternative operation modes, Energy and Buildings, Volume 40, Issue 6, 2008, Pages 1060-1066, ISSN 0378-7788, DOI: 10.1016/j.enbuild.2007.10.005.

[41] Rottmayer, S.P., W.A. Beckman, and J.W. Mitchell. 1997. Simulation of a single vertical U-tube ground heat exchanger in an in?nite medium. ASHRAE Transactions 103~2!: 651–659.

[42] Cenk Yavuzturk - “Modeling of vertical ground loop heat Exchangers for ground source Heat pump systems”, PhD thesis, Technical University of Berlin, Germany 1988

[43] H. Y. Zeng, N. R. Diao, and Z. H. Fang - A Finite Line-Source Model for Boreholes in Geothermal Heat Exchangers The Ground Source Heat Pump Research Center, Shandong Institute of Architecture and Engineering, Jinan 250014, China Heat Transfer—Asian Research, 31 (7), 2002

[44] G. Sutton, Darin W. Nutter, and Rick J. Couvillion - A Ground Resistance for Vertical Bore Heat Exchangers With Groundwater Flow Matthew University of Arkansas, Department of Mechanical Engineering, Fayetteville, AR 72701 J. Energy Resour. Tech-

nol. -- September 2003 -- Volume 125, Issue 3, 183 (7 pages) DOI:10.1115/1.1591203

[45] Wolfram Rühaak, Peter Schätzl, Alexander Renz, Hans-Jörg G. Diersch - Numerical modeling of Geothermal Processes: Issues and Examples DHI-WASY GmbH, Waltersdorfer Strasse 105, 12526 Berlin, Germany, e-mail: w.ruehaak@dhi-wasy.de

[46] H.-J.G. Diersch, D. Bauer, W. Heidemann, W. Ruhaak, P. Schatzl, Finite element modeling of borehole heat exchanger systems: Part 2. Numerical simulation, Computers & Geosciences, In Press, Corrected Proof, Available online 18 November 2010, ISSN 0098-3004, DOI: 10.1016/j.cageo.2010.08.002.

2.3.2 Mathematical reference

References:

[1] R. Al Khoury, T.Kölbel, R.Schramedei - “Efficient numerical modelling o borehole heat exchangers” - Computers & Geosciences 36 (2010) 1301–1315

[2] L. Lamarche , B. Beauchamp - “New solutions for the short-time analysis of geothermal vertical boreholes”

2.3.3 References on parameter estimation

References:

[1] JA Nelder, R Mead - A simplex method for function minimization - - Computer J., 1965

[2] GenOpt: a generic optimization program - Wetter, Michael; Reférence Building Simulation, 7, 2001, Rio de Janeiro, Brazil, p. 601-608

[3] R. Hooke and T. A. Jeeves. ’Direct search’ solution of numerical and statistical problems. Journal of the Association for Computing Machinery, 8(2):212–229, 1961.

[4] W. A. Austin - “Development of an in situ system for measuring ground thermal properties”, Bachelor of Science Oklahoma State University Stillwater, Oklahoma 1995

[5] Shonder, J.A., and J.V. Beck. 1999. Determining effective soil formation thermal properties from field data using a parameter estimation technique. ASHRAE Transaction,105 (1): 458-466.

[6] Spitler, J.D., Yavuzturk, C., Rees, S.J., 1999. More comments on in-situ borehole thermal conductance testing. Source 12 (2), 4–6.

[7] Wagner and C. Clauser, J. - “Evaluating thermal response tests using parameter estimation for thermal conductance and thermal capacity”, Geophys. Eng. 2 (2005) 349–356

2.4 Convergence of the result

As described above, the valid time scale of an evaluation technique is dependent of the model in use (analytical or numerical). To find the right time period for evaluating the test (minimum time and test duration), one has to proof the validity of the model by reaching a convergence of the result in time.

The convergence of the result of a TRT (e.g. heat conductance) can be proofed by step wise evaluation of the test data. If the measurement data is following the predicted model of heat transfer in the underground, the result will take a constant value after a certain time. If the result does so, one can assume, that the heat transfer in the underground follows the predict evaluation model and the evaluation time is large enough to provide the statistical precision. This shall be explained on the common evaluation of a single constant power pulse with the infinite LSA, but can also be applied to numerical evaluations.

Step-wise evaluation

As we assume here an evaluation with the approximated solution of the line source method, the evaluation is done by calculating the linear regression (slope) of the average fluid temperature on the semi-logarithmic plot, which results in the soil heat conductance. Moving either the starting or the ending point in time of this regression will show a change of the result as function of these points, viz. as function of time. Figure 8 below shows all three kinds of convergence curves, which are described in the following paragraphs.

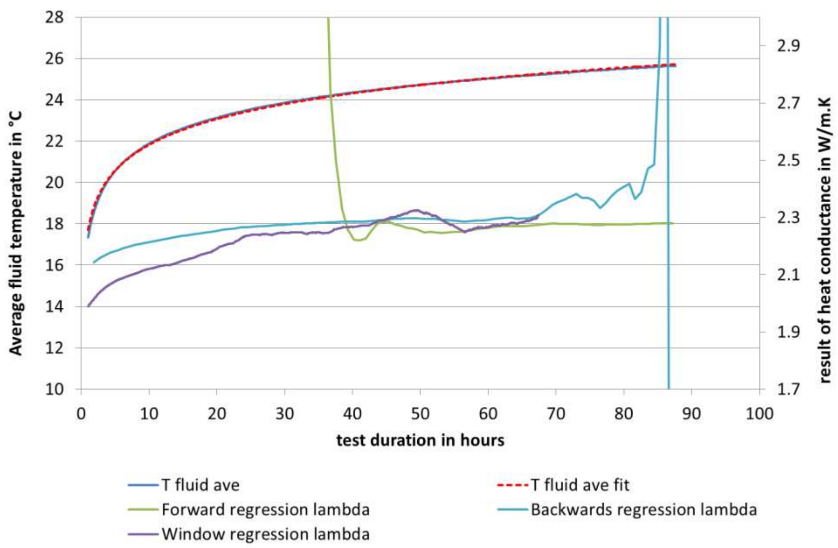


Figure 8: Behaviour of the result of the heat conductance with time by applying the forward and backward regression method as well as the moving window method.

Backward regression

We assume the ending point in time of the TRT measurement as the end point of the evaluation, viz. the logarithmic regression (Eqn. 5). The initial start point of the evaluation t_{start} is set to t = 0. This evaluation starting point is now enlarged step-wise. Each of these steps will result in a new regression and thereby to a result as function of this start point $\lambda(t_{start})$ (see blue line in Figure 9).

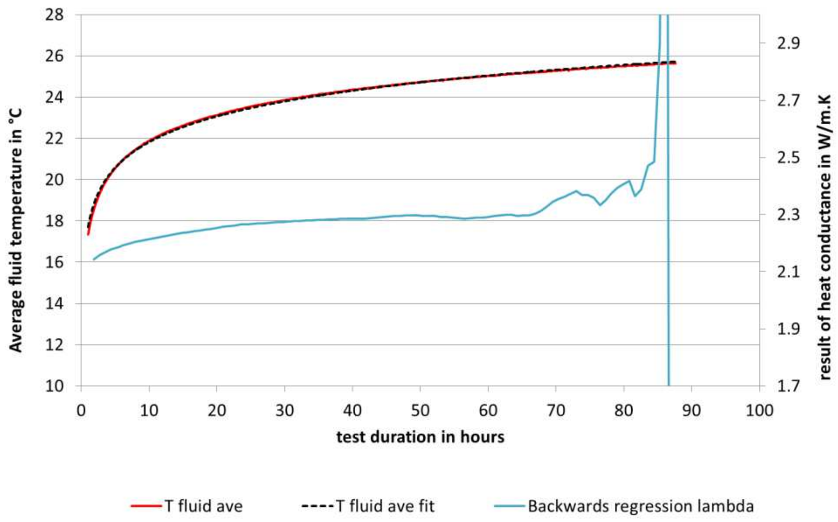


Figure 9: Behaviour of the result of the heat conductance with time by applying the backward regression method.

Forward regression

The start point in time for the evaluation shall be, how described above (see chapter 2.2.1), at the theoretical minimum time criterion of the approximated solution (for detailed numerical models this starting point can be set to zero). The first regression has to be made between this start point t_{start} and the last point of the measurement. Analogous to the backward regression, the end point of the regression is now decreased, resulting in a time dependent lambda value $\lambda(t_{end})$.

Choosing t_{start} too small (smaller than the minimum time criterion) will cause that convergence of the result will not be reached. If the minimum time criterion is not yet known (e.g. from the backward regression), the forward regression has to be applied continuously, moving t_{start} forward.

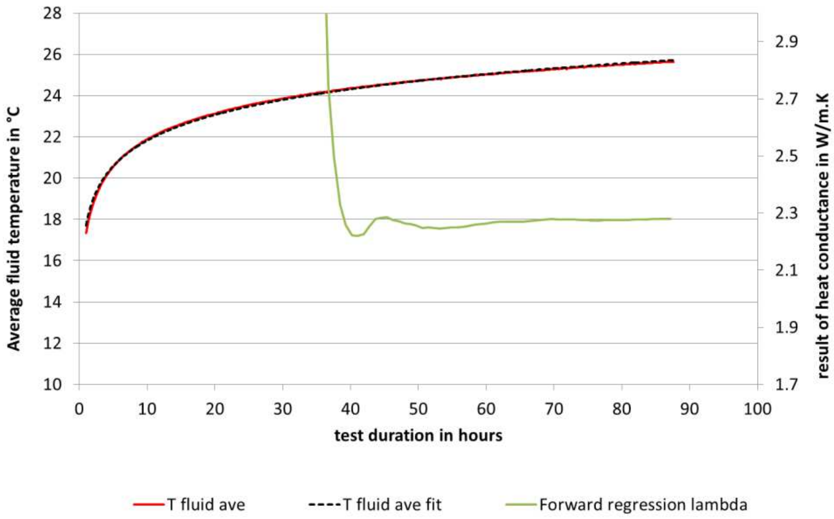


Figure 10: Behaviour of the result of the heat conductance with time by applying the forward regression method.

Convergence of the result

If the time period of evaluation is chosen correctly and the assumption of the applied solution is valid, the forward regression $\lambda(t_{start})$, as well as the backward regression $\lambda(t_{end})$ will lead to a convergence of the result in time.

That means that the regression will reach its final result value and will not change with time.

Moving window Method

An additional method of finding the evaluation period is the so called moving window method. The evaluation of the measurement data is restricted to a time frame (window) whose starting point in time is moved over the measurement period. The result of the lambda value of the time frame shall here be referenced on the start time of the evaluation frame. Figure 11 shows the convergence curve of the moving window. Due to an insufficient amount of data in the 20 hour window of evaluation, the convergence curve is fluctuating.

The Moving Window Method can identify local disturbances in time that cannot be seen directly in the measurement curve of the average fluid temperature (see Figure 12). Comparing the Moving Window convergence curve to the Forward and Backwards Regression Method can give addition hints to find the physical minimum time criterion and thereby the valid evaluation period.

The Moving Window Method alone is not capable of the finding evaluation period.

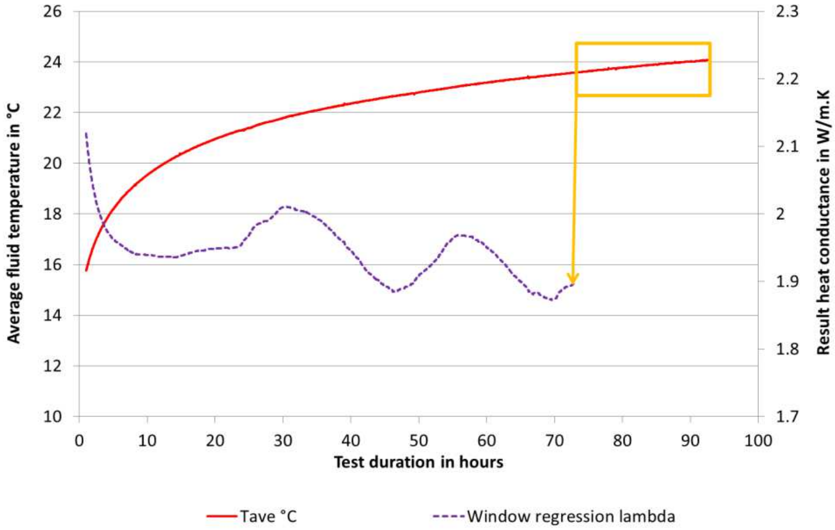


Figure 11: Sinusoidal behaviour of the moving window with decreasing character. The regression of the yellow window results in the marked point.

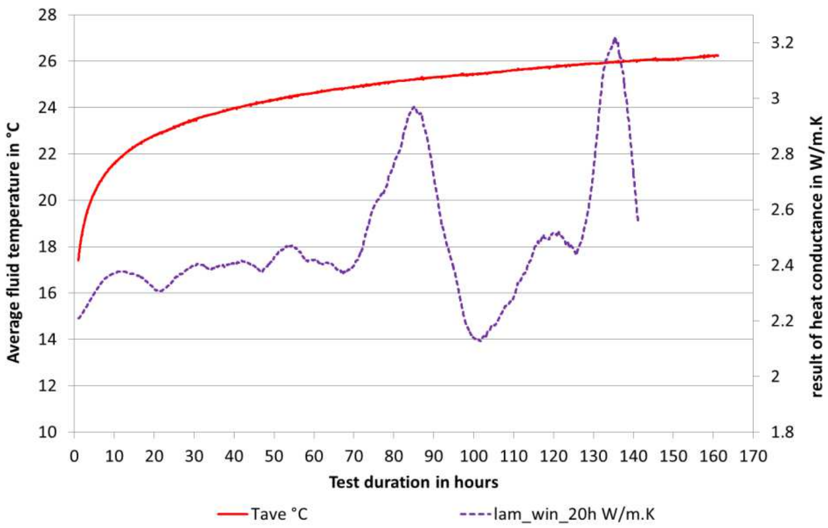


Figure 12: Determination of disturbance using the moving window method.

Interpretation

Both curves, forward and backward regression, should show the following characteristic (beginning from t_{start} respectively t_{end}). For small evaluation periods, the curves are fluctuating, due to a low statistical density (not enough measurement data). Afterwards the regression curve should reach a constant value within a defined range and for a defined duration (see convergence criteria subtask 4).

If convergence cannot be reached, one can assume, that the amount of measurement data is too small to guarantee a statistical reliable value or, the measurement data is not behaving according to the applied evaluation model. If this evaluation is made during the running test, an extension of the test duration can guarantee the statistical precision needed.

A monotone increase of the result can indicate the presence of ground water. This means, that the result obtained by applying the linear regression is dependent to the period of time which it is applied to, and by this unique. If the influence of the ground water is too strong, and so is the increase of the result in time, the applied evaluation method of the infinite LSA is invalid.

References:

[1] Tatyana V. Bandos, Álvaro Montero, Pedro Fernández de Córdoba, Javier Urchueguía, Improving parameter estimates obtained from thermal response tests: effect of ambient temperature variations, Geothermics 40 (2011) 136-143.

2.5 Power calculation

When calculating the effective thermal power injected or extracted in/from the borehole out of the temperatures measured at ground level, it is obligatory to consider the temperature dependency of the heat carrier fluid.

$$\dot{Q} = \frac{\dot{m}}{\rho(T_{ave})} \cdot c_v(T_{ave}) \cdot (T_{in} - T_{out}) \qquad \textbf{Eqn. 33}$$

Where cv is the volumetric specific heat capacity.

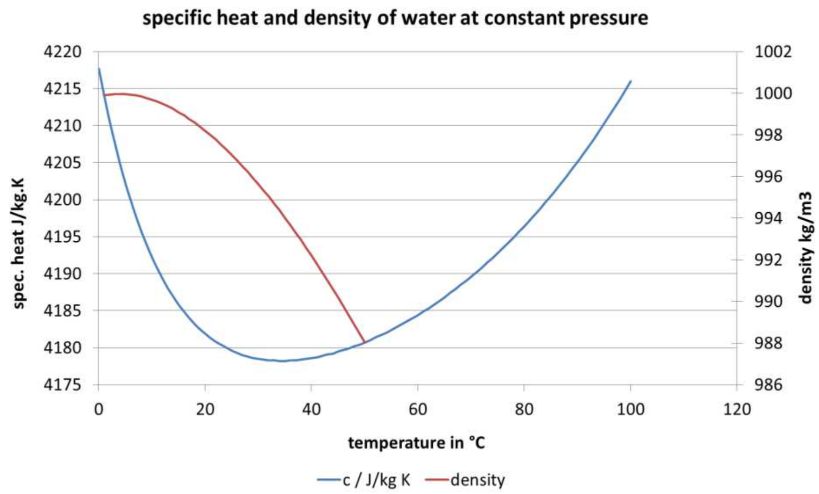


Figure 13: Temperature dependency of the specific heat capacity and density using water as heat carrier fluid.

2.6 Far field temperature

Many measurements of the undisturbed ground temperature base on purging of fluid resting in the ground heat exchanger, assuming that the fluid is in equilibrium with the underground and has thereby the same temperature. The evaluation period of the purging can either be the full or half of the piping volume or several times till it reaches a constant value.

Purging only the first half of the volume with a high temporal resolution is preferred because you do not have to take into account the electrical power input of the pump or ambient coupling.

Evaluating this first fluid circulation allows to draw rough conclusions on the temperature profile of the undisturbed ground temperature. One has to consider that even for short purging periods, heat transfer between the purged fluid and the surrounding underground occurs. There is currently ongoing research to correct the measured temperature profile by a numerical model, but there are no publications known so far.

Another aspect that has to be considered is the aspired fluid velocity. Small velocities enable a high temporal data density, but on the other side, lead to small Reynolds numbers and thereby to large fluid velocity gradients in the piping, so that errors in the temperature measurement may occur.

2.7 Effective thermal borehole resistance

The effective thermal borehole resistance is characteristic for the quality of the grouting/filling, and thereby for the quality of the thermal coupling of the fluid to the underground.

As mentioned in chapter 2.2.5 the effective borehole resistance is defined as a virtual thermal resistance between average fluid temperature at GSL and the theoretical calculated temperature at the borehole wall. Nevertheless, one can try to interpret the effective value by describing the heat transfer effects in the borehole analytically or numerically. Due to the various free parameters as location of the piping and the heat conductivity of the filling, a clear determination of the influences on the borehole resistance is not possible in most cases.

References:

[1] D. Marcotte, P. Pasquier, “On the estimation of thermal resistance in borehole thermal conductivity test”, Renewable Energy 33 (2008) 2407–2415

[2] M.H. Sharqawy et al. “Effective pipe-to-borehole thermal resistance for vertical ground heat exchangers”- Geothermics 38 (2009) 271–277

[3] Hellström, G. 1991. Ground Heat Storage. Thermal Analysis of Duct Storage Systems: Part I Theory. University of Lund, Department of Mathematical Physics. Lund, Sweden

2.8 Advanced topics of TRT evaluation

2.8.1 Effects of possible ground water influence:

Recognition, influence on result, invalidity of LSA method

The presence of any kind of ground water flow in the region thermally influenced by the thermal response test is not considered in the evaluation of a TRT regarding only heat conductance. It can change as well the direction of heat transfer in the ground as well as transport induced or extracted heat away from the borehole, so it does not contribute to the temperature raise at the borehole.

Very small influences of ground water flow can be neglected and are often referred to as a effective heat conductance. If the influence gets too big, the model assumption of a line source with only heat conductance is no more valid. In this case the result of the evaluation will not converge in time. For the convergence criteria please see chapter 2.4.

In the following different kinds of ground water and their influence on the temperature response are described.

2.8.1.1 Differentiation between types of ground water flow

- Normal" Lateral, porous media or fractured
- Convection, small scale or large scale
- Seepage / rainfall into borehole
- Thermo/pressure siphon (vertical movement)
- Rainfall and runoff (hillside)
- Drilling or nearby pumping

Effect on TRT:

- Transient conductance: higher or lower with time
- Erratic conductance
- Infinite conductance
- Lower borehole resistance (compared to theoretical)

⚐ Attention: The following effects can lead to the same influence of the temperature response, but are not related to ground water flow.

- Power drift
- Measure power, should be noticeable in data
- Ambient T/radiation effect on not well protected sensors
- Measure ambient temperature, temperature in borehole
- Sensor drift
- Calibrate
- Badly backfilled borehole: setting

2.8.1.2 Lateral, porous media (Darcy)

- Along complete interval
- In (one or more) depth intervals
- Enhanced heat transfer = larger conductance; a-typical temperature profile

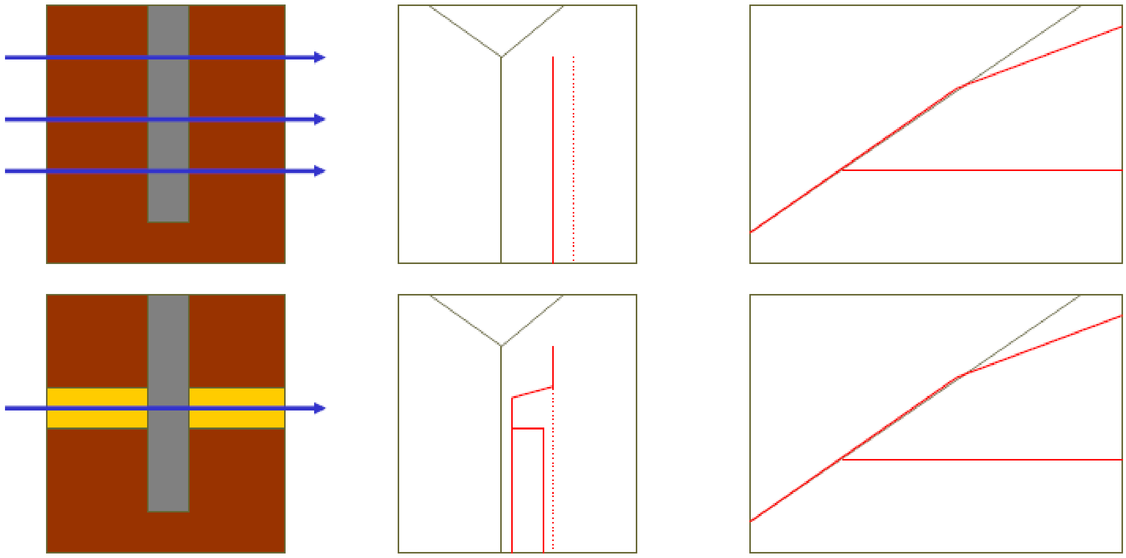


Figure 14: Schematic picture of ground water flow (gwf) type, influence on temperature profile in depth, and influence on temperature response in time

2.8.1.3 Lateral, fractured media (probabilistic) Probability that fracture hits (or not) borehole

Behaviour comparable to e.g. high hydraulic conductance layers

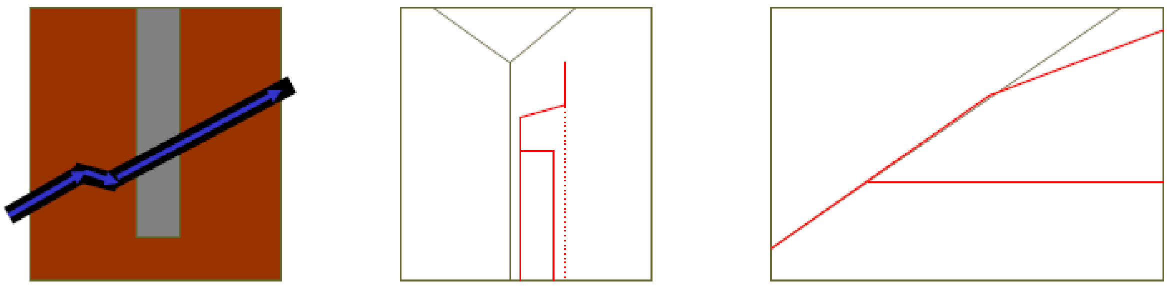


Figure 15: Schematic picture of ground water flow (gwf) type, influence on temperature profile in depth, and influence on temperature response in time

2.8.1.4 Convection, porous media

Small scale

- Mainly effect on borehole resistance, annular conductance
- Filled or open boreholes (open = porosity 100%)
- Large scale
- Increased mixing & losses, incre

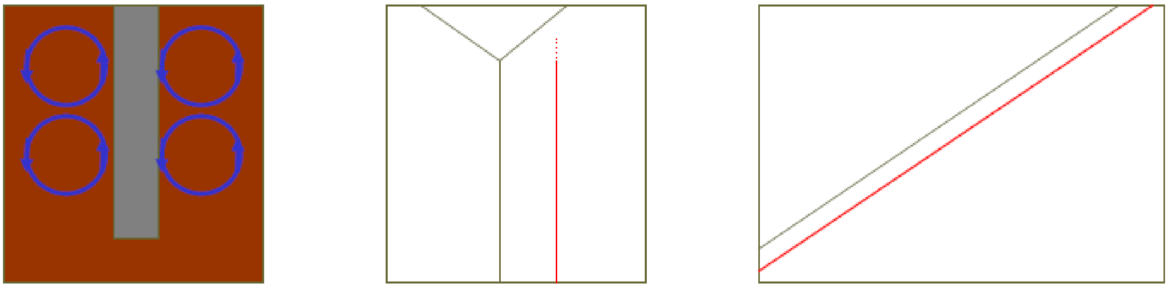


Figure 16: Schematic picture of ground water flow (gwf) type, influence on temperature profile in depth, and influence on temperature response in time

2.8.1.5 Vertical movement in borehole

- Infiltration of rainwater
- Thermo or pressure siphon (not properly sealed boreholes)
- Enhanced heat transfer = larger conductance; a-typical temperature profile
- Temperature rain

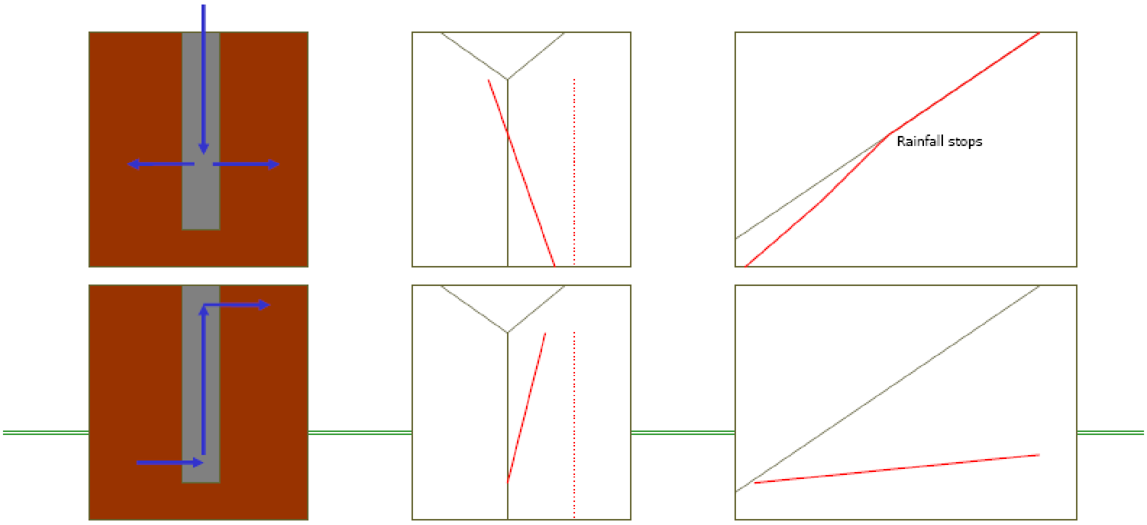


Figure 17: Schematic picture of ground water flow (gwf) type, influence on temperature profile in depth, and influence on temperature response in time

2.8.1.6 Pumping or drilling nearby

- Lowering or hightening of local water table + flow
- Temperature effect of water/air
- Erratic behaviour

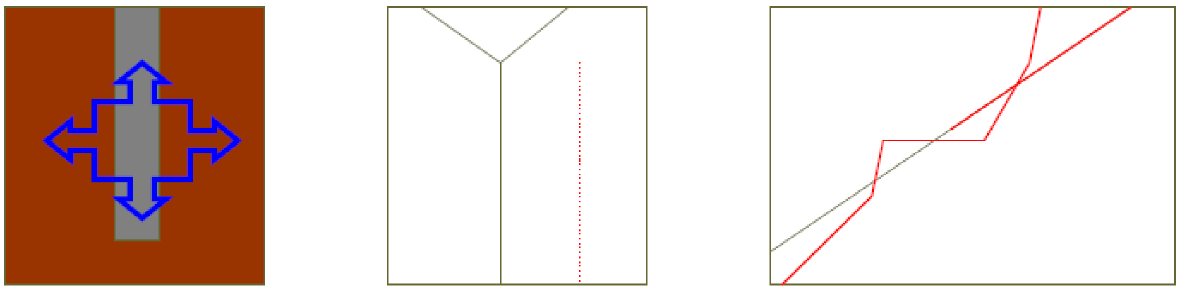


Figure 18: Schematic picture of ground water flow (gwf) type, influence on temperature profile in depth, and influence on temperature response in time

2.8.1.7 Evaluation - TRT data with regard to GW flow

- Check if ground water flow (may) occur
- Establish if estimates converge to stable estimate

- If increase with time in heat-injection: possible GW flow
- Use additional sensors to evaluate quality of data
- Ambient temperature sensor, temperature sensor borehole, power drift
- Convection may show as low R_b, transient R_b
- Use multi pulse test to obtain more information, heating and cooling combined
- Temperature profiles before & after tests: depth anomalies
- Temperature profiles during test: depth anomalies

- Inverse modelling with model using heat conduction & mass transport
- Use additional measurements (if nearby observation possible) to measure geometry of T-field

2.8.1.8 References

[1] Gelder, A.J., van. 2001. Geothermal response tests with heat extraction and heat injection: Examples of application in research and design of geothermal ground heat exhangers. Europäischer workshop über Geothermische Response Tests, EPFL, Lausanne, 25th and 26th of October 2001.
[2] Gustafsson, A.M., Westerlund, L., 2010. Multi-injection rate thermal response test in groundwater filled borehole heat exchanger. Renewable Energy 35 (5), 1061–1070.
[3] Pahud, D., 2000. Two response tests of two “identical” boreholes drilled to a depth of 160 m near Luzern. In: Proceedings of Response Test Workshop in the Framework of IEA ECES Annex 12 and 13, pp. 1–11.
[4] S. E. A. Gehlin, G. Hellstrom, Influence on thermal response test by groundwater flow in vertical fractures in hard rock, Renewable Energy, Volume 28, Issue 14, November 2003, Pages 2221-2238, ISSN 0960-1481
[5] Sarah Signorelli, Simone Bassetti, Daniel Pahud, Thomas Kohl - “Numerical evaluation of thermal response tests” Geothermics 36 (2007) 141–166
[6] Wagner, R., Clauser, C., 2002. Berechnung der Entzugsleitung einer Erdwäarmesonde: Einfluss von Diffusivität, ihrer Temperaturabhängigkeit und Grundwasserströmung. In: Eugster,W.J., Laloui, L. (Eds.), Proceedings of Workshop on Geothermische Response Tests—Tests de Résponse Géothermique. Swiss Federal Institute of Technology, Lausanne, Switzerland, October 2001, pp. 89–99.
[7] Witte, H.J.L. 2006. Geothermal Response Tests using controlled multi-power level heating and cooling pulses (MPL-HCP): Qauntifying ground warer effects on heat

transport around a borehole heat exchanger. In: Stiles (ed). The Tenth International Conference on Thermal Energy Storage, Ecostock 2006 Proceedings. May 31 - June 2, 2006, Stockton College New Jersey (USA).

[8] Witte, H.J.L., 2002. Ground thermal conductivity testing: Effects of groundwater on the estimate. Wärmetransport in der Kruste - Beiträge zur allgemeinen und angewandten 3. Kolloquium des AK Geothermik der DGG 3-4 October 2002, Aachen, Germany.

[9] Witte, H.J.L., Gelder, A.J, van & Spitler, J.D. 2002. In-situ measurement of ground thermal conductivity: The dutch perspepctive. ASHRAE Transactions, Volume 108, No. 1.

2.8.2 Step pulse solution including recovery and heat extraction

The evaluation of TRTs with multiple power input step pulses is desired for various reasons. The evaluation of power injection, extraction and recovery pulses can give hints to possible heat transfer effects other than conduction, e.g. ground water flow.

Also the application of several different heat pulses in serious is promising to enable the evaluation of the ground heat capacity. This approach is still R&A. See also chapter 2.9.
Also this test design can be applied if, for any reason, the evaluation of a single heat pulse TRT is not valid. For example due to non-constant mass flow in the ground heat exchanger. The application of the step pulse method allows the repetition of the TRT with only small waiting period. The evaluation afterwards includes the original, invalid test, the recovery phase and the repeated TRT. Figure 19 shows an example of such a test design. The evaluation can be performed with the analytical solution or numerical modelling (see chapter 2.2.4).

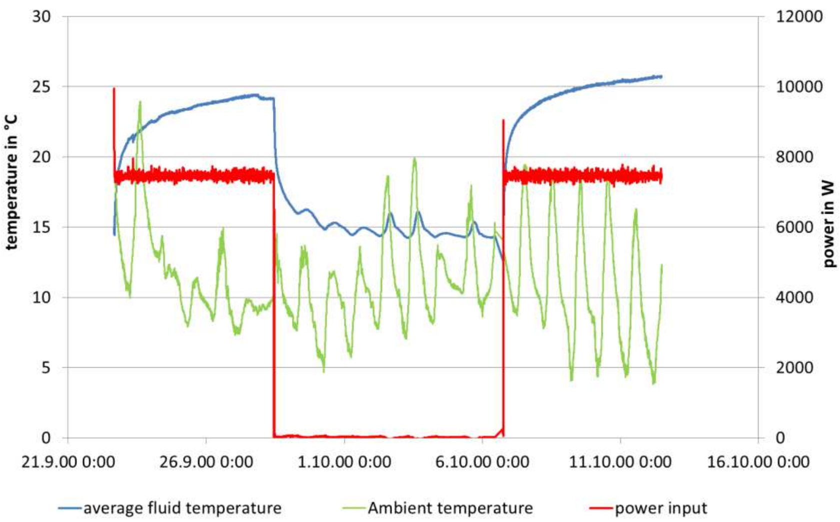


Figure 19: Repetition of an invalid test after a waiting period with recovery.

Reference:

[1] Cenk Yavuzturk - "Modeling of vertical ground loop heat Exchangers for ground source Heat pump systems", PhD thesis, Technical University of Berlin, Germany 1988
[2] H.J.L. Witte, A.J. van Gelder; Groenholland BV "Geothermal response tests using controlled multi-power level heating and cooling pulses (mpl-hcp): quantifying ground water effects on heat transport around a borehole heat exchanger "

2.8.3 Overestimation of average fluid temperature and analytical correction

Using the arithmetic average of the fluid inlet and outlet temperature at the ground surface level is a rather rough estimate of the complex development of the fluid temperature along the borehole length. Considering the influence on the λ value, this estimate is valid if the temperature change in time is behaving like the actual in-depth average of the fluid temperature insides the pipes. Marcotte and Pasquier [1] suggest a method how to give a better estimate of the average fluid temperature.

Also mentioned in chapter 2.2.6.1 "Average fluid temperature".

Reference:

[1] D. Marcotte, P. Pasquier - "On the estimation of thermal resistance in borehole thermal conductivity test", Renewable Energy 33 (2008) 2407–2415.

2.8.4 Corrections on fluctuating power

It is also possible to filter out power fluctuations produced by undesired influence of ambient temperature, although not as an analytic correction to the temperature. This filtering technique is based in using ambient temperature data to estimate its effect on fluid temperature and, then, filter out the effect [1].

Reference:

[1] Tatyana V. Bandos, Álvaro Montero, Pedro Fernández de Córdoba, Javier Urchueguía, Improving parameter estimates obtained from thermal response tests: effect of ambient temperature variations, Geothermics 40 (2011) 136-143.

[2] Beier, R. A., 2008, Equivalent Time for Interrupted Tests on Borehole Heat Exchangers, International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research, Vol. 14, No. 3, pp. 489-505.
[3] Beier, R. A. and Smith, M. D., 2005, Interrupted In-Situ Tests on Vertical Boreholes, ASHRAE Transactions Vol. 111, Part 1, pp. 702-713.
[4] Beier, R. A. and Smith, M. D., 2003, Minimum Duration of In-Situ Tests on Vertical Boreholes, ASHRAE Transactions Vol. 109, Part 2, pp. 475-486.
[5] Beier, R. A. and Smith, M. D., 2003, Removing Variable Heat Rate Effects from Borehole Tests, ASHRAE Transactions Vol. 109, Part 2, pp. 463-474.

2.8.5 Heat loss correction

This chapter is related closely to chapter 2.8.4 “Fluctuating power input”. If the power losses to the ambiance can be measured, the problem reduces to the evaluation of the non-constant power input.

For tests with bad insulation of the piping or without temperature sensors in the fluid pipes at GSL, one can also try to estimate the power losses to the ambient, also this is not advised.

Since the thermal response test is performed on a single well the theoretical model used in the data evaluation does not consider interactions between wells, assumes constant injection/extraction power and does not take into account the coupling of the measuring system with the environment. The main sources contributing to the coupling are:

a) Natural fluctuations in the electricity grid affecting the power supplied to the heaters and

b) Although thermally isolated, the heat exchange between different sections of the hydraulic circuit with the environment. These interactions cannot be avoided completely as evidenced by the experimental data but a simple energy balance model can help understand the phenomenon.

PROPOSED MODEL

For simplicity let’s consider the measuring system as composed of three main subsystems: hydraulics (TRT), connection pipes to BHE and the BHE itself as depicted in figure 1.

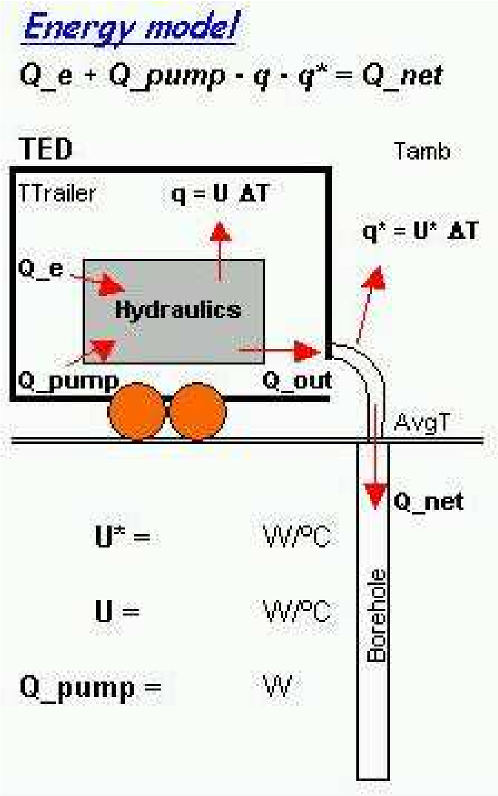


Figure 1.- System components used in the energy model

Using a simplified energy model leads to the following energy balance equation:

$$Q_{\_net} = Q_{\_e} + Q_{\_pump} - q - q^{*}$$ **Eqn. 34**

Where:

$Q_{\_net}$. rate of energy input to the BHE (Watts).

$Q_{\_e}$: rate of energy input to the heat carrying fluid supplied by the electric heaters (Watts).

$Q_{\_pump}$: energy contribution from pump and friction in the hydraulic circuit (Watts).

q : rate of system heat loss to the surroundings inside the trailer/housing cabinet (Watts).

q* : rate of system heat loss to the exterior ambient (Watts).

Assuming the hydraulics is at a temperature equal to the average temperature of the heat carrying fluid determined at its inlet and outlet points thus the rate of heat loss inside the trailer/housing cabinet can be express as:

$$q = U\,(T_{f\_av} - T_{in}) = U\,\Delta T \qquad \textbf{Eqn. 35}$$

T_{f_av} **:** Average fluid temperature at the outlet points of the trailer/housing cabinet (ºC).

T_{in} **:** Ambient temperature inside trailer (ºC).

U : System overall heat transfer coefficient (W/ºK)

Similarly, **q*** can be expressed by:

$$q^* : U^*\,(T^*f_{\_av} - T_{amb}) \qquad \textbf{Eqn. 36}$$

$T^*_{f\_av}$ **:** Mean fluid temperature of the connecting hoses (ºC).

T_{amb} **:** Exterior ambient temperature (ºC).

$U`$: System overall heat transfer coefficient (W/ºK)

Therefore, the useful or thermal power delivered to the borehole is given by:

$$Q_{\_net} = Q_{\_e} + Q_{\_pump} - U\,(T_{f\_av} - T_{in}) - U^*\,(T^*_{f\_av} - T_{amb}) = Q_{th} \qquad \textbf{Eqn. 37}$$

Using the equation solution to the Line Source Model applied in data evaluation:

$$T_f(\lambda, R_b) = \frac{Q_{th}}{4.\pi.\lambda.H}\left[\ln\left(\frac{4.\lambda.t}{r^2 C}\right) - \gamma\right] + \frac{Q_{th}}{H} R_b + T_{sur} \qquad \textbf{Eqn. 38}$$

Replacing eq.[4] into eq.[5] leads to:

$$T_f = [Q_{\_e} + Q_{\_pump} - U(T_{f\_av} - T_{in}) - U^*(T^*_{f\_av} - T_{amb})]\left\{\frac{1}{4.\pi.\lambda.H}\left[\ln(\frac{4.\lambda.t}{r^2 C}) - \gamma\right] + \frac{R_b}{H}\right\} + T_{sur}$$

Eqn. 39

In this expression ***Q_pump*; *U*** and ***U**** are variables used to fit eq.[6] to the experimental data thus allowing the estimation of the thermal power contribution of the pump and the overall heat loss coefficients of the rest of the system.

CONCLUSIONS OF EXPERIMENTAL STUDY

- Long-term fluctuations exhibited by the experimental curve are mainly governed by corresponding long term fluctuations of ambient temperature and, to a lesser extent, by fluctuations of electric power supply.
- Short-term fluctuations exhibited by the experimental curve are governed by corresponding short-term fluctuations on electric power supply.
- The combined effect of fluctuations of both variables shape the curve bringing a closer resemblance to the features presented by experimental curve.

Reference:

[1] Tatyana V. Bandos, Álvaro Montero, Pedro Fernández de Córdoba, Javier Urchueguía, Improving parameter estimates obtained from thermal response tests: effect of ambient temperature variations, Geothermics 40 (2011) 136-143.
[2] Busso A., et al., “Two applications for Thermal Response Test data evaluation – Trnsys Type300 and TRT Analysis Tool”, Effstock 2009 Proceedings
[3] Busso A., “HEAT LOSS CORRECTION IN THERMAL RESPONSE TESTS”, IEA ECES Annex21, 2009. Published on www.thermalreponsetest.org

2.8.6 Drift and Conditional Estimation

The proposed drift’s method doesn’t change the general logic of calculation of ground thermal conductance, but the way of estimating b.
Given the residual model $T(t) = m(t) + Y(t)$, the expectation of temperature increments, called drift, is

$$D(t,\Delta t) = ET\ [(t+\Delta t) - T(t)] = m(t+\Delta t) - m(t) = b\ (\ln(t+\Delta t) - \ln(t))$$ **Eqn. 40**

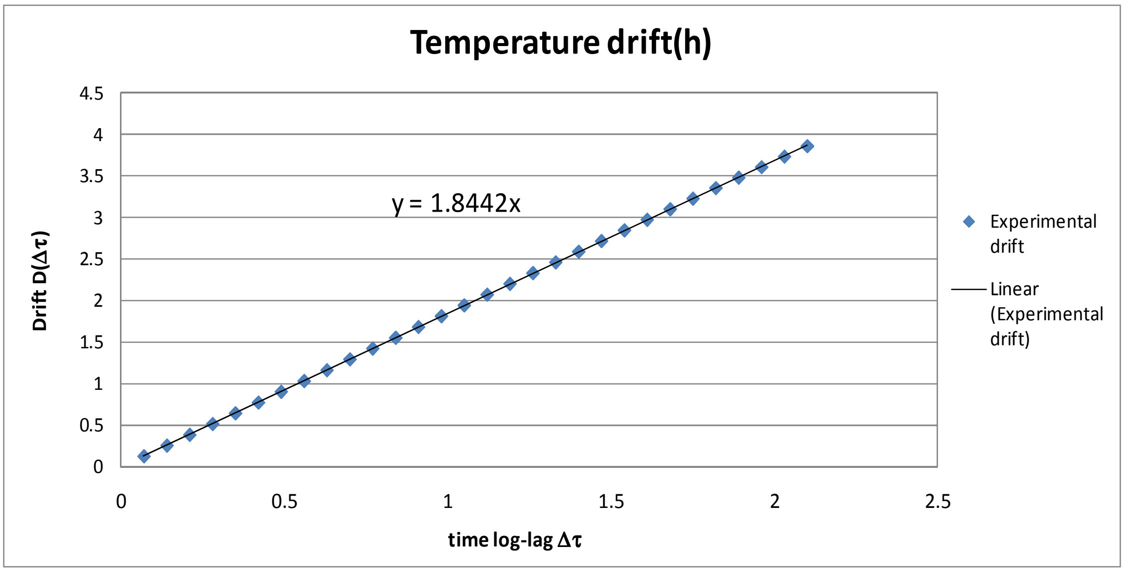


Fig. a- Linear regression on the experimental drift of temperature in the space of time-log increments

The drift method splits in two phases the estimation of parameters *b* and *a*:

- the estimation of the slope *b* by regression on the experimental drift (*Fig. a*)

$$b^D = \sum_{j=1}^{nj} \psi_j^b D^*(\Delta\tau_j)$$ **Eqn. 41**

- the estimation of the intercept *a*, conditioned by the preceding estimate, by regression on the experimental temperature

$$a^D = \sum_{j=1}^{nj} \psi_j^a T_f(t_\alpha) + \psi_0^\alpha$$ **Eqn. 42**

Once calculated λ_g it is then possible to calculate R_b. Ground volumetric heat capacity c_g can vary within a variability range, so as borehole thermal resistance, R_b, has a variability range. Realistically these two variables are independent; joint probability distribution is therefore the product of corresponding mono-variate distributions:

$$f(c_g, R_b) = f_C(c_g) f_R(R_b)$$ **Eqn. 43**

Optimality of one parameter implies other's optimality: it is therefore sufficient to consider one variable that varies along the conditioning line $\omega_1 \ln(c_g) + \omega_2 R_b + \omega_3 = 0$.

Conditioning relation reduces of one dimension bivariate law variability domain and identifies an included sub-domain of existence ($c_{g,max}$, $c_{g,min}$, $R_{b,max}$, $R_{b,min}$) of a couple of possible values for parameters based on TRT measures.

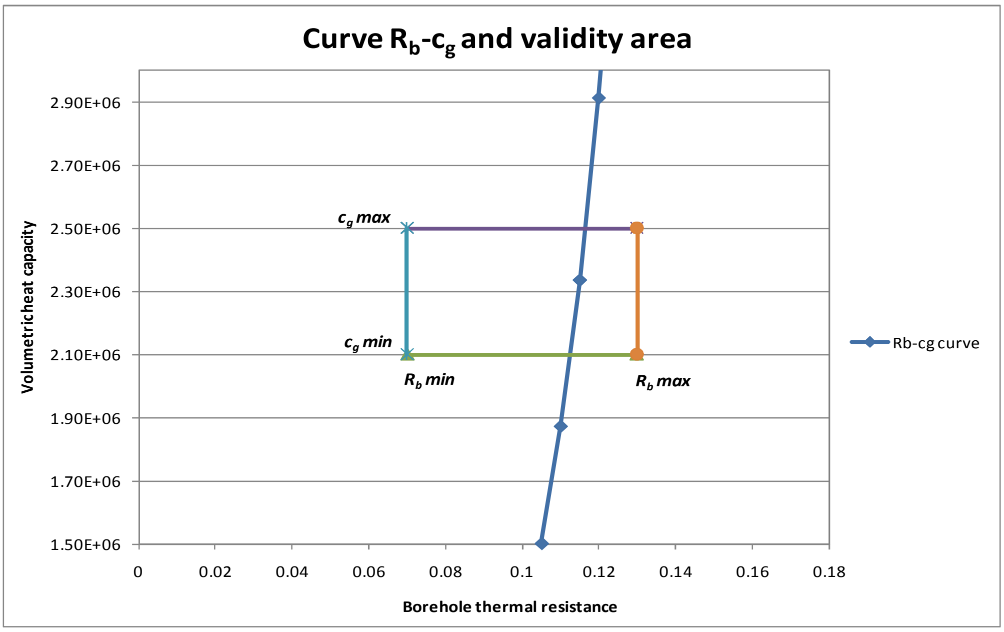


Figure 20: Curve validity area: through the intersection between the curve and the domain we obtain a smaller validity area

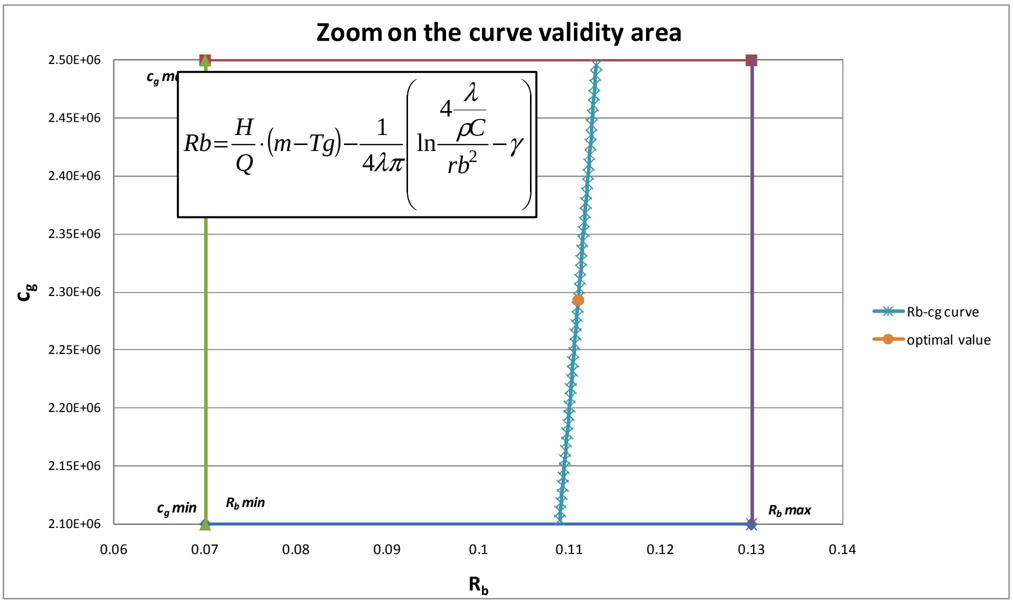


Figure 21: Zoom on the validity area of R_b-c_g curve and R_b equation

The sub-domain identifies a conditional probability distribution. Optimal value results:

$$c_{g0} = E[c \mid c, R \in L] = \int_{c_{L\min}}^{c_{L\max}} c\, f(c, R \mid c, R \in L)\, dc \qquad \textbf{Eqn. 44}$$

and by substituting it in the equation we can find R_b optimal value.

2.9 Include cg in the evaluation

This chapter is related to chapter 2.2.4 “Step pulse temperature response” and chapter 2.2.6.3.

The effect of the specific heat capacity of the ground and the effective borehole resistance R_b on a single heat pulse are hard to separate from each other. The both can be described as a parallel shift of the temperature response. Therefore it is tried to separate the effects by more complex test designs, e.g. step pulse tests, recovery periods or variable flow rates.

The subject is still handled as R&D.

Reference:

[1] Roland Wagner and Christoph Clauser - Applied Geophysics, RWTH Aachen University, Aachen, Germany; "Evaluating thermal response tests using parameter estimation for thermal conductance and thermal capacity" - 2005 J. Geophys. Eng. 2 349

2.10 Depth resolved evaluation

The depth resolved, or layer dependent, evaluation of the ground heat conduction by using TRTs is strongly connected to the measurement of temperature profiles. These can be measured during the heat pulse or while recovery phase of the ground. The knowledge of the temperature profile of the undisturbed ground is essential.

As a benefit, this technique allows higher precision in the design of GCHP systems or simply, the identification of layer with ground water flow, or simply a more detailed knowledge of the geology.

The crucial point, when using a standard TRT with fluid heating is the effect of internal heat transfer in the borehole, also known as short circuit heat transfer. This effect influences the amount of heat which is effectively injected per time in each layer / depth.

Therefore, one can basically differ between two methods:

Hot (ohmic) wire

The heating of the underground is realized by introducing an ohmic resistance heating wire in the borehole together with the ground heat exchanger. The heating wire is independent of the effect of the thermal shirt circuit, This means, it introduces a constant heating rate along the borehole, which enable the evaluation with the analytical infinite LSA. Vertical heat transfer in borehole direction is neglected due to small measurement times. Because the heat carrier fluid is not used for heating or cooling, the principle of the effective thermal borehole resistance is not applicable here, and cannot be evaluated. The measurement of temperature profile can be realized by measuring in the heat exchanger pipes or in the borehole filling, while and after the heating phase. Measurement devices are optical fibre or sensor lowering in the heat exchanger. An advantage of this method is the high resolution of the in-depth heat conductance.

Fluid heating with numerical modelling

The second method is based on the standard TRT using fluid heating/cooling. Again measurement of the temperature profile can be realized with optical fibre or sensor lowering in the heat exchanger or in the borehole filling.

Because with this method, the thermal short circuit between up- and downstream of the heat carrier fluid has to be taken into account one has to use a numerical model, which considers as well the thermal short circuit as well several ground layers. The TRT is evaluated by comparing the TRT measurement date at GSL as well the temperature response of the temperature profiles while, or after the heat pulse. By doing parameter estimation on the numerical model, using borehole resistance R_b, short circuit resistance R_a, and the heat conductance values of all layers as free parameters, the model is fitted to the measurement data.

Figure 22 shows the result of such an evaluation, comparing the measured temperature profile with the numerical model prediction. This type of evaluation results in an in-depth profile of the heat conductance.

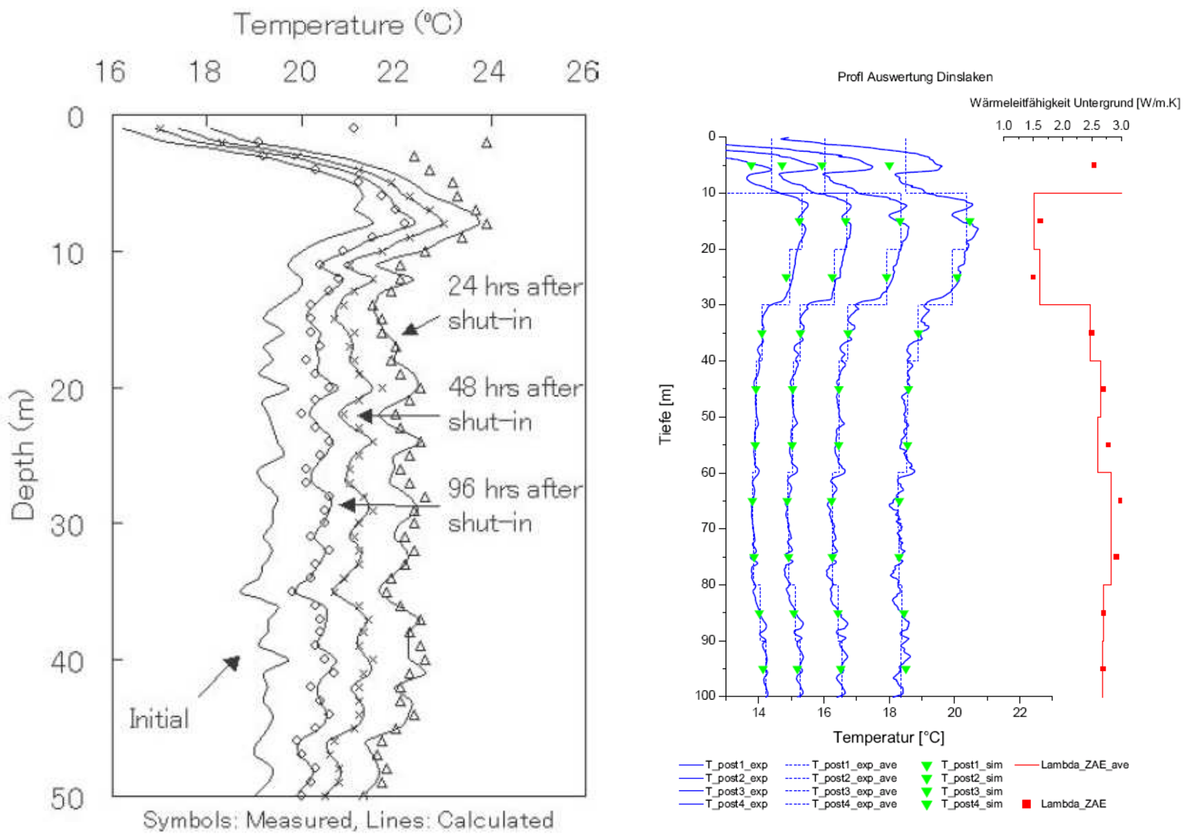


Figure 22: Two examples of an evaluation of in-depth profiles using the fluid heating method. Left: A numerical model fitted to optical fibre measurement while the heat pulse [3]. Right: A numerical model fitted to lowering sensor measurement while the recovery period [7].

Reference:

[1] Fujii, H., Okubo, H., Nishi, K., Itoi, R. Ohyama, K. and Shibata, K.,An improved thermal response test for U-tube ground heat exchanger based on optical fiber thermometers,Geothermics,Vol.38,No.4,pp.399-406,2009.12.

[2] Fujii, H., Okubo, H., Chono, M., Sasada, M., Takasugi, S. and Tateno M. , Application of Optical Fiber Thermometers in Thermal Response Tests for Detailed Geological Descriptions ,Proceedings of EFFSTOCK2009,Paper No. 21,2009.06.

[3] Fujii, H., Okubo, H., and Itoi, R.,Thermal response tests using optical fiber thermometers,Geothermal Resources Council Transactions,Vol.30, 545-551,2006.09.

[4] Signorelli S 2004 Geoscientific investigations for the use of shallow low-enthalpy systems PhD Thesis Swiss Federal Institute of Technology, Zürich

[5] Sarah Signorelli, Simone Bassetti, Daniel Pahud, Thomas Kohl - “Numerical evaluation of thermal response tests” Geothermics 36 (2007) 141–166

[6] M. Proell – “Tiefenaufgelöste Bestimmung der Wärmeleitfähigkeit bei Thermal Response Tests”, Bavarian Center for Applied Energy Research (ZAE Bayern), Division 1: Technology for Energy Systems and Renewable, Proceedings “Der Geothermiekongress 2010” Karlsruhe, 17.-19. November 2010, (german)

[7] M. Proell – "Method for layer dependent evaluation of the ground heat conductivity", Geophysical Research Abstracts, Vol. 13, EGU2011-9754, 2011, EGU General Assembly 2011

[8] M. Proell – „Vergleich verschiedener Methoden zur Bestimmung thermischer Untergrundeigenschaften",Bavarian Center for Applied Energy Research (ZAE Bayern), Division 1: Technology for Energy Systems and Renewable Energies, 2010 (german)

[9] Geowatt AG, "Messung Wärmeleitfähigkeitsprofil / Identifikation Grundwasserströmung
(Enhanced Thermal Response Test, eTRT)" , Europäisches Patent EP1959213

3. Available evaluation software for automatic evaluations

This collection of available software for TRT evaluation is the state of knowledge of the members of the Annex21 participants. There is no claim of completeness. For further software suggestions, please contact the webmaster of www.thermalresponsetest.org.

Numerical modes using parameter estimation:

- GPM [1] [2] [3]
- Type300 (TRNSYS) – Busso/Cabral [6]
- TRT Analysis Tool – Busso/Cabral [6]
- MULTISIM [8]

Analytical evaluation software:

- Ground loop design GLD [7]
- TRT Analysis Tool – Busso/Cabral [6]
- GeoLogik [4]

Reference:

[1] J. A. Shonder J. V. Beck - 2A New Method to Determine the Thermal Properties of Soil Formations from In Situ Field Tests”
[2] Shonder, J. A., and J. V. Beck. 1999. “Determining Effective Soil Formation Thermal Properties from Field Data Using a Parameter Estimation Technique.” ASHRAE Transactions 105, Pt. 1: 458–66.
[3] Beck, J. V., and J. A. Shonder. 1998. “A Parameter Estimation Technique for Determining Soil Thermal Properties in the Design of Heat Exchangers for Geothermal Heat Pumps.” In Proceedings of the ASME Heat Transfer Division, 3:221–40.
[4] T. Röhrich, GeoLogik Software GmbH, http://www.geologik.com
[5] SANNER, B., MANDS, E., SAUER, M. & GRUNDMANN, E., (2008): Thermal Response Test, a routine method to determine thermal ground properties for GSHP design. - Proc. IES Heat Pump Conference 2008, paper #4.35, 12 p., Zürich
[6] Busso A., et al., “Two applications for Thermal Response Test data evaluation – Trnsys Type300 and TRT Analysis Tool”, Effstock 2009 Proceedings
[7] Thermal Dynamics Inc. – “Ground loop design” http://www.groundloopdesign.com
[8] Poppei, Schwarz, Mattsson, Laloui, Wagner, Rohner - "Innovative Improvements of Thermal Response Test", Intermediate Report August 2006

4. Comparative evaluation of reference test data

This chapter is about the comparison of test evaluation and is divided into two parts. The first part shows the comparison of evaluation results on a good quality reference data set. The data set consists of real experimental data and information.

4.1 Different results on reference data set

City	Wels
Country	Austria
Tester	ZAE Bayern
"standard test" - single heat injection step pulse	
	SI units
Information on the borehole	
Effective depth heat exchanger [m]	150
borehole profile available [yes/no]	yes (german)
underground properties	claystone
guess value heat capacity ground (J/m^3/K)	2.20E+06
guess value heat conductance ground (W/m/K)	2.5
heat exchanger type (double-U, single-U, coaxial)	2-U
borehole diameter [m]	0.133
tube diameter / wall thickness [mm]	32 / 2.9
Information on the test	
average mass flow rate [m^3/h]	1.286
average temperature difference inlet/outlet [K]	4.83
turbulente flow [yes/no]	yes
average thermal power	7191
controlled values	power, fluid rate
measurement time step	60s constant
Information on the undisturbed ground temperature	
Tg [°C]	11.73

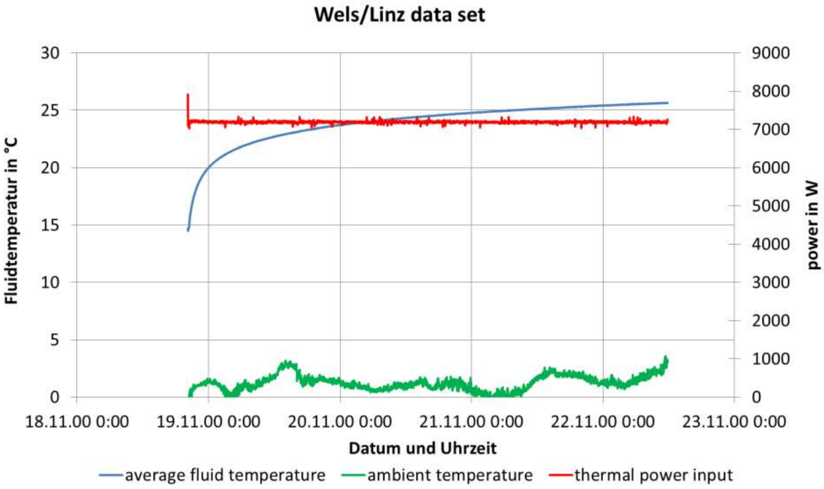


Figure 23: Diagram of the Wels TRT measurement for comparative evaluations.

Table 1: Evaluations on the Wels/Linz (AUT) data set.

	lambda W/m.K	R_b m.K/W	from h	till h
Tester 1 LSA	2.27	0.111	25	87.50
Tester 1 NUM*	2.24	0.107	0	87.50
Tester 2 LSA FIT*	2.26	0.105	0.52	87.60
Tester 3 LSA	2.18	0.106	6.14	72.00

** NUM: numerical evaluation; LSA: analytical solution with parameter estimation*

City	Ravensburg
Country	Germany
Tester	ZAE
"standard test" - single heat injection step pulse	
	SI units
Information on the borehole	
Effective depth heat exchanger [m]	193.5
borehole profile available [yes/no]	no
underground properties	sand- and claystone
guess value heat capacity ground (J/m^3/K)	2.20E+06
guess value heat heat conductance ground (W/m/K)	2.3
heat exchanger type (double-U, single-U, coaxial)	2-U
borehole diameter [m]	0.2
tube diameter / wall thickness [mm]	40/3.7
Information on the test	
average mass flow rate [m^3/h]	0.816
average temperature difference inlet/outlet [K]	5.1
turbulente flow [yes/no]	yes
average thermal power	9629
controlled values	power,fluid rate
measurement time step	60-120s not constant
Information on the undisturbed ground temperature	
Tg [°C]	14.7

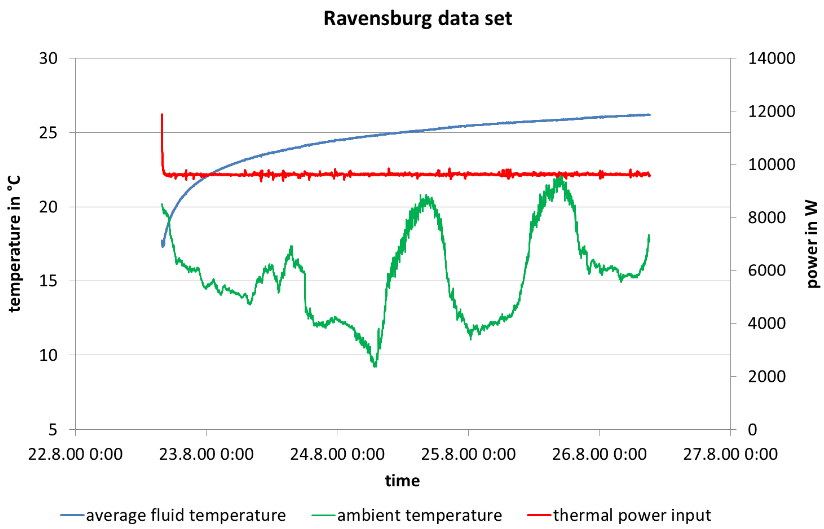


Figure 24: Diagram of the Ravensburg TRT measurement for comparative evaluations.

Table 2: Evaluations on Ravensburg (GER) data set.

	lambda W/m.K	R_b **m.K/W**
Tester 1	2.30	0.080
Tester 3	2.28	0.081

One can see that the evaluations performed by different members of the expert group are very consistent within the precision of the results. Although the evaluation periods were chosen different for the Wels data set the evaluation lead to the same result.

4.2 Times of convergence of different evaluation techniques on ref. data set

Applying convergence evaluation on a mono pulse constant power pulse test should show if and when the different techniques/models come to the same result. Also the method with fast result convergence shall be identified.

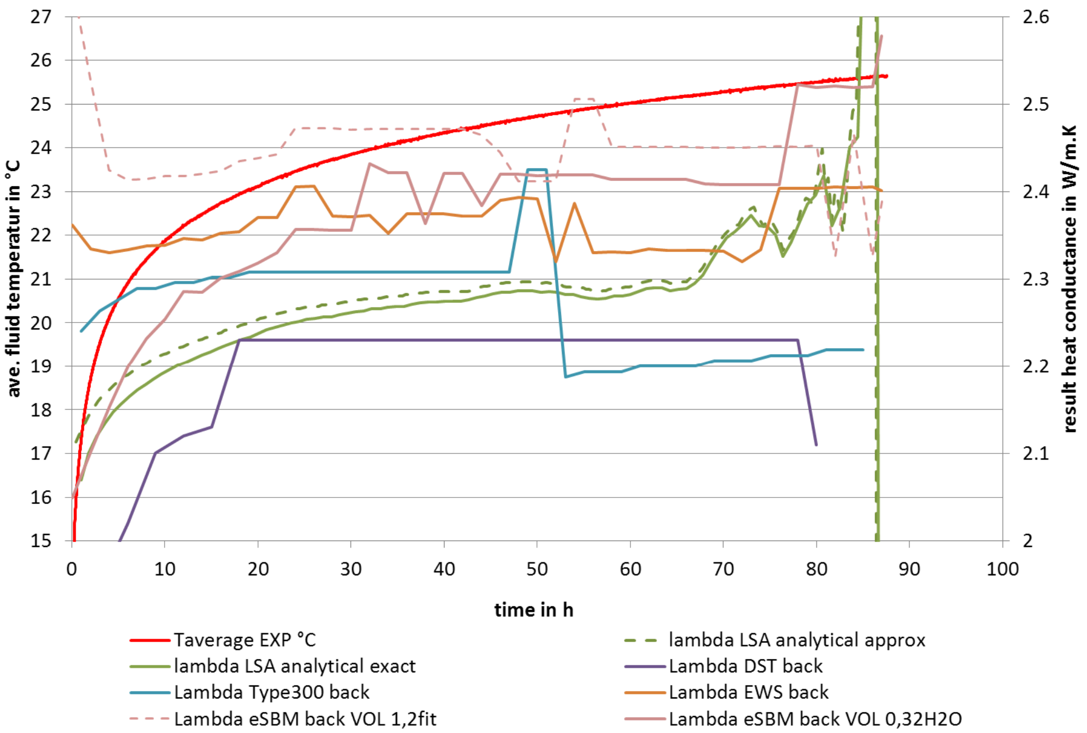


Figure 25: The results of the Backwards Regression Evaluation Method (see chapter 2.4) for different evaluation methods/models.

The compared evaluation models are:

- The exact solution of the line source approximation (see chapter 2.2.1) - *LSA analytical exact*.
- The simplified solution of the line source approximation (see chapter 2.2.1) *LSA analytical approx.*
- The TRNDSTP model [2] [3]
- The TYPE300 model by Busso et al. [1]
- The EWS single heat exchanger model by Huber Energietechnik [4]
- The Trnsys Version of SBM by Hellström [5] [6] with the enhancements for fluid (VOL H2O) and borehole capacity (VOL fit) described by Witte et al. [7] [1]

Regarding the result of the backwards regression in Figure 25 on can see a accordance of the result of the heat conductance within range of 0.25 W/m.K around an average value of 2.3 W/m.K . All numerical models show a stable convergence of the result of about 60 hours, except Type300. The convergence of the analytical evaluations show only good convergence over approx.. 20 hours, with a monotone decrease of the result for times smaller than 45 hours.

Further, there seems to be a small perturbation in the fluid temperature response at hour 50, that can be notice by naked eye. The convergence curve of Type300 show a strong reaction to this perturbation. Also the analytical solutions show small influence, as well as the Huber EWS model and the SBM VOLfit model.

Reference:

[1] Busso A., et al., “Two applications for Thermal Response Test data evaluation – Trnsys Type300 and TRT Analysis Tool”, Effstock 2009 Proceedings
[2] Pahud, D. & Hellström, G. (1996): The New Duct Ground Heat Model for TRNSYS. - Proc. Eurotherm Seminar 49, Eindhoven, 127-136
[3] PAHUD D., FROMENTIN A. & HADORN J.-C. 1996b. The Duct Ground Heat Storage Model (DST) for TRNSYS Used for the Simulation of Heat Exchanger Piles. User Manual, December 1996 Version. Internal Report. LASEN - DGC- EPFL, Switzerland.
[4] Wetter M., Huber A. (1997). Vertical borehole heat exchanger EWS Model. TRNSYS Type 451.
[5] P. Eskilson, Superposition Borehole Model, Manual for Computer Code, Department of Mathematical Physics, University of Lund, Schweden, 1986
[6] S. Holst, Type 146 TRNSBM – Modified Version for separate ground layers, TRANSSOLAR, 1997
[7] Witte H.J.L., van Gelder A.J. (2006), Geothermal response test using controlled multipower level heating and cooling pulses (MPL-HCP): quantifying ground water ef-

[1] VOL H2O: The capacity of the water in the heat exchanger is taken into consideration in addition to the SBM model. VOL fit: The heat capacity of the borehole (piping, fluid) is fitted as a free variable in the parameter estimation.

fects on heat transport around a borehole heat exchanger, Ecostock 2006, 10th int. conf. on thermal energy storage, The Richard Stockton college of New Jersey, USA.

F. SUBTASK 4

Thermal Response Test Procedure

Content Subtask

1. Background

Underground Thermal Energy Storage (UTES) is a reliable and sustainable technology for cooling and heating of buildings and industrial processes and is now wide spread across the world. In the past 30 years, various UTES applications have been constructed. During this time, the International Energy Agency (IEA) Implementing Agreement, Energy Conservation through Energy Storage (ECES), has been a platform to develop much of the expertise in UTES.

The acronym UTES refers to underground thermal energy storage in general, and is often divided into subgroups according to the type of storage medium that is used. The acronym BTES (Borehole Thermal Energy Storage) refers to storage systems using boreholes or ducts and pipes in the ground.

The thermal conductivity of the ground and thermal resistance of the borehole heat exchanger (BHE) are the two most important design parameters for BTES systems. These two parameters may be determined from in situ measurements, which then provide reliable design data. They will allow optimization of borehole spacing and depth as well as the total borehole-length related to the application.

Such tests are usually economically feasible when designing BTES systems comprising more than a few boreholes. The economics are justified by right sizing the borefield which typically has a significant upfront capital cost. Improved accuracy in the thermal response test is necessary for the optimal design of the borefield. The measurement method has rapidly developed in the last decade and is now usually referred to as Thermal Response Test or just TRT but may also be called a Formation Thermal Conductivity Test. The objective of the TRT is to evaluate the heat transfer characteristics of the borehole ground formation.

Already the completed IEA ECES Annex 8, Annex 12 and Annex 13 were to some extent concerned with Thermal Response Testing. Especially in Annex 13 the first formal guidelines for TRT were prepared. Parts of this sub-task closely follow these recommendations.

2. Basic Principle

In this measurement method, a defined thermal load is applied to a borehole heat exchanger and the measured temperature development over time is analyzed. There are basically two ways to operate the TRT equipment; to inject or extract heat into/from the tested borehole. This is done by circulating a fluid, through the borehole, that is warmer (injection) or colder (extraction) than the surrounding ground, see Figure 1. There also exists TRT equipment where both modes are available. Various TRT units have been developed in different countries. The size and shape of such equipment vary from suitcase, to caravan, to shipping containers.

The first step of the test is to determine the undisturbed ground temperature. This is usually made by temperature logging in the borehole, or by evaluating the fluid temperature of the circulating fluid before the heating/cooling is switched on.

The thermal response is the measured change in the mean temperature of the fluid's inlet and outlet temperatures over time. Uncontrolled temperature fluctuations may result from the varying ambient air temperature or corresponding fluctuations in the power supply to the electric heater and/or to the circulation pump. Air temperature and the power consumption are therefore often measured to detect and separate such disturbances in the evaluation.

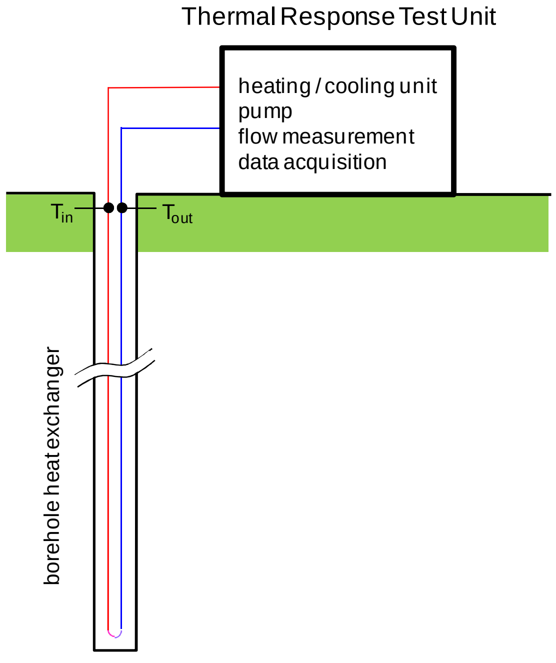


Figure 1: Thermal response test set-up.

The borehole resistance is defined as the thermal resistance between the fluid in the pipe and the boundary between the borehole and the formation. The borehole resistance is also estimated during the Thermal Response Test procedure. This parameter characterizes the construction of the BHE from the heat transfer point of view. Consequently the design of the test borehole should be the same as the final design if the measured borehole resistance is to drive the final borefield design.

3. Site Description

The TRT begins even prior to the drilling and completion of the test borehole. Information should first be gathered and reviewed prior to the initiation of the test and should typically be comprised of the following elements:

- Geographical Coordinates of the test
- Climate
  - Annual average air temperature
  - Annual average ground temperature
  - Temperature swing
  - Annual average rainfall

- Desktop study
  - A desktop study should be performed to review the local geological and hydrogeological conditions from any relevant sources in order to establish a first guess of anticipated heat transfer characteristics.

4. Test Borehole Design

The thermal response test procedure must be geared as close as possible to the operational parameters of the planned system including: borehole location, borehole depth, borehole diameter, and the borehole configuration etc. The borehole itself must be accessible with the test equipment and the necessary resources like electricity or water need to be provided reliably during the test duration.

For planning and performing a reliable Thermal Response Test to achieve an accurate evaluation, sufficient information regarding the geology, the drilling, the borehole heat exchanger and the grouting is required. It is important to compile a detailed documentation with design values, construction and completion information on the test borehole and to transfer it to the tester prior to the measurement. Correct and exact values are crucial for the quality of the resulting data.

4.1 Drilling Completion

Drilling activities have a significant impact on the TRT. It is important to record a number of parameters related to the drilling activities in order to prevent contamination of the test as well as to ensure an accurate evaluation. Typical data required are given in Table 1. Drilling contractors should be given specific instructions regarding required data collection before and during completion of the test borehole. Specific attention should be focused on the log of the geological layers with respect to depth, an example is shown in Figure 2. Identification and quantification of the type and magnitude of ground water influence is also critical. Ground water influence may make the acquisition of meaningful property measurements impossible or inadvertently skew results leading to substantial error and an incorrect borefield size.

Table 1: Drilling Completion Record

Drilling company		
Beginning of drilling work	Date / Time	
End of drilling work	Date / Time	
Data on geology (on site) in particular layer index with information on possible water entry available?		
Comments regarding geology		
Exact depth of drilling	[m]	
Exact borehole diameter	[mm]	
Volumetric heat capacity of subsoil (estimate)	[MJ/m³K]	

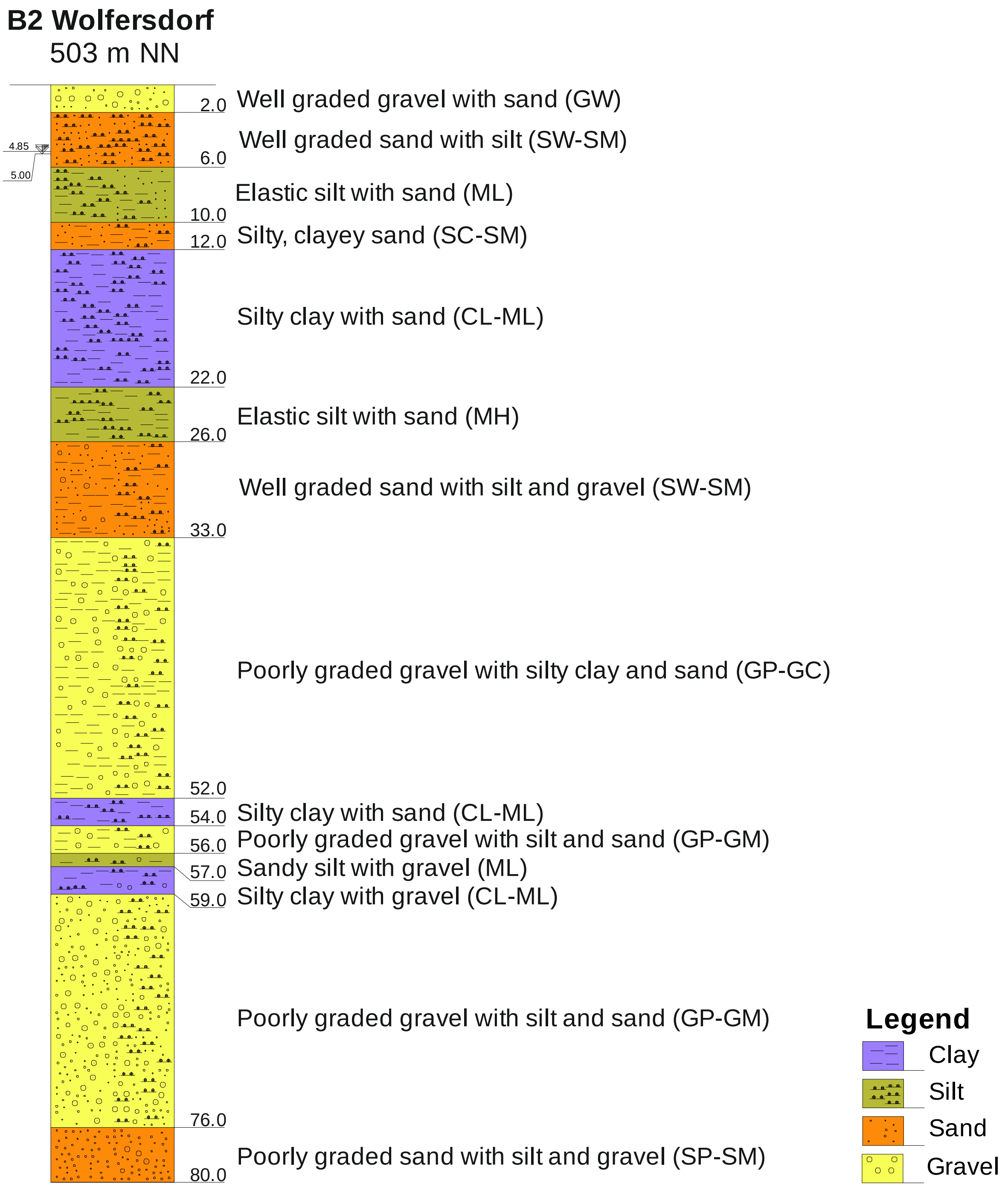


Figure 2: Sample of a drilling log

4.2 Borehole Heat Exchanger Specification

The test borehole should be developed with consideration for the final purpose of the test. If one of the purposes of the TRT is to estimate the borehole resistance of the planned installation then the test borehole should conform to the identical specifications as planned for the geo-exchange field as a whole. Specifically, the diameter, depth, piping specifications, pipe separators, centering devices, number of u-loops, heat transfer fluid properties, and grout thermal conductivity and specific heat capacity shall conform to project specifications. A sample specification for a borehole heat exchanger is given in Table 2 below:

Table 2: Heat Exchanger Specification

Type of heat exchanger	1-U; 2-U; coaxial	manufacturer
Installation of bore hole piping	Date	dd.mm.yyyy
Starting time	Time	hh:mm
Material of bore hole piping	PE100-RC, PE-RT, PE-X, PB, PA	PE100-RC
Exact depth of bore hole from bottom of bore hole to top of borehole	[m]	100
External diameter of pipes	[mm]	0.32
Wall thickness of pipes	[mm]	0.029
Spacers utilized?	Yes/No	Yes
Vertical distance between spacers	[m]	1
Separation distance between pipes	[mm]	36
Centering device	Yes/No	No
Vertical distance between centering	[m]	0
Separation distance between pipes due to centering	[mm]	0

Operating conditions (load, temperatures, etc.) of the test itself should be almost identical to those of the planned system.

4.3 Grouting Specifications

The composition and conductivity of the grout utilized during the TRT must be specified for the test borehole and must be identical to that planned for the final system design. It is imperative to both supervise and record the actual grouting application for the test borehole. The minimum parameters to be recorded regarding the grouting material and installation are indicated in Table 3 below:

Table 3: Specification of the grouting

Grouting material for borehole	Description of grouting material mixture and composition; product manufacturer and type of material	
Date of grouting	Date	
	Time	
Quantity expected / calculated	[m³]	
Quantity used	[m³]	
Thermal conductivity (from product documentation or estimated from Mixture receipt)	[W/(m.K)]	
Remarks	Document any experiences during and after grouting (e.g. losses due to cracks, settlement, refill, etc.)	

Grout conductivity impacts the borehole resistance significantly and is therefore the focus of significant attention in the design of the borehole. Many grouting materials (cement containing grouts) undergo an exothermic chemical reaction during the installation of the grout and mixture with water. This heat can significantly impact the undisturbed formation temperature measurement or the temperature development during the thermal response test. For this reason, the TRT may not commence until sufficient time has elapsed between the development of the borehole and the commencement of the TRT data collection (see 6.2.1).

5. Test Equipment Description

A wide variety of test equipment may be utilized to execute the TRT. The equipment should be designed with sufficient flexibility to consider the intended range of tests for many different sites. As the test unit must be transported to multiple sites, it is advantageous to design with mobility and ease of setup in mind. A typical hydraulic layout is shown in Figure 3, an equipment with a heat pump is given in Figure 4.

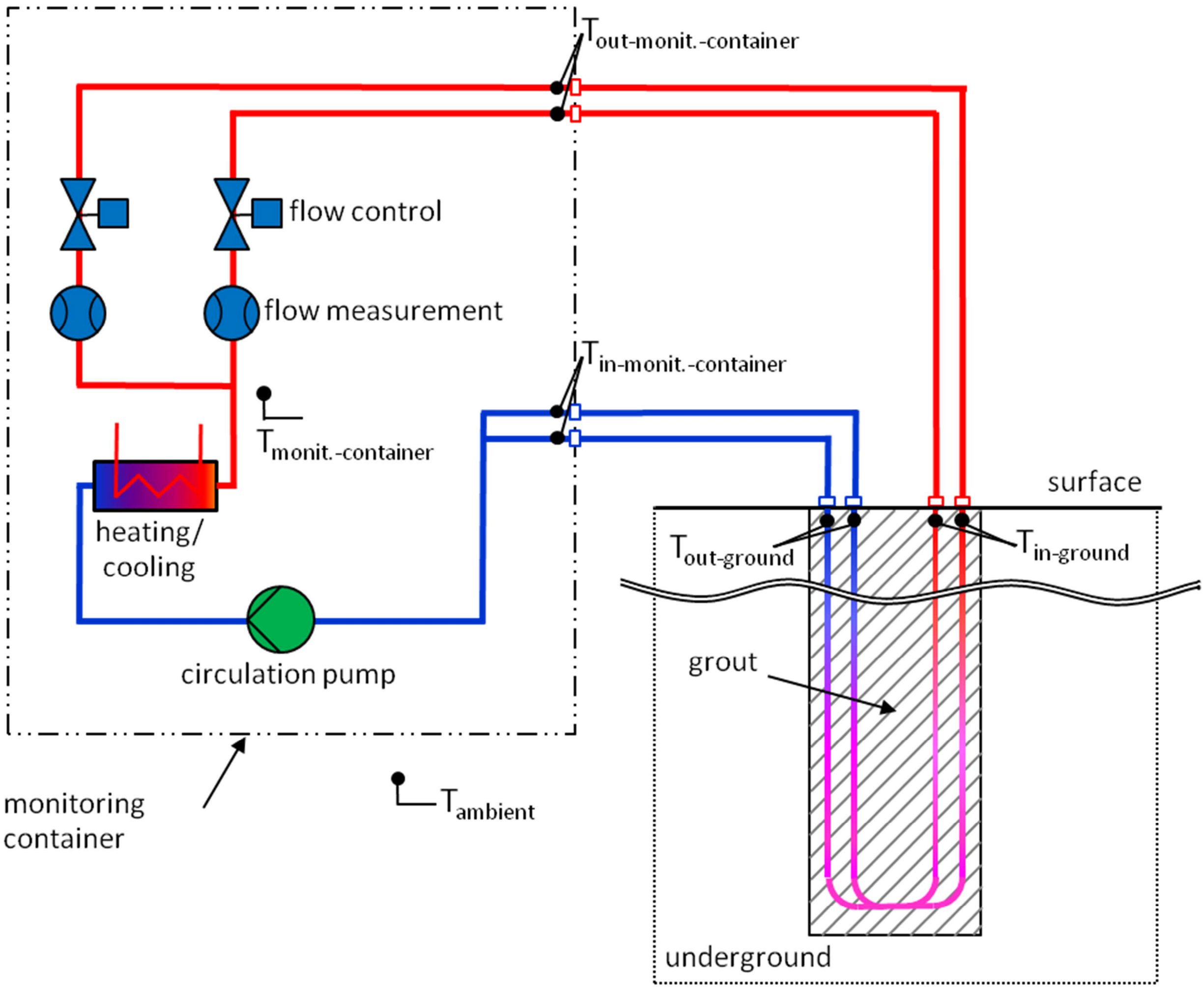


Figure 3: Hydraulic scheme of a typical TRT equipment

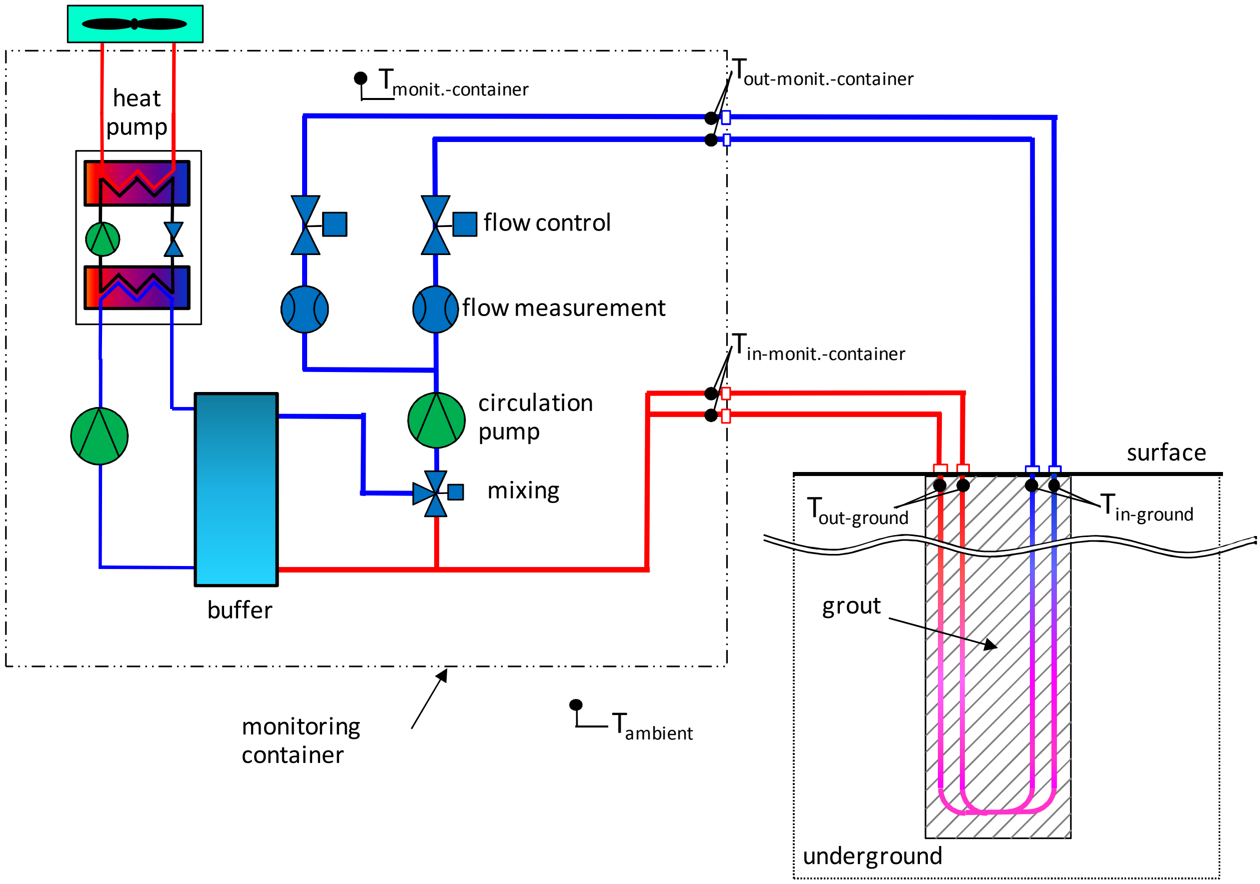


Figure 4: Hydraulic scheme of a TRT equipment with heat pump

5.1 Set Up of Test at Site and Ambient Influences

Because the tests are performed outdoors, the test equipment should be shielded from ambient influences including temperature, solar radiation, and precipitation effects.

The sizes for TRT weatherized containers range from boxes like large suitcases via trailers up to large sea-containers.

Contained piping and heating elements should be well insulated and the whole container may be ventilated to prevent overheating of the electronic equipment which can affect the accuracy significantly. All exposed piping should have sufficient insulation such that there is no noticeable influence of ambient conditions on measured values. To limit ambient influences, the length of piping runs should be as short as possible.

Furthermore, care should be taken so that the surrounding ground or nearby activities will not influence the measurements. Surface water flowing or infiltrating into the borehole, especially during rain or snow melting may significantly skew the measurement of thermal conductivity values and should be prevented by borehole cover. Drilling of nearby boreholes (see 5.3 and 6.2.1 and 6.3) or excavation work that may cause an induced flow of ground water near the test hole has to be postponed after the test. Also pumping of ground water, e.g. for water supply, even at a longer distance from the test site, has to be considered at evaluation of data.

5.2 Thermal Pulse Generation

The centerpiece of the TRT equipment is the generation of a heat or cold injection pulse to the underground which is done either by an electric heating element or by a heat pump.

Frequently, variations in the thermal energy injection rate while testing give rise difficulties during evaluation. However, the degree of the problem is related to the evaluation method used. Data analysis using the line source method requires a very consistent thermal power rate throughout the entire test duration. With parametric analysis, on the other hand, it is possible to accommodate variations in thermal pulse power during the measurement period.

In order to maintain constant injection power rate with resistive heating designs, the source power must be kept constant. Mains or grid power supplies in different regions are notoriously unstable even in developed nations and may vary significantly over the course of a multi-day test. Either regulation of the voltage or active control of the supply/return temperature differential at constant mass-flow rate is required to provide sufficient consistency in the heat injection rate. Proper thermal insulation of all piping is compulsory in order to ensure the true temperature differential as seen by the borehole is controlled.

The thermal power should be selected in a range that the expected temperature changes during TRT operation are in the same range as in regular operation of the later system. Underground thermal conductivity should be estimated prior to the test and together with the length of the borehole heat exchanger these factors may be used to select an appropriate thermal power for the TRT.

During the test a constant mass-flow rate is suggested to avoid changes of heat transfer properties in the BHE and to maintain a constant heat pulse. . In most cases the flow rate during tests should be kept on a low turbulent regime (Reynolds number >3000). To adjust the flow rate to achieve the appropriate turbulence, a frequency controlled pump or a modulating control valve is recommended. A change from turbulent to laminar flow or vice versa should be avoided as this will result in a significant change to the heat transfer characteristics of the BHE mid test. Simultaneously, a sufficient temperature differential between supply and return is required ($\Delta T \sim 5$ K is preferable, but a minimum $\Delta T > 3$ K) in order to achieve an adequate measurement accuracy. The pumping power necessary to circulate fluid through the BHE must also be accounted for within the measurement methodology. Analyses which utilize only the power measurement from the resistive heaters neglect this contribution to the thermal pulse and thereby introduce measurement error.

5.3 Hydraulic Connection

A TRT can be carried out some days after completion of the borehole heat exchanger when all thermal disturbances due to drilling and the chemical reaction heat from cementious grouting have decayed. The required time span is approximately 4-7 days (see 6.2.1).

The test rig should be set up as close as possible to the borehole to minimize the piping connection lengths and thus the ambient influences. Proper thermal insulation of the piping is strictly recommended.

Typically the borehole heat exchanger pipes are filled with fluid during construction. It is advantageous to utilize water as the heat transfer fluid because of the minimal environmental impact and the known thermal parameters but in case of freezing water with antifreeze of a well know heat capacity can be used. In any event, the same fluid has to be used in the BHE as in the test rig.

To avoid disturbance during connection of the TRT equipment to the BHE it is recommended to fill up the whole test rig and all piping and to purge it prior to connection in order to remove all air trapped in the system. Typical equipment setups include a purge tank and/or air vents and a pressure tank. During the test the whole system should be pressurized to avoid cavitation in the pump and associated flow control issues.

5.4 Instrumentation

The overall accuracy of the determination of the underground thermal conductivity λ and the borehole thermal resistance R_b should be not lower than ± 5%. The total error must be considered which consists of single errors either random or systematic in nature. Random errors result from sensors or data acquisition as well as the evaluation (data fitting). Systematic error may be introduced from known deviations between the model assumptions and the real world borehole e.g. non-uniform conductivity in reality when the model assumes uniformity. Ambient influences tend to introduce systematic cyclical variations associated to typical diurnal weather fluctuations. Poorly calibrated instrumentation may also introduce systematic errors and thereby skew the measurement consistently in one direction. An error analysis must compile all the single errors in order to determine a total error which is specified in the final report.

During a Thermal Response Test several measurements are made and stored at regular intervals. The following recommendations should be met at least:

- Selection of sensors

  The typical temperature range for TRT is 0 – 40 °C while the typical temperature difference for determination of the thermal power is 5 K. Therefore matched platinum resistance temperature sensors are recommended (e.g. Pt100) which are selected in pairs such that temperature difference measurements may have an accuracy of ±0.01 K.

  Flow rate in the BHE-pipe should be kept turbulent (Reynolds number >3000) while the temperature difference is ΔT ~ 5 K. Magneto-inductive or ultrasonic flow meters are recommended due to their higher accuracy and should be selected with appropriate turn-down ratios for the piping configuration of the apparatus. Aside from their high accuracy they are not sensitive to contaminated fluid and have a low pressure drop.

- Location of sensors:

  - Temperature measurement

    Highest accuracy can be achieved if the sensor is installed directly in the fluid flow ideally combined with mixing devices for truly turbulent flow. Temperature sensors in immersion sleeves must be strictly avoided due to the additional uncertainty which may have serious error contributions whilst also being hard to estimate.

  - Flow rate measurement

    Flow meters are specified a certain number of upstream and downstream pipe diameters to prevent flow distortion or swirl, caused by bends, T- sections, valves etc. as they have a significant influence on the measuring accuracy.

- Measurement accuracy:

  - Temperature measurement

    To achieve a high overall accuracy for temperature difference measurement an accuracy in the range ±0.01 - ±0.05 K is required. Selection of matched sensors and calibration against each other is recommended.

  - Flow rate measurement

    For high accuracy flow rate measurement different techniques are available. Common turbine flow meters reach only a measurement accuracy of ±2 - ±5%. As magneto-inductive or ultrasonic sensors show a much higher accuracy of

±0.1 - ±0.5% their usage is strictly recommended in order to achieve the requisite overall accuracy. Careful attention should be made to the design flow rate to avoid low flow rates as these instruments lose accuracy at lower flow rates.

- Temperature dependency of density and specific heat capacity of the fluid:

  For calculation of the mass flow rate from the volumetric flow rate the fluid density and for thermal power calculation the specific heat capacity is required. Fluid density and specific heat are required in order to convert the volumetric flow rate into a mass flow rate and finally to calculate the thermal power. Increased accuracy is obtained by correcting these parameters according to temperature. The reference temperature for the density is at the location of flow measurement, whereas that correction of the specific heat capacity has to be done with the mean value of supply and return temperature of the borehole.

- Data acquisition system:

  The data acquisition system has a typical instrumental error which results from different sources. The instrumental error should be small enough to allow an error of temperature measurement – a typical analogue signal – of at most ±0.05 K.

  Rough operational conditions of field measurements have to be considered when the equipment is selected.

  It is recommended to calibrate the total measurement chain from sensor to data acquisition system to correct systematic errors of the measurement chain to the greatest possible extent.

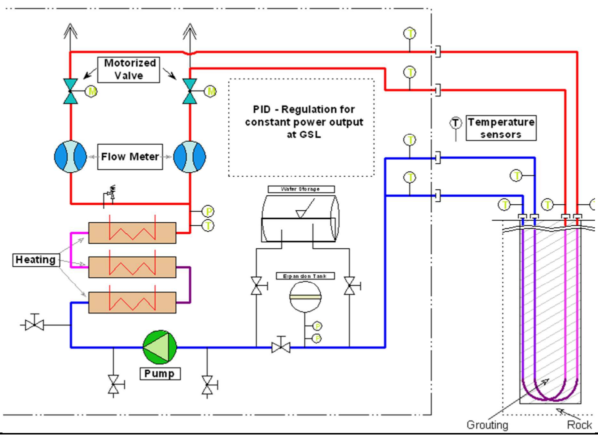
  Additional influences should also be considered as they may partially be avoided by a thorough experimental setup and test operation. Some error sources result from local conditions and are unavoidable, but must be quantified. A sensitivity analysis of the evaluation process is therefore recommended. Such errors are:

  - Unknown heat transport fluid
    Specific heat capacity and density have to be determined from separate samples.
  - Squeezed or blocked BHE pipes
    The required flow rate cannot be achieved and is then not representative for the planned operation
  - Fluid leakage
    Power measurement is incorrect due to incorrect flow measurement
  - External thermal losses or gains
    Heating power is not constant and power measurement is impacted
  - Power loss during test
    Heating power is not constant
  - Instable power supply
    Heating power is not constant

An example data sheet of typical Thermal Response Test equipment is given on the following page.

Thermal Response Test Equipment Data	
Country: Germany	
Contact Person: Dipl.-Phys. Manfred Reuß	
Organization/Company: ZAE Bayern	
Address: Walther-Meißner-Str. 6 85748 Garching Germany	
Phone: +49 (0) 89 3229442-30	
Email: reuss@muc.zae-bayern.de proell@muc.zae-bayern.de	

General TRT data

Type: Heat injection	**No TRTs:** 1	Size, weight: 3.5 x 1.8 x 1.8 m
Aim: Research, development, commercial		Pump: type, capacity (range)
Powered by: Electricity, three-phase current (400V/220V), 16A 50Hz		Heater: electric <12kW (controlled)
Built on/in: Trailer		HP/Cooler: none
Principle outline 		Temperature measurements: • Pt100 (inside, ground level surface, ambient and more) • Pt1000 100m length – temperature profile measurement • Nimo-T datalogger – temperature profile measurement
		Flow rate measurements: • magnetic flow meter in each circle
		Voltage stabilization: No
		Electricity measurement: Yes
Remote Data Collection: Yes		GPS: No
Logger: PC - Linux		Remote Control: Yes

TRT Experience

Years of operation:	9 years
Number of performed measurements:	>100 (20-30 tests per year)
Typical borehole depths:	20m to 300m
Applications:	BHE, energy piles (only measurement)
Typical collector type:	1U, 2U, coaxial pipe
Typical fluid type:	water, water/glycol
Typical groundwater temperature:	10-13°C
Geographical area:	Germany, Austria, Switzerland, Italy, Great Britain
Analysis Method:	numerical / line source / online evaluation

6. Thermal Response Test Specifications

6.1 Environmental Protection

To acquire reliable data the experimental setup of the TRT has to be sheltered against environmental impacts on the measurements. Such influences are solar radiation, humidity, heavy rainfall and high or extreme low ambient temperatures. A well insulated container for the monitoring equipment and the fluid conditioning unit can reduce this impact significantly. This container should be positioned as close as possible to the borehole to minimize the length of piping runs. Additionally exposed pipes should have sufficient insulation such that there is no noticeable influence of ambient conditions on measured values. The grouting of the borehole up to top will provide a sealing to avoid ingress of runoff from heavy rain showers.

6.2 Undisturbed Ground Temperature Measurement

The undisturbed ground temperature is measured immediately prior to the commencement of the TRT.

After completion of the construction of the borehole and an idle period the fluid in the BHE is in thermal equilibrium with the underground i.e. the temperature in the fluid column is equal to the surrounding underground. Therefore the undisturbed ground temperature can be determined by measuring the fluid temperature before injection of any heat pulse. Several procedures have been developed which give reliable results.

6.2.1 The following general procedures should be applied for the any undisturbed ground temperature measurement:

- The U-tubes must be filled with water or anti-freeze solution.
- The measurement may commence only when the working fluid is in thermal equilibrium with the surrounding ground formation. Drilling friction and curing of the grout generates heat. Three (3) days minimum better 4 – 7 days must lapse between the vertical borehole installation and the TRT.[1]
- The probe sensor shall be calibrated prior to the test and be capable of an accuracy of ±0.05 K.
- Where temperature profiles are to be determined, the granularity of measurements with respect to depth should be recorded at a minimum of every 2m.

As the temperature response of a TRT is calculated as the sum of the undisturbed ground temperature and the temperature increase due to the thermal pulse injected the inaccuracy of the undisturbed ground temperature will result in a shift of the temperature response being evaluated. This will directly influence the borehole resistance R_b i.e. a too high undisturbed ground temperature will result in impune a smaller borehole resistance R_b.

6.2.2 Temperature Measurement While Circulating

The undisturbed ground temperature may be measured by fluid circulation prior to commencement of heat extraction or injection when the fluid temperature is in equilibrium with the underground. For temperature measurement the regular sensors install at the borehole

[1] As most of the disturbance is caused by curing of the grout in case of doubt the producer of the grout should be contacted for information on this time period.

inlet are used. However, the action of circulation alone introduces heat via the mechanical energy of pumping itself. Therefore the only temperature readings included in the evaluation are those ranging from start of the circulation pump to the time period a single volume element needs to travel from the U-tube inlet and back to the outlet. During this measurement turbulent flow (Re > 3000) is required to ensure complete mixing of the measured fluid. Typically a measuring interval of 10 s provides sufficient data. The mean value over the whole period for one circulation gives the mean undisturbed ground temperature.

Single data points demonstrate significant variations especially at the beginning which result from the depth dependent temperature profile in the ground (see Figure 5). Temperatures measured at the borehole outlet can be assigned to a location before circulation with respect to time and flow velocity. On its way from the starting point to the borehole exit a fluid element passes through areas of different temperature such that the fluid temperature is distorted by heat exchange. With an appropriate simulation model and sufficient temperature readings it is possible in this manner to also establish a thermal profile of the borehole.

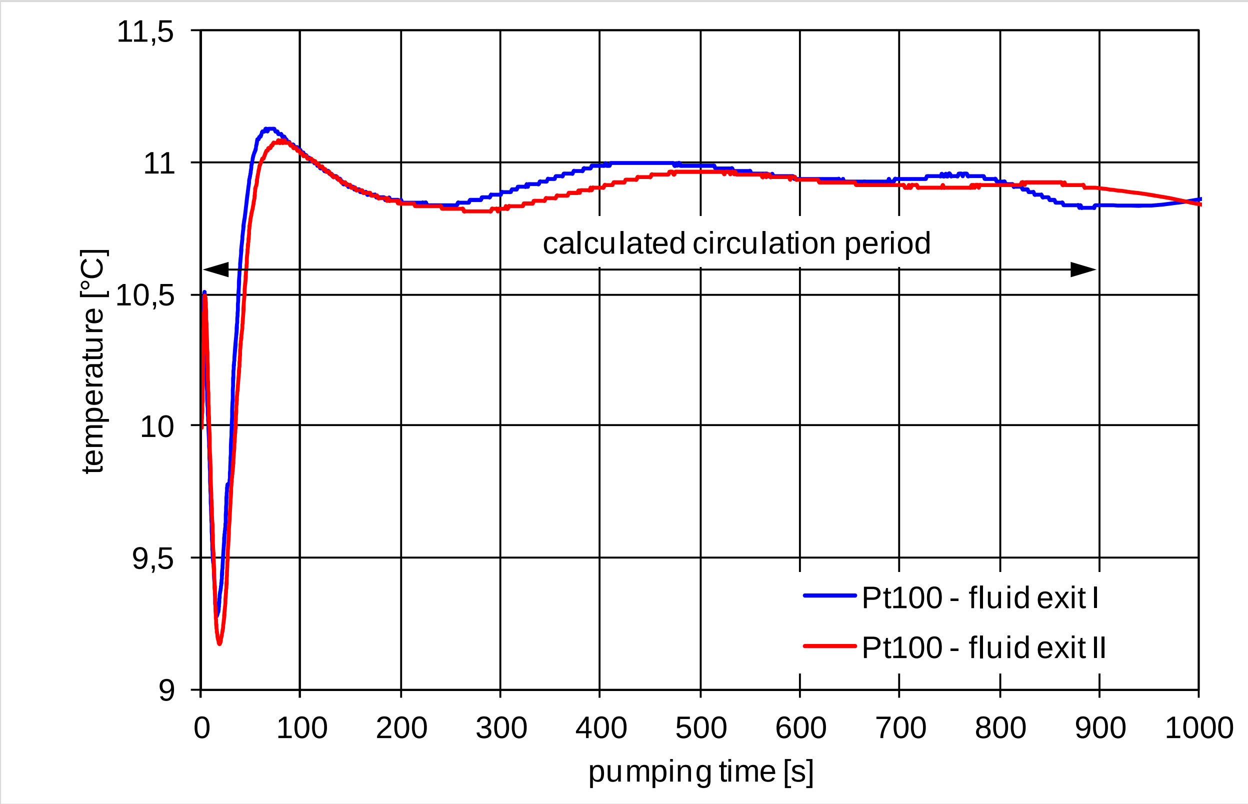


Figure 5: Measured fluid temperatures from circulation

6.2.3 Dropped Temperature Sensor

The undisturbed ground temperature may be measured by insertion of a temperature sensor inside the piping prior to its connection to the test rig. This sensor has to be very small with respect to the pipe diameter to avoid any displacement and mixing of the fluid which may influence the temperature in an uncontrolled manner. In addition, small sensors have the advantage of a low heat capacity and rapid response characteristics. It is ideal if two sensors are used in parallel, one in each shank of the U-pipe which minimizes any disturbance. Compared to the fluid circulation method, the dropped sensor technique introduces no major disturbances in terms of mixing occur.

The depth should be held constant for sufficient time to allow the temperature reading to settle prior to taking a reading. However, the settling period should not be so long as to permit influence of the temperature measurement by the power of the temperature sensor itself.

6.2.4 Temperature/Depth Sensors

There exist floating data sensors that record both temperature and pressure in order to correlate temperature measurements with depth. Such a device is inserted in one shank of the U-pipe and is sinking down to the bottom of the borehole slowly while measuring pressure and temperature continuously. . It is again important that the heat capacity is negligible and the sinking velocity is slow to gain enough data readings. After finishing the measurement the logged data is exported for evaluation. Such a device is suitable for U-pipe BHEs but not for a coaxial type.

6.2.5 Temperature Measurement with Distributed Temperature Sensing

In principle also fiber-optical systems can also be used to measure temperature and pressure. These physical properties influence the optical properties of a glass fibers locally and thus influence the light transport. This technique is called Distributed Temperature Sensing (DTS). A sufficiently thin fiber optic cable is inserted in the fluid of the BHE which is in equilibrium with the underground. To gain an acceptable accuracy a reference temperature sensor must also be installed too in order to calibrate the fiber optic data set.

6.3 Test Execution

After determination of the undisturbed ground temperature the real test may commence. If the hydraulic circuit is purged and the required flow rate is set the heater is started an a constant heat pulse is injected into the underground. The flow rate must not be changed during the entire test and the heating power is to be kept constant by a control unit.

It is recommended to perform the test with water, because the physical properties (density, heat capacity, temperature dependent) are well known. However, it should then be considered that the test results especially the borehole resistance, will need to be transformed to the heat carrier fluid from that planned for the proposed final design. Make sure the physical properties of this fluid are known and noted in the documentation.

Alternatively, using the same heat carrier fluid in the TRT as in the planned operation of the system has the advantage accurately measuring the proposed system’s borehole resistance. If an anti-freeze solution is utilized, the flow meter selected must be able to maintain accurate measurement.

Injection/extraction heat transfer rates and their corresponding flow rates shall be selected to provide turbulent flow with a Reynolds number >3000 and differential loop temperature $\Delta T \sim 5$ K (see 5.4). Sensors for measurement of the inlet and outlet temperature of the fluid must be placed in the U-pipe at the top of the borehole immediately below ground level. Flow rate and temperatures are measured continuously and recorded directly. It is permissible for data reduction reasons to record mean values every few minutes as long as the frequency is still sufficient to identify disturbances.

Frequently it is not considered that heat transport processes in the underground are relatively slow and a TRT therefore requires more time than a comparable measurement with other materials. In principle the test duration is several days and the test period depends on the evaluation method.

No drilling activities shall be performed within 10 m of the test borehole within 5 days prior to the test or while data logging is ongoing for the test.

Upon completion of the test, water in the borehole must be blown out to sufficient depth (2 – 3 m below surface) to ensure adequate freeze protection, or replaced with appropriate antifreeze solution. Then the pipes have to be closed by fixed caps to avoid any contamination from outside.

6.4 Evaluation of Measurements

There are different methods to evaluate the temperature response of a TRT. By far the most common is the direct evaluation of the thermal conductivity from the simplified analytical solution of the line source model (Eq. 1). All other methods like the evaluation with numerical models as well as with complicated analytical solutions are based on the fitting of the model to experimental data by variation of the desired model variables the so called free parameters (numerical, generally nonlinear parameter identification).

$$T_f(t) = \frac{\dot{Q}}{H \cdot 4\pi \cdot \lambda} \ln(t) + \frac{\dot{Q}}{H}\left[\frac{1}{4\pi \cdot \lambda}\left(ln\left(\frac{4a}{r_b}\right) - \gamma\right) + R_b\right] + T_g \qquad \text{Eq. 1}$$

$T_f(t)$ mean fluid temperature [°C]
$\dot{Q}$ total injected heating power [W]
H length of the borehole heat exchanger [m]
λ ground thermal conductivity [W/m.K]
a temperature conductivity (thermal diffusivity) ($a = \lambda/c$) [m²/s]
c specific volumetric heat capacity [J/m³K]
r_b borehole radius [m]
γ Euler's number (=0.5722…)
R_b thermal borehole resistance [m.K/W]
T_g undisturbed ground temperature [°C]

The above mentioned direct evaluation procedure requires minimum effort and the approximation errors are negligible if all required boundary conditions are fulfilled. The time dependency can be separated (Eq. 2) as follows:

$$T_f(t) = k \cdot \ln(t) + m \qquad \text{Eq. 2}$$

with

$$\lambda = \frac{\dot{Q}}{H \cdot 4\pi \cdot k} \qquad \text{Eq. 3}$$

Therefore the thermal conductivity of the underground can be evaluated directly from the slope of the straight line which results if the temperature response is plotted versus the natural logarithm of time. The example in Figure 6 shows that for a properly executed test the temperature response plotted versus ln(t) is a perfect straight line.

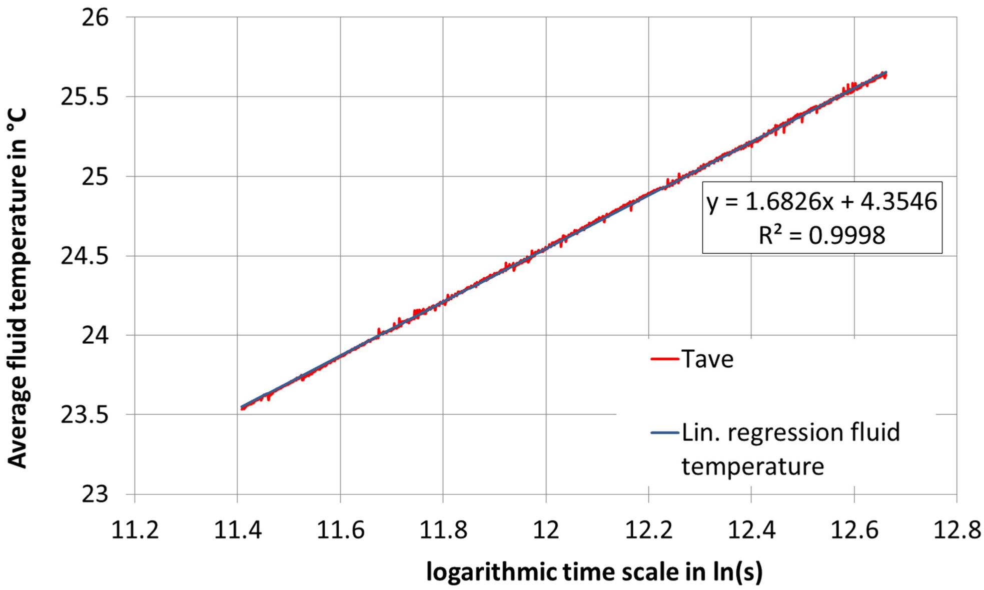


Figure 6: Linear regression of the temperature response as a function of ln(t)

After determination of the thermal conductivity from Eq. 3 the borehole thermal resistance and the volumetric heat capacity of the underground are left as unknown parameters. It is important to understand that only one of these two values could be determined as according to Eq. 4 both parameters have the same effect With only one equation and two unknowns, it is not possible to determine both variables. The volumetric specific heat capacity has a much smaller influence and is easier to estimate from the knowledge of the geology. Therefore this value is fixed as boundary condition and is simply specified in the evaluation report as an initial assumption.

$$R_b = \frac{H}{\dot{Q}}\left(m - T_g\right) - \frac{1}{4\pi \cdot \lambda}\left(ln\left(\frac{4a}{r_b}\right) - \gamma\right) \qquad \text{Eq. 4}$$

The borehole thermal resistance is then the parameter to be identified. If steady heat flux is assumed in the borehole R_b describes the ration of the 'temperature difference between mean fluid temperature and the mean temperature at the borehole wall' and 'specific heat flux injected' (see Figure 7).

There are two equivalent ways to determine R_b either from Eq. 4or from Eq. 5 which deliver the same result.

$$R_b = \frac{H}{\dot{Q}}\left(T_f(t) - T_g\right) - \frac{1}{4\pi \cdot \lambda}\left(ln\left(\frac{4a}{r_b}\right) - \gamma\right) \qquad \text{Eq. 5}$$

Using Eq. 5 the mean value of R_b is calculated over that time period which is used for determination of the thermal conductivity λ.

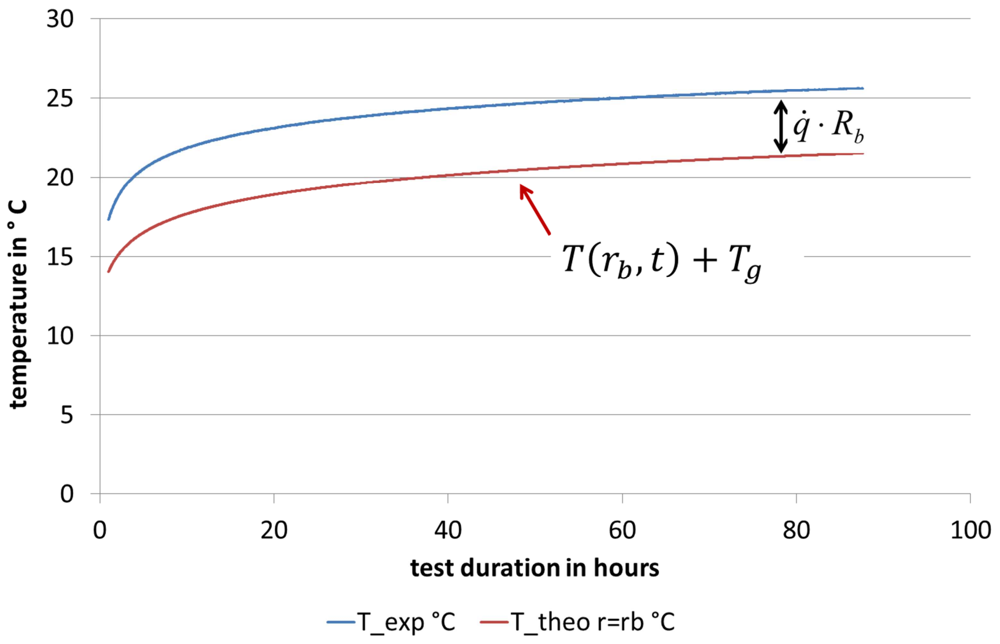


Figure 7: Demonstration of the borehole resistance

The indirect evaluation procedure of the temperature response is the fitting of an appropriate model (analytical or numerical solution) typically by numerical, nonlinear parameter identification. In this case the free parameters are varied systematically until the deviation of the temperature responses of the model and of the measured data reach a minimum. It must also be considered here also that borehole resistance and thermal capacity cannot be determined together because there is no unique solution.

6.4.1 Duration of the Heating Pulse

The determination of the minimum duration of the heating pulse is based on the requirement that the result must not change significantly while increasing the heating and measuring period. The result should be the thermal conductivity converging over time against a constant value.

6.4.2 Convergence of the Result

The convergence of the result – the thermal conductivity – is calculated from the sequential stepwise evaluation of the temperature response. If the assumptions in the model and approximations of the evaluation method agree well with the real conditions the result of the evaluation will converge with sufficient measuring time towards a constant value. Conversely, it can be interpreted that in the case of proved convergence of the result the heat transport in the underground agrees very well with the model assumptions.

Sequential Forward-Evaluation

Within the sequential forward-evaluation the starting point of the evaluation is assumed to be known and kept fix. The evaluation is carried out stepwise from the starting point by increasing the total time interval of evaluation with each step. Thus the last point of the resulting curve of λ over testing time (see Figure 8) is the mean estimate over the entire evaluation period. At the beginning there occur significant deviations from the final value because of the small amount of data. For valid model assumptions the curve converges against a constant value.

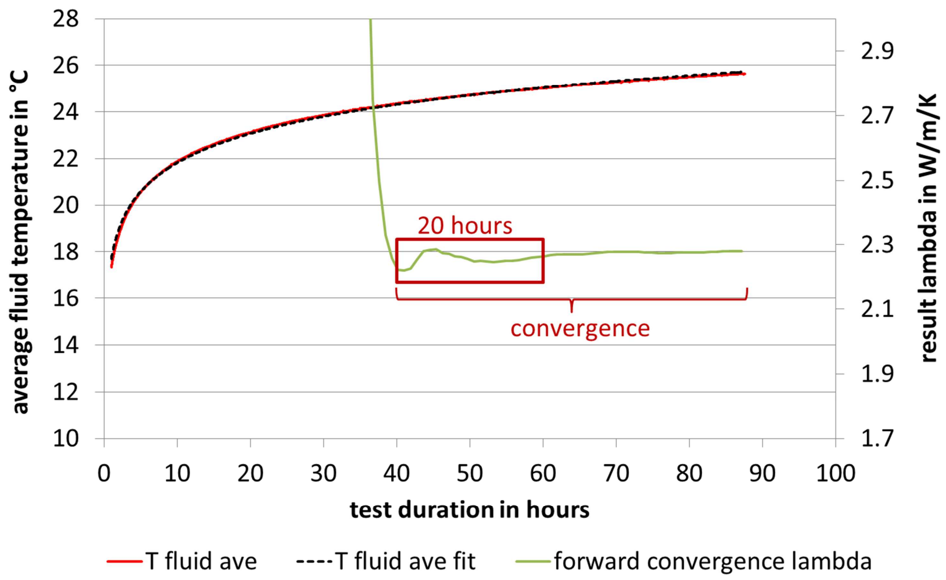


Figure 8: Convergence of the λ-curve over time for sequential forward-evaluation

If the starting evaluation point is chosen too early (shorter than the minimum time criterion) the curve is typically not converging even if the rest of the model assumptions are correct. The more detailed the model is the smaller the starting point can be chosen.

The criterion recommended for convergence of the thermal conductivity is $\Delta\lambda/\lambda = \pm$ 5% for a time period of 20 hours at which the minimum time period of the test must not fall below 48 hours.

Sequential Backward-Evaluation

The determination of the backward-convergence curve is carried out analogically to that of the forward-convergence. For each point of the backward-convergence curve the endpoint is fixed and the starting point is moving stepwise backward in time. The advantage is that for correct model assumptions the temperature response is not subjected to any further restriction for a long measurement period. In contrast to the starting time of the forward-convergence curve requires the minimum time criterion at the beginning of the test.

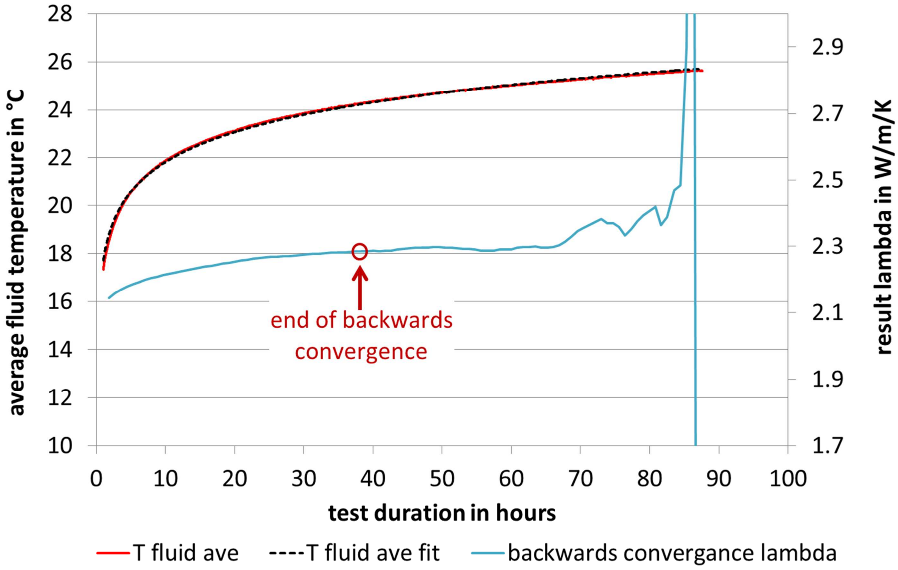


Figure 9: Convergence of the λ-curve over time for sequential backward-evaluation

Similar to the forward-convergence curve the backward curve starts with significant fluctuations occur due to the small number of data points. This effect diminishes with increasing time period. Following the test backwards in time the λ-curve converges. When passing the minimum time criterion the deviations increase again. Thus with this procedure the true minimum time criterion can be determined.

6.4.3 Minimum Time Criterion

Basically the selection of the correct evaluation period is crucial for all evaluation methods. The assumptions regarding the evaluation model as well as the approximate solution of this model have to be fulfilled exactly for this evaluation period. The starting point of this period the so called minimum time criterion cannot be determined exactly by calculation but results from test evaluation as shown in chapter 6.4.2.

Initially a theoretical minimum time criterion exists (see Eq. 6) which defines the validity of sthe line source model on which the approximate solution (Eq. 1) is based within a desired accuracy:

$$\frac{a \cdot t_{start}}{{r_b}^2} \geq n \qquad \text{Eq. 6}$$

Table 4 gives, for the evaluation model of Kelvin’s line source, the error in per cent of the approximate solution (Eq. 1) relative to the exact solution.

Table 4: Theoretical minimum time criterion according to Eq. 6 and the related approximation error of Eq. 1 with respect to the exact solution of Kelvin’s line source theory.

n	5	10	20	40	50	100
Error (%)	10.5	5.3	2.5	1.5	1.0	0.5

The thermal response of the borehole heat exchanger itself is dominant over the thermal response of the underground formation during the initial portion of the TRT. The time after which this dominance subsides defines a physical minimum time criterion. For analytical models these are for example:

- Heat injection of single-U or double-U-pipes happens in the borehole along more than one line which does neither agree exactly with the line source nor withe the cylinder source theory.
- The thermal grout typically has a different thermal conductivity and heat capacity than the surrounding underground so that the assumption of homogeneity typically is not fulfilled.
- The model assumption of an effective borehole resistance requires quasi-steady-state heat transport in the borehole.

These deviations do not influence the evaluation result significantly when after a sufficiently long heating period the temperature has reached a quasi-steady-state. After this period, the amount of thermal energy for heating up of the borehole itself is small compared to the total injected amount of heat. The power remaining in the borehole itself for a certain time can roughly be estimated from the increase of the mean fluid temperature and the heat capacity of the grout. The total injected heat over a time period can be estimate analog from the increase of the mean fluid temperature and the heat capacity of the grout.

To assess the physical minimum time criterion by means of the test evaluation there are the two procedures available as described in 6.4.2:

The forward-convergence-curve is determined by initially using a starting time $t_{start} = 0$ and increasing t_{start} stepwise until the required convergence occurs. Is no feasible t_{start} found which leads to convergence, the test is not valid.

The second method the backward-convergence-evaluation method is also described in 6.4.2.

In principle this procedure of convergence is also applicable for evaluation by parameter identification with numeric models.

Similar to the forward-convergence continuous evaluation during the test run by backward-convergence permits an online determination of the required test time. When convergence is reached the test can be stopped.

6.4.4 TRT and Groundwater

The evaluation of TRT-measurements under heavy groundwater influence is actually a subject of research. Appropriate evaluation models which consider convective heat transport in the groundwater may allow a valid evaluation. Nevertheless this has to be verified by the convergence method.

6.4.5 Re-starting Dynamic Test Phase

Retesting a borehole may become necessary due to malfunction of the equipment, loss of power, or other uncontrolled circumstances. If retesting at the same borehole is necessary, typically a rather long standby period is required to gain a full thermal regeneration of the underground. It is recommended to wait until the loop temperature returns to within 0.25 K of the equilibrium ground temperature. This recovery of temperature is required when utilizing the line source method for evaluation of the thermal conductivity as failure to do so would contaminate any subsequent test result.

It is possible to continue testing immediately after an interruption of constant heat injection/extraction if alternative evaluation methods are utilized. Such methods like a multi-pulse-test are beyond the scope of this specification but may be found elsewhere.

6.5 Designated Use of Test Results

6.5.1 Mathematical Models

When applying the underground thermal properties and borehole parameters acquired from a TRT it must be considered the mathematical models of the BHE are approximations which are valid only when specific assumptions are true. It is therefore strongly recommended that the TRT results are only utilized when the mathematical model used for the evaluation is the same as the model utilized for the design calculations.

If different models are used for TRT evaluation and system design the TRT results should be review using the design model and the test data. Examples for difference in the models which lead to differences and require correction of the parameters are:

- Underground thermal conductivity determined with a TRT is an effective value which may include groundwater influence to a certain extent. If the design model treats conduction and groundwater influence (convection) separately, the use of these TRT results has to be check thoroughly; groundwater influence must never be considered twice in the effective thermal conductivity and in the design model as convection.
- The design model uses a depth dependent variable thermal conductivity (and possibly also a variable heat capacity), while the TRT evaluation gives only an effective mean value throughout the whole borehole length. Or vice versa a enhanced thermal response test is performed giving depth dependent parameters while the design model uses only effective values.

6.5.2 Boundary Conditions and Operational Parameters

Additionally, the planned operation and the TRT should have consistent boundary conditions and operational parameters.

6.5.3 Undisturbed Ground Temperature

In a TRT the undisturbed ground temperature at one single time and one location below surface is determined. It should be considered that the vertical temperature profile is influenced at the surface by ambient conditions in the upper 10 – 20 m. Thus the mean underground temperature is disturbed especially for short BHEs and varies with the season.

However many design models use the annual average of the undisturbed ground temperature as starting value. Especially for short BHEs the undisturbed ground temperature determined with the TRT should be checked and if necessary it should be corrected with respect to seasonal influences.

6.5.4 Borehole Resistance

The borehole resistance gained from a TRT is not one constant value but an aggregation of all heat transport processes in the borehole over the entire borehole length:

- Heat transfer from the circulated fluid to the pipe wall.
- Heat conduction in the pipe wall of the BHE
- Multidimensional thermal conduction in the borehole grout
- Possibly contact resistance between BHE pipe, grout and borehole wall

It also considers the thermal short circuit between the upward and the downward shanks of the U-pipes which have different fluid temperatures. This short circuit effect depends mainly on the duration of stay i.e. the ration of borehole length and flow rate as well as on the type of the circulated fluid as far as density and heat capacity. These parameters also influence the heat transfer between fluid and pipe whereupon the flow condition (turbulent or laminar) is of major importance.

Generally the operational conditions during the TRT should be as close as possible those of the later installation, although some deviation may not be avoidable, e.g.:

- Type of heat transport fluid: Pure water in TRT, water-antifreeze-mixture in the later operation.
- Temperature regime: Heat injection during TRT, heat extraction in the later operation.
- Flow rate and flow conditions: Different requirements for TRT and in the later operation.
- TRT is carried out at a first test borehole, later boreholes may have for any reason different parameters (borehole length, diameter, grout,...)

If a relevant parameter in the design calculation for the planned operation deviates from TRT, the assignability of the borehole resistance gained from TRT should be re-verified. If necessary, this value may need to be adjusted using an appropriate borehole resistance model.

Because the thermal borehole resistance depends on the estimated value of the underground heat capacity and the undisturbed ground temperature all the values have to be documented together. Single results should not be used without respect of the relevant assumptions. Specifically due to the connection between borehole resistance and the underground specific heat capacity, these two parameters should be applied as a pair when used in subsequent calculations.

6.6 Documentation of Test Results

All information used for performing the test as well as the evaluation and results of the Thermal Response Test must be well documented in a report to ensure relevant data is communicated for the subsequent design process.

The report should include the following items at least:

- Detailed description of the property
- Theoretical background – mathematical model used for evaluations
- Description of the experimental setup
  - Listing of all available information on the drilling, geology and BHE
  - Brief description of the test equipment (Type and mounting of the sensors, type of control, etc.)
  - Description of the location (specific characteristics)
- Test procedure
  - Description of the heat transfer fluid as well as operational parameters while measuring the undisturbed ground temperature and while performing the test itself
  - Description of the test procedure and identification and explanation of any anomalies
  - Presentation of all relevant measuring results and probably discussion of peculiarities
  - Boundary conditions used in the evaluation and estimated values
  - Result of the evaluation with specification of uncertainties of the measurement and the results
- Summary and conclusions

The measured data must be archived and on demand transferred to the client. This e.g. may be necessary, for example, if the models for TRT evaluation and system design differ from each other. The data are required for reviewing the TRT results with the design model.

7. Literature

[1] 2007 ASHRAE Handbook on HVAC Applications, Chapter 32: Formation Thermal Conductivity Testing

[2] C448 SERIES-13 - Design and installation of earth energy systems

[3] Eskilson, P. 1987. Thermal analysis of heat extraction boreholes. Doctoral Thesis, Lund University, Sweden.

[4] Gehlin, S., 1998. Thermal Response Test, In-Situ Measurements of Thermal Properties in Hard Rock. Licentiate Thesis, Luleå University of Technology, Department of Environmental Engineering, Division of Water Resources Engineering. 1998:37. 41 pp.

[5] Gelder, A.J., van. 2001. Geothermal response tests with heat extraction and heat injection: Examples of application in research and design of geothermal ground heat exhangers. Europäischer workshop über Geothermische Response Tests, EPFL, Lausanne, 25th and 26th of October 2001.

[6] H.S. Carslaw, J.C. Jaeger, Conduction of Heat in Solid, Oxford University Press, Oxford

[7] Henk J.L. Witte - "Error Analysis of Thermal Response Tests (Extended Version)", INNOSTOCK 2012 conference, Groenholland Geo-Energysystems, Valschermkade 26, 1059CD Amsterdam, Netherlands, Phone: 31-20-6159050, e-mail: henk.witte@groenholland.nl

[8] Witte, H.J.L. 2006. Geothermal Response Tests using controlled multi-power level heating and cooling pulses (MPL-HCP): Qauntifying ground warer effects on heat transport around a borehole heat exchanger. In: Stiles (ed). The Tenth International Conference on Thermal Energy Storage, Ecostock 2006 Proceedings. May 31 - June 2, 2006, Stockton College New Jersey (USA).

G. SUBTASK 5
Dissemination Activities

Content Subtask

1. Background

The objective of the dissemination activity was to support knowledge transfer and market adoption of TRT both on national and international level. Finland was selected as a task leader of dissemination activities.

This subtask integrated the activities of the other subtasks. Each subtask was responsible for the production of designated parts of the overall information dissemination activity.

The main tool for dissemination was through thermalresponsetest.org website. The main objective of the website was not only to offer technical information on TRT as scientific papers and studies but also to provide general information about the benefits of TRT.

2. The Annex 21 website

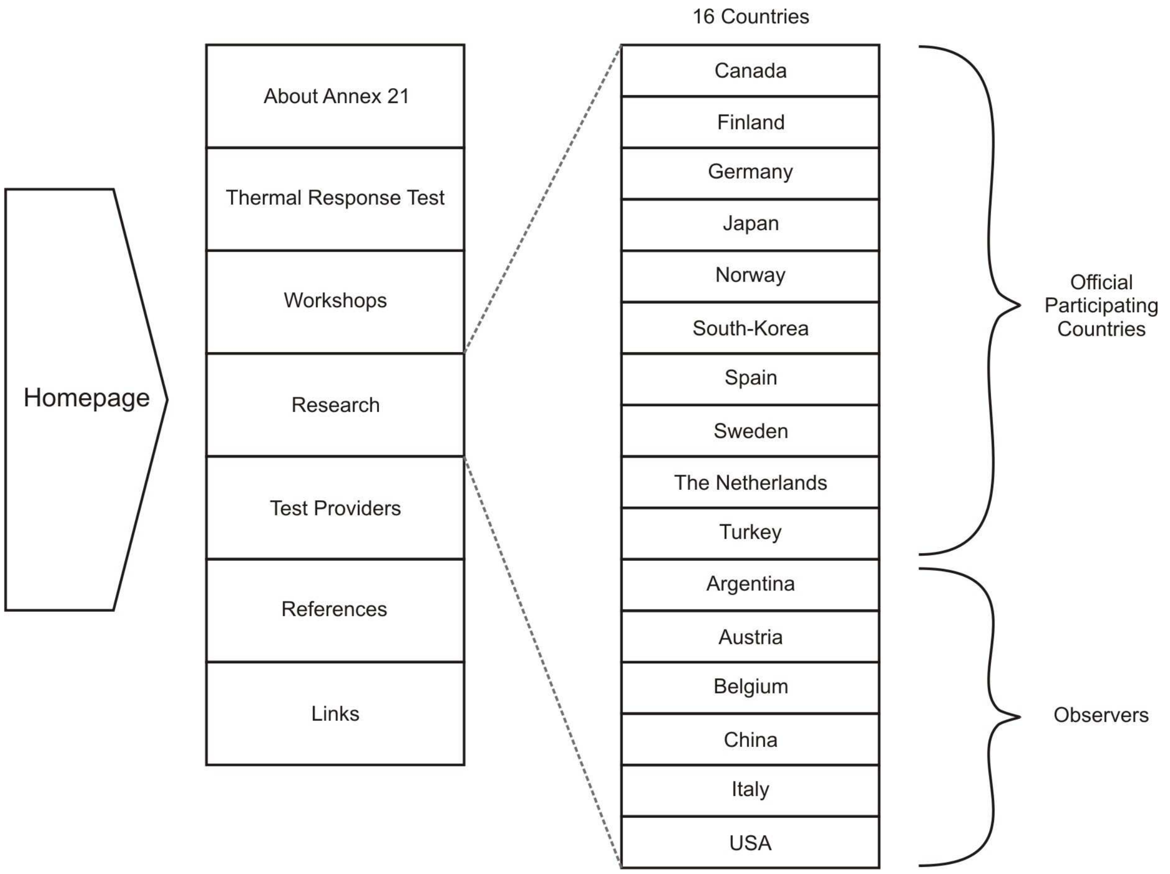
The major goal of the dissemination plan was to create publicly accessible website and invite the new countries to participate in Annex 21. The first website drafts were non-public. Participants were asked to brainstorm about ways to collaborate on dissemination.

The discussions about the structure of the website were held on the workshops and were the general look of website was accepted (picture 1). The pages made public on October 2010.

The contents of the website made only in English. Participants did not find it necessary to translate the pages other language at this moment. For test providers there were ability to have TRT forms in their national languages.

The layout was kept very simple and easy to use because there was no web editor program to use (picture 2). The website was almost started from a scratch. The first sketch was done by Mr Ilkka Martinkauppi. In the bigger problems was helped by Mr Arto Laiho. Moreover all our team in this Annex 21 project (5 scientists) assisted in producing the website contents and lay-out.

The home of the website is maintained temporarily on the server of Geological Survey of Finland (GTK). The website is updated only by request. All requested changes and ideas concerning the layout and contents of the website were gathered during workshops, and sent to webmaster Mr Martinkauppi. Requested updates were then implemented and taken into practice. Mr Martinkauppi was the only webmaster of the site.



Picture 1. Structure of the Annex 21 website consisting of 24 pages.

Within the context of dissemination of the results of the research activities performed by Annex 21 participants, the website was planned to present an overview of the publications, scientific papers and presentations given by experts. However, only some publications were displayed on the site. Participants were free to send documents, reports and any other publications to be published on the website. The information for the website was collected via email. The activity for input from the participants varied a lot. Numerous reminders were sent.

One of the major results of the Annex 21 was an information database including list of TRT providers and their references. This goal was fully achieved:

- Annex 21 description and participating countries are presented
- Observing countries are included
- List of held events and workshops is presented

- List of references is presented
- Links to IEA and ECES websites are included
- Links to conferences, training courses and other geothermal energy events will be presented on the website

Picture 2. Annex 21 homepage is located at http://thermalresponsetest.org/.

Thermal response test providers there given the possibility to share information about their activities and services, including technological capabilities. From the website one can download TRT provider`s form and return it after filling on the pages (picture 3). The TRT forms were delivered all over the world and were returned by 45 TRT service providers from 16 countries. The result was achieved and satisfactory. The providers varied from consulting companies to universities and to research centers.

Thermal Response Test Equipment Data

Country:

Contact Person:

Organisation/Company:

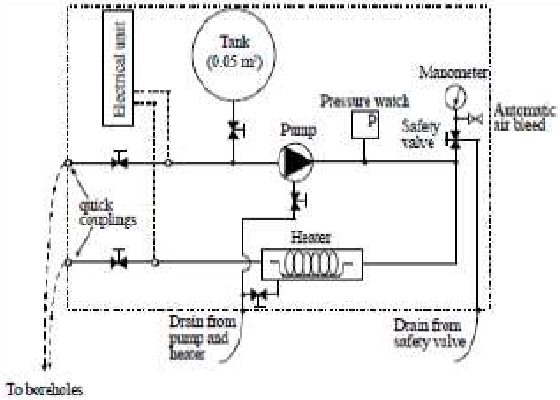
Address:

Phone:

Email:

General TRT data

Type: *Heat injection and/or heat extraction*	No TRTs: *XX*
Aim: *Research/development/commercial*	
Powered by: *Electricity, gas, oil, etc.*	
Built on/in: *Trailer, pallet, container, portable, stationary, etc.*	



Principle outline

Size, weight: *L+W+H, kg*	
Pump: *type, capacity (range)*	
Heater: *type and capacity (range)*	
HP/Cooler: *type and capacity (range)*	
Temperature measurements: - *Measurement, type, accuracy*	
Flow rate measurements: - *Measurement and type of sensor*	
Voltage stabilization: *Yes/No*	
Electricity measurement: *Yes/No, accuracy*	
GPS: *Yes/No*	
Remote Control: *Yes/No*	
Remote Data Collection: *Yes/No*	
Logger: *type*	

TRT Experience

Years of operation: *XX*

Number of performed measurements: *XX Research/development/commercial*

Typical borehole depths: *XXX*

Applications: *BHE, energy piles, heat pipe BHE's, etc.*

Typical collector type: *1U, 2U, 3U, coaxial pipe, heat pipes, etc. type of filling*

Typical fluid type:

Typical groundwater temperature: *XX*

Geographical area: *Measurement region*

Analysis Method: *Numerical / Line source / Automatic / Direct / etc.*

Picture 3. Empty TRT form for download.

3. The future of the website

Thermalresponsetest.org website will be integrated into IEA ECES website as soon as possible.

Dissemination activity was essential for the success of Annex 21. Dissemination is crucial for sustainability of Annex 21's outputs in the long run. Overall dissemination plan of Annex 21 could be updated in light of experience. There may be novel ways to show case projects` work, experiences and results of Annex 21 on this website.

Acknowledgment

Jarmo Kallio (Mr)

Manager, Lic.Phil. (Geology)

Energy and Resources

Geological Survey of Finland

H. Summary and Conclusion

Content

1. Summary

The Thermal Response Test turned out as a real story of success of international cooperation within the implementing agreement 'Energy Conservation through Energy Storage' (ECES). This cooperation leaded to an unbelievable fast introduction of a new technological development into the market. Within few years TRT became a standard procedure for site investigation for BTES and borehole heat exchangers for ground source heat pumps.

The first mobile test units were constructed in Sweden and USA in 1995 and introduced within the framework of Annex 8. The TRT has then been further developed with respect to test procedures and methods for test evaluation in Annex 13. For high temperature storage applications it has also been a part of Annex 12. Additionally intensive scientific investigation worldwide was initiated which is reflected in the large number of presentations and papers at the stock conferences from 2000 onwards.

Based on this development and further experiences from practical application in the market Annex 21 'Thermal Response Test' was started to share experiences and to initiate further R&D. To cover the wide field of subjects the Annex was arranged in five subtasks:

- Subtask 1: TRT state-of-the-art study
- Subtask 2: new developments
- Subtask 3: evaluation methods and developments
- Subtask 4: standard TRT procedures
- Subtask 5: dissemination activities

The state-of-the-art study gives a nice overview. Starting with the historical development which dates back with first ideas to 1983 and first mobile equipments in 1995, a brief description of the test procedure itself, the theoretical background and operational experiences is given. A questionnaire was developed to collect information and data on TRT equipments and activities worldwide. Within a short period of about 10 years, TRT spread rapidly to about 40 countries around the world. The vast majority is using the heat injection procedure while heat extraction was done in less than 10% of the test carried out. A major application of TRT is still for R&D purposes but a continuously increasing number of tests are for commercial projects. For data analysis the most common evaluation model is still Kelvin's Line Source model, followed by numerical models and the Cylinder Source model. However, it was difficult to reach all TRT suppliers especially those who are working only on the commercial market without research activities.

In subtask 2 a list of new developments is given with a brief overview on the subject itself with examples and an assessment of advantages, benefits and problems. The topics covered more or less detailed are:

- Use of fiber optics and enhanced TRT
- TRT while drilling
- Step pulse test
- Nimo-T (Non-wired Immersible Measuring Object for Temperature measurement)

- TRT for Energy Piles
- TRT for special geometries
- Groundwater influence

An important issue within TRT is the evaluation method which was discussed in detail in subtask 3. This section covers analytical methods use the line source and cylinder source approximation and gives a description of the evaluation for the most common single pulse but also for step pulse test. All test methods require a number of input parameters which may influence the result. A detailed sensitivity analysis helps to assess the importance of these parameters. Additionally numerical methods are discussed within this report. It also covers the convergence of the result which is important for determination of the validity as well as the duration of the test. Advanced topics like groundwater influence, step pulse solution including recovery and heat extraction and corrections of fluctuation of different parameters are examined. Also a comparison of different evaluation procedures was carried out with a reference data set.

Of significant importance is also the work carried out in subtask 4 Thermal Response Test Procedure. In this section basic requirements were defined which should be compiled to general national or international guidelines or standards on TRT. It covers the required boundary conditions like the description of the site geology, the borehole design an specification of the test equipment as well as the test performance and evaluation. Regarding the equipment sensors, data logging and measurement accuracy are specified. Finally also the important aspect how to use the test results correctly is discussed. If the test parameters differ from the designed operation the test results cannot be applied directly in the design process anymore but must be recalculated to the new conditions.

Subtask 5 was responsible for dissemination activities and designed a website for display of the information available from the subtasks and the participating countries.

2. Conclusions

The outcome of the Annex 21 Thermal Response Test can help new countries to step into this new technology without passing through the whole process of R&D and to solve typical problems by themselves but to rely on the competence of an international team of experts. From this report valuable information can be extracted regarding the required test equipment, the test performance and the data evaluation as well as the application of the gained results.

In some countries the fast growing application of the Thermal Response Test procedure in the design process as a result of the introduction into the commercial market led to a fast growing number of test providers. In such booming markets sometimes unreliable fellows with lack of the theoretical background and practical experiences try to offer such services. This becomes even worse if they use poor designed TRT equipments. One objective of Annex 21 was to provide information which can be compiled for official technical guidelines and national or international standards. In Germany the VDI 4640 Guideline 'Thermal Use of the Underground' is expanded by an additional part 5 (VDI 4640 part 5 'Thermal Response Test') based on the outcome of Annex 21. The official draft will be published at the beginning of 2014.

As mentioned in the paper of Henk J.L. Witte 'Error Analysis of Thermal Response Tests' in the Appendix I of this report further R&D is required 'to incorporate this analysis in a wider scope aimed at understanding the relation between a single test and repeated tests at the same location or interpreting tests performed at several locations'.

To gain an improved quality it is important not only to define specifications in guidelines and standards but also to provide quantitative quality control by certifying test performers and test equipment. The European legislation has established a system of quality control of products and services as a result of the liberalization of global trade and the demand of the market. National accreditation bodies are responsible to assess and certify the technical competence of relevant laboratories which provide such services. It may be helpful to use such implemented structure of quality control in addition to standards and guidelines. Nevertheless it is important to provide reliable certification procedures based on scientific knowledge. Future R&D is required to develop a technique e.g. reference measurement which allows the comparison of equipment and evaluation of different test providers.

I. Appendix I

ERROR CHARACTERIZATION OF THERMAL RESPONSE TEST EQUIPMENT

Error Analysis of Thermal Response Tests (Extended Version)

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This is the extended version of the paper "Error Analysis of Thermal Response Tests" presented at the INNOSTOCK 2012 conference.

1. Introduction

The purpose of a Thermal Response Test (Gehlin 1998, Austin 1998, van Gelder et al. 1999) is to measure the equivalent thermal conductivity of the ground volume tested and thermal resistance of the borehole heat exchanger. The method is based on Fourier's law of heat conduction, which states that the heat flux in a material is proportional to the temperature gradient and thermal conductivity. A borehole heat exchanger of sufficient length with respect to it's radius can be considered as a line source, and the analytical solution of Kelvin's Line Source (Ingersoll & Plass 1948, Carslaw & Jaeger 1959) can be used to solve the heat equation and is widely used to evaluate TRT data. With the line source, by applying a constant heat flux to the ground heat exchanger, the thermal conductivity can be inferred from the constant power rate and the slope of the temperature change with log-time. Once the equivalent thermal conductivity is inferred and far field temperature is measured, the borehole resistance can be derived as well.

The method has been in use as a laboratory technique since at least 1905 (Niven 1905, Stålhane & Pyk 1931) and is well understood. Nevertheless, especially for the field tests, until now a systematic evaluation of the different sources of uncertainty (error) and their effect on the quality of the result has not been made. Some authors have at least characterized the theoretical error of the sensor array (Austin 1998, Witte et al 2002) used for carrying out the test, but other sources of error – such as fluid parameters, heat exchanger length, borehole radius but also model error or standard deviation of the regression coefficients, have so far not been considered.

To estimate the error of a TRT is not so straightforward as it may first seem. First of all, the TRT is based on a model, such as the infinite line source model (ILS), that makes very specific assumptions concerning the process. If any of these assumptions are not true, the measurement procedure cannot be used to obtain estimates of the parameters of interest (equivalent thermal conductivity and borehole resistance). The most important assumption is that conduction of heat is the only heat transport process. For instance, in situations where there is groundwater movement (advection) this is not true and the method cannot be used. Common tests use heat injection at fairly high power rates (> 50 W/m). In these tests thermally induced convection can occur which also invalidates the main assumption of the test. Other assumptions made are that the properties of the medium (thermal conductivity, heat capacity, initial temperature) are isotropic and spatially quasi-constant, that power rate during the test is constant, that the borehole heat exchanger can be represented by a line source and that the internal heat capacity of the borehole heat exchanger can be ignored or that there is no axial heat transport.

Secondly, with a TRT on a single borehole heat exchanger we are not able to obtain a representative sample of the thermal conductivity of the total ground volume, as we only have one single observation of a limited ground volume even if the same borehole is tested more than once. In that sense it is only a crude approximation to treat the result with classical statistical theory as an estimate of the true thermal conductivity of the ground, with an associated standard deviation. In fact, the thermal conductivity of the ground especially will vary as a function of space and time because the ground is not a homogeneous medium but exhibits variations in composition at different spatial scales. Then it becomes a Geo-statistical problem and probabilistic methods need to be employed (Chiles & Delfiner 1999, Bruno et al 2011). Even in one single test this may affect the result: as the temperature gradient progresses through the ground with time the actual ground volume that is tested increases and the equivalent thermal parameters vary according to its evolution. In an extreme case, for instance a test on a steeply inclined geology such as glacial push ridges, this will lead to inconclusive tests as no final estimate of "the" ground thermal conductivity is possible simply because the approximation of a quasi-constant value does not apply.

Thirdly, the test method itself introduces error, this includes errors in the sensors used or error in the power generation for the constant power pulse. Also changes in ambient conditions or even groundwater movement (rainfall, nearby extractions) introduces error.

For the purpose of this paper I consider only the estimate of the thermal conductivity and borehole resistance of one single test on one single borehole heat exchanger. The ground volume around the borehole heat exchanger that is tested is considered to be sufficiently isotropic and spatially constant in composition, so that the equivalent thermal conductivity coincides with the constant value of the parameter. To what extent this singe estimate of the equivalent ground thermal conductivity at one point location is representative of the real (reservoir) ground thermal conductivity, or how repeated tests on the same borehole should be treated, is not the subject of this paper. The error (estimate of the precision) of this single test can therefore be treated by classical statistics.

So far researches have tried to address several issues that may arise with TRT, such as variable heat rate effects or interrupted tests (Beier & Smith 2003, 2005), ground water flow (Signorelli et al 2007), inappropriate model (Bandos et al 2009, Lamarche & Beauchamp, 2007) or effects of heat capacity of the borehole (Bauer et al 2011a, Bauer et al 2011b). Also vertical profiles of thermal conductivities, that may vary between different strata, have been measured using fiber-optics (Fujii et al 2009). However, an analysis of the different possible error sources and their magnitudes has so far not been made. Austin (1998) and also Witte et al. (2002) present a calculation of the sensor array of the TRT, but that calculation does not consider any other error sources.

In a TRT the parameters of interest (thermal conductivity and borehole resistance) are estimated as a function of other variables that are repeatedly measured during the test, measured once before of after the test or estimated independently. The total error, the difference between the real value of the thermal conductivity and the estimated value, is the complex combination of:

1) Measurement error, the error associated with the precision of the sensors used in the equipment and the variations in measurements carried out repeatedly during the experiment (sampling in time). These errors introduce random variations during the test and thereby reduce the precision.

2) Parameter errors, errors in parameters that are measured once and separately (such as borehole length or fluid density) or that are estimated or obtained from other sources (such as borehole diameter, heat capacity of the fluid). This type of error is more serious, as it does not vary during the experiment but introduces bias in the result.

3) Propagation of the individual errors and the method by which they should be combined.

4) Error of the evaluation model used, the final results are obtained by the application of a theoretical relationship. Even if such relationship is evaluated using the true values of all parameters, the result (the estimate of thermal conductivity and borehole resistance) is still only an approximation of the true values.

In this paper I present a characterization of the errors associated with the first three sources listed above, and will give some general remarks about the approximation by the evaluation model.

1 Methods

Although different models are in use to evaluate the TRT results, the most widely used model is the Infinite Line Source Model (ILS). We therefore take the well-known ILS equation as a starting point and explore in a systematic way the different error sources of the variables and parameters of the equation.

In the following I will treat all errors in principle as standard deviations of the parameter. For many of the parameters involved however it is not possible to define the standard deviation. Then at least the range of the error can be estimated, where values near the centre are more likely to occur than values near the end of the error range (in qualitative terms it is a confidence interval). I will call this the *error range*.

First I will present the ILS equation and the specific parameters of interest, their estimators and to which type of error they contribute. Following this the precision and accuracy of the individual parameters will be discussed, with examples based on common sensor technology or common methods to obtain values of second type of parameters. After the individual parameters have been described a formula will be presented which combines the individual errors to an overall error for the estimate of thermal conductivity and borehole resistance. Finally some general remarks will be presented and some guidelines with regard to improving the TRT itself.

The propagation of errors is calculated using general procedures as outlined in Ellison et. al (2000) and Taylor (1997). For equations with independent parameters U and V and involving only addition / subtraction the error of the final result X can be calculated by adding the individual errors in quadrature:

$$\sigma_X = \sqrt{(\sigma_U)^2 + (\sigma_V)^2} \qquad 1$$

For equations involving multiplications or fractions, the errors are given by:

$$\frac{\sigma_X}{X} = \sqrt{(\frac{\sigma_U}{U})^2 + (\frac{\sigma_V}{V})^2} \qquad 2$$

There are some other simplifying rules, but they are not used here.

For equations where the parameters are not independent, or where the equations cannot be expressed as simple sums, products or fractions of the parameters, a numerical procedure is applied where the values of the parameters are varied by a small amount (usually about 1%) and the effect on the final result calculated. The fractional change in the result is a measure of the sensitivity of the parameter of interest to that parameter, and these are multiplied by the estimated error of the parameter and then added in quadrature to obtain the total composite error:

$$\sigma_X = \sqrt{\sigma_U \left(\frac{\partial X}{\partial U}\right)^2 + \sigma_V \left(\frac{\partial X}{\partial V}\right)^2} \qquad 3$$

The contribution of each partial derivative is estimated with a numerical procedure, where U is varied by a small amount and the effect on X calculated:

$$\frac{\partial X}{\partial U} = \frac{\Delta X}{\Delta U} \qquad 4$$

The total error is then calculated by:

$$\partial X = \sqrt{\left(\partial U \frac{\partial X}{\partial U}\right)^2 + \left(\partial V \frac{\partial X}{\partial V}\right)^{2^2}} \qquad 5$$

A spreadsheet with the calculations as presented in this paper is available on our website (http://www.groenholland.com /en/publications/trt_error.zip)

2 Infinite Line Source Equation

The ILS (Ingersoll & Plass 1948, Carslaw & Jaeger 1959) model includes both the conductivity and the borehole resistance. Gehlin (1998) gives a good review of the basic theoretical development of the ILS as applied to thermal response tests.

The basic equation for the time evolution of the average temperature at the borehole wall is:

$$T_f = \frac{Q}{4\pi\lambda H}\left[\ln\left(\frac{4\frac{\lambda}{C}t}{r_0^2}\right)-\gamma\right]+\frac{Q}{H}R_b+T_g \qquad 6$$

With Q the power rate, estimated by:

$$Q=\frac{\sum_{t=1}^{n} q_v(t)\rho c\left(T_{out}(t)-T_{in}(t)\right)}{n} \qquad 7$$

Where:

q_v	:	volume flow circulation medium	m^3/s
ρ	:	density circulation medium	kg/m^3
c	:	heat capacity circulation medium	J/(kgK)
T_{ret}	:	return temperature circulation medium	^oC
T_{in}	:	injection temperature circulation medium	^oC
T_f	:	average temperature of circulation medium	^oC
T_g	:	far field (ground) temperature	^oC
λ	:	ground thermal conductivity	W/mK
H	:	ground loop length	m
R_b	:	borehole resistance	K/(W/m)
y	:	Eulers constant	-
t	:	time	s
r_0	:	borehole radius	m
k	:	coefficient of the regression T_f with ln(t)	K/ln(s)
C	:	the ground thermal capacity	J/(kgK)

From this equation the thermal conductivity is estimated by calculating the slope *k* of the temperature increase with the log-time and inserting this into:

$$\lambda = \frac{Q}{4\pi Hk} \qquad 8$$

Once the thermal conductivity has been estimated (and the ground temperature measured) the borehole resistance can be calculated by (Bruno et al 2011):

$$R_b = \frac{H}{Q}(m - T_g) - \left[\frac{1}{4\pi\lambda}\left[\ln\left(\frac{4\frac{\lambda}{C}}{r_0^2}\right) - \gamma\right]\right] \qquad 9$$

where:

m : is the intercept of the slope of the regression T_f with ln(t) K

Table 1 gives an overview of all parameters and the associated type of error.

Table 1. Different parameters and estimators in the ILS analysis of TRT results, indicating the type class of the error: 1: measurement error, 2: parameter estimate error, 3: combination error, 4: model error.

Parameter of interest	Estimator	type class of error				note
		1	2	3	4	
λ_{TPT}	$\lambda = \frac{Q}{4\pi Hk}$			x		Estimated equivalent thermal conductivity at one location
Q	$\frac{\sum_{t=1}^{n}\left(q_v(t)\rho c\left(T_{out}(t) - T_{in}(t)\right)\right)}{n}$			x		Power rate, time dependent
ρ			x			density of the circulation medium,
c			x			heat capacity of circulation medium
Tin(t)		x				Fluid injection temperature
Tret(t)		x				Fluid return temperature
$q_v(t)$		x				fluid volume flow rate

H				x			Length of borehole heat exchanger
k						x	Slope of the regression eq. $T_f(t) = m + k.\ln(t)$
m						x	Intercept of the regression eq. $T_f(t) = m + k.\ln(t)$
T_f	$\frac{T_{ret}(t)+T_{in}(t)}{2}$	a			x	x	Fluid average temperature, see below
	$T_g + \frac{\lvert T_{ret}(t)-T_g\rvert - \lvert T_{in}(t)-T_g\rvert}{\ln\left(\lvert T_{ret}(t)-T_g\rvert / \lvert T_{in}(t)-T_g\rvert\right)}$	b					
	$T_g + \frac{p\left(\lvert T_{in}(t)-T_g\rvert^{p+1} - \lvert T_{ret}(t)-T_g\rvert^{p+1}\right)}{(1+p)\left(\lvert T_{in}(t)-T_g\rvert^{p} - \lvert T_{ret}(t)-T_g\rvert^{p}\right)}$	c					
C				x			Mean heat capacity of the ground volume
Tg	$\frac{\sum_{d=1}^{n} T(d)}{n}$ where d = depth			x			mean undisturbed ground temperature (assumed constant and isotropic)
Rb	$R_b = \frac{H}{Q}(m-T_g) + \left[\frac{1}{4\pi\lambda}\left[\ln\left(\frac{4\frac{\lambda}{C}}{r_0^2}\right) - \gamma\right]\right]$				x		Estimated borehole resistance, assuming constant and isotropic conditions
r_o				x			average borehole radius
t			x				Time

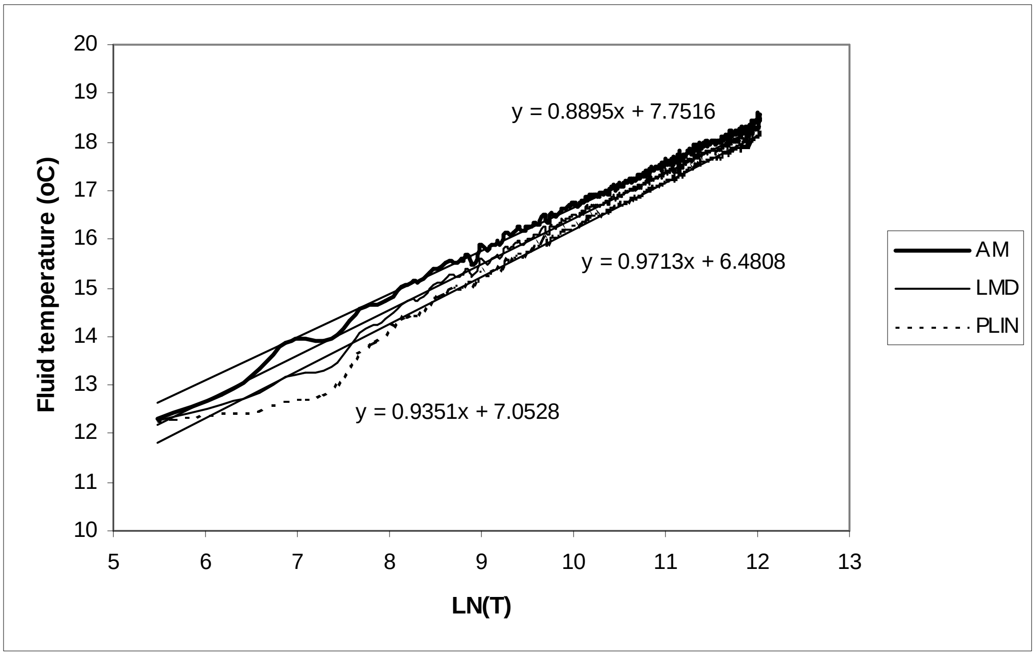
Some remarks about the terms in the table can already be made. First of all, with all parameters one should distinguish between the (unknown) true value x and the estimated (measured) value x^*. For the sake of readability and brevity I have not done that.

Secondly, it is worthwhile to note here that the average fluid temperature that is calculated from the fluid injection and fluid return temperatures can be approximated in different ways (Marcotte & Pasquier 2008). The standard method is to calculate the arithmetical mean (a), but this is only correct when the heat flux is constant along the entire borehole, which is not normally a realistic assumption. When a constant temperature on the pipe wall is assumed, the average log mean difference (b) is a good estimator of the steady state average fluid temperature (Incropera & Dewitt 1985).

Marcotte & Pasquier present an equation (c) where they assume the fluid temperature variation at power p, $|\Delta T(x)|^p$, varies linearly within the pipe between $|\Delta T_{inject}(x)|^p$ and $|\Delta T_{return}(x)|^p$.

The fact that these different methods to calculate average mean fluid temperatures do not yield equal differences in time (the rate of change is affected) means they will yield different results of estimates of thermal conductivity and borehole resistance as well. An example of the effect of the different averaging methods on the linear regression equation is shown in figure 1. In this typical example, the resulting thermal conductivity values estimated would be: 2,11 (AM average), 1.94 (LMD average) and 2,01 (PLIN average). Also note that, in comparison with the AM method, another parameter (T_g) is introduced that needs to be estimated seperately.

Figure 1.Effect of different averaging methods (AM: Arithmetical Mean; LMD: Log Mean Difference; PLIN: P-linear average with p=-0.9).



3 Results

3.1 Measurement errors.

The measurement errors relate to the repeated measurements of the process variables, specifically the measured flow rate, injection and return fluid temperatures. In some cases the electrical power input is measured by a watt-transducer to obtain a direct measurement of power input. The measurement error can be separated in three distinct error types:

1) Accuracy (the closeness of the measured value to the true value). This type of error introduces a bias in the results and should be zero. This is achieved by proper calibration of the sensor system. I assume these errors are zero.
2) Precision, the degree of scatter of the measurement when repeated measurements are made under perfectly constant conditions. This error depends on the characteristic and quality of the sensor system itself and the way in which it is installed in the system.
3) Perturbation of the actual value of the parameter measured, for instance small changes in fluid temperature do occur during measurements. Strictly speaking this is not a measurement error but related to the sampling frequency and how the sensor measures (time-averaging or instantanuous readings).

The measurement error during a test is a result of the precision and perturbation errors. An evaluation of the quality of a test should include a comparison at least of the measured variation with the calculated error range based on the sensor system's precision. Measurements that need to be considered are: flow, injection and return fluid temperature, power input (in the case of watt transducers) and time.

Fluid flow is measured with a flow meter, of which different type exist, with different characteristics. In general volume flow will be measured with an electro-magnetic type flow meter, as this is a robust and easily integrated instrument, other methods include differential pressure, vortex, sonic or mechanical flow meters. It is also possible to directly measure mass flow (by e.g. using a coriolis type flow meter). Errors of flow meters are usually stated as a percentage of flow measured, sometimes with an additional minimum value below a certain threshold. There can be an additional temperature dependence of the error, but this error is very small and ignored here. Table 2 lists some typical errors as given by the manufacturers for different types of flow meters. The absolute error is calculated at a flow rate of 1.5 m^3/hrs and 20 ^oC, this is indication of the maximum error of flow expected in a typical TRT.

Table 2. Relative and absolute errors of different type of flow meters, data from manufacturers.

Sensor type	Relative error %	Absolute error (@ 1.5 m3/hr)
Electro-magnetic (0-1.5m^3/hr) installed in DN50 pipe	±0.33%	± 0.0050 m^3/hr
Coriolis-mass	± 0.15%	± 3.36 kg /hr
Coriolis-volume	± 0.25%	± 0.0004 m^3/hr

Ultrasonic	± 0.50 %	± 0.0075 m3/hr

Fluid injection and return temperature. Temperature can be measured by several different sensors types. Due to its ruggedness, stability of measurement over time and easy of installation PT100 type will normally be used (PT500 or PT1000 are essentially the same but have a different ohmic resistance at 0 ^{o}C). PT100 sensors are manufactured according to a norm (IEC 60751) and available in different classes, class A tolerance is 0.15 + 0.002|T|; class B tolerance is 0.3 + 0.005|T|.

Form the tolerance statement it is clear that there is a temperature dependence on the precision of the sensor, in the range -50 to +50 ^{o}C this error is 0.1K, in the range -25 to +25 ^{o}C it is 0.05K, in the range -5 to +5 ^{o}C the additional error is 0.01K. Within the typical temperature range of a TRT the total temperature sensor error increases from 0.15 to 0.25K. When calculating the temperature difference the errors can be added in quadrature, the error interval on ΔT ranges from 0.21K to 0.35K.

The error on the temperature measurement is fairly large in view of the most interesting quantity (temperature difference) used for calculating the power rate. It is therefore worthwhile to carefully calibrate the two installed sensors and obtain a matched pair for the temperature difference measurement. In a careful calibration of the actual sensors in the TRT of Groenholland, we achieve a measured error interval on ΔT of ± 0.06K.

Table 3.Typical error of the PT100 temperature sensor in the process temperature range -5 - 50 ^{o}C.

Sensor type	**Relative**	**Absolute**
PT100 @ 0.5 ^{o}C	± 30.0%	± 0.15K
PT100 @ 50 ^{o}C	± 0.5%	± 0.25K
PT100 pair, ΔT, @ 20 ^{o}C, 5K ΔT	± 5.4%	± 0.27K
PT100 matched pair, ΔT, @ 0 ^{o}C	± 1.2%	± 0.06K

Watt-transducers, with Thermal Response Test utilizing direct electrical heater elements sometimes a watt-transducer is used to measure (electrical) power input and use this as an estimate of thermal power input. Although the precision of these meters can be quite good (relative error range < 2%), not all electrical power is necessarily completely transferred to the fluid. Also, heat rejection to the fluid by the pump (which is often cooled by the fluid) is not measured. Therefore, the watt transducer is included for completeness but not evaluated further.

Measurement of time. The time drift of data loggers is normally small, especially with regard to the measurement period. Typical clock accuracy for data logger's range between 180s/year and 492 s/year. For a test duration of 100 hours, this would yield a clock error of $8.6\ 10^{-4}$ s to $1.6\ 10^{-3}$ s. This is so small that it is further ignored.

3.2 Parameter errors.

Included here are parameters that are measured once before the test and parameters that are estimated based on other sources such as literature values. These parameters include the circulation medium density and heat capacity (as well as viscosity and thermal conductivity, but those are not parameters in the ILS equation), borehole heat exchanger length, heat capacity of the ground volume tested and borehole diameter.

Density and heat capacity of the fluid medium are needed in the calculation of the heat rate. The fluid parameters vary with fluid type, mixing ratio and temperature. Due to the dependence on temperature they will vary during the experiment as well. The physical properties of water are well documented, but in Thermal Response Tests other fluids can be used. Especially anti-freeze mixes of water and monoethyleneglycol (MEG) or monopropyleneglycol (MPG) are used. The error in the estimated properties of those mixes then depend on:

1) The physical properties of the pure product, these are obtained from manufacturers data properties (I use data published by DOW chemical) and the accuracy or precision of these data is not known. As the chemical composition of the product is quality-controlled during production one may assume these values to be fairly accurate. Another source of pure-product data are the correlations and mixing rules published by different authors (see Witte, 2010, Haider Kahn 2000 and Melinder 2010 for an overview)
2) The mixing ratio between water and the product. This mixing ratio needs to be estimated. In general the circulation fluid used for a TRT will have a antifreeze content of up to 35% by volume.
3) The variation of the properties with temperature changes during the experiment.

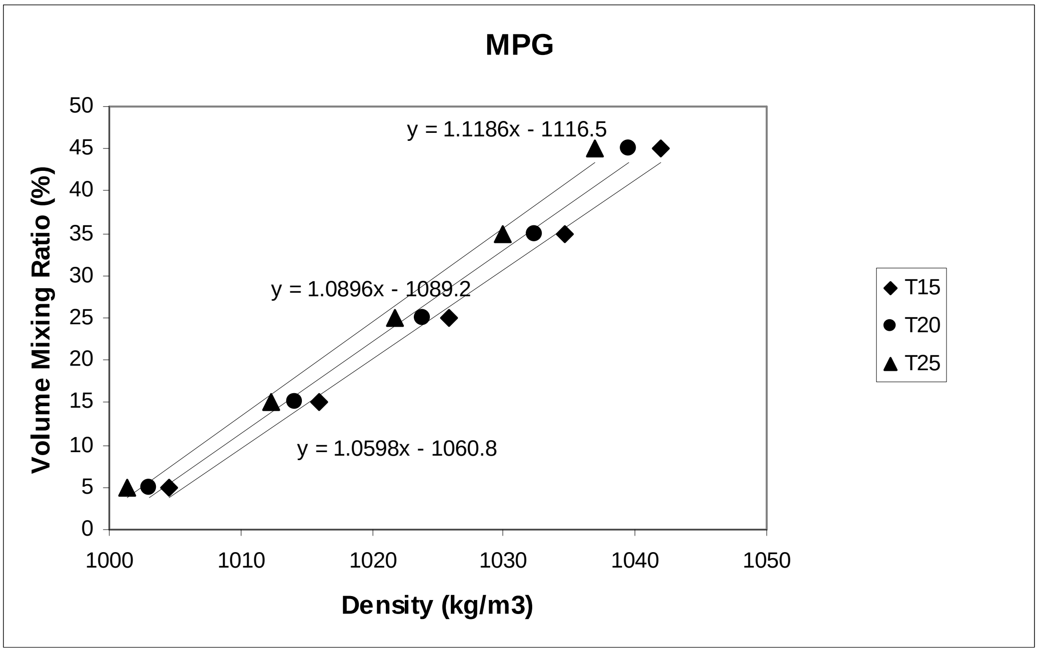
To estimate the mixing ratio a sample from the fluid used in the test is taken and the density and temperature of this sample is measured. With this data the mixing ratio can be estimated from a look-up value in a table of temperature - density data of different mixing ratios. The density can be measured with a precision of about 1:1000 and temperature better than 0.5 ^{o}C. Figure 2 shows the change in density for MPG and MEG for different mixing ratios at bulk temperatures of 15, 20 and 25 ^{o}C, table 4 shows the maximum errors of the density and mixing ratio estimates.

Considering the error introduced by the density and temperature measurements the combined maximum error for estimating the mixing ratio for MPG is 1.04% and for MEG 0.98%.

Table 4. Maximum error range in fluid properties (mixing ratio and resulting error in heat capacity) for MPG (35% by volume) and MEG (35% by volume), based on density measurement.

Fluid	Property	Relative	Absolute
MPG	Density	1.5%	16.2 kg/m^3
MPG	Mixing ratio	2.9%	1.0 % point
MPG	Heat capacity	2.0%	90.0 J/kgK
MEG	Density	1.5%	13.8 kg/m^3
MEG	Mixing ratio	2.8%	0.98 % point
MEG	Heat capacity	2.0%	90.0 J/kgK

Figure 2. Relationship between density (kg/m^3) and volume mixing ratio (%) at three different bulk temperatures for MPG (top) and MEG (bottom).



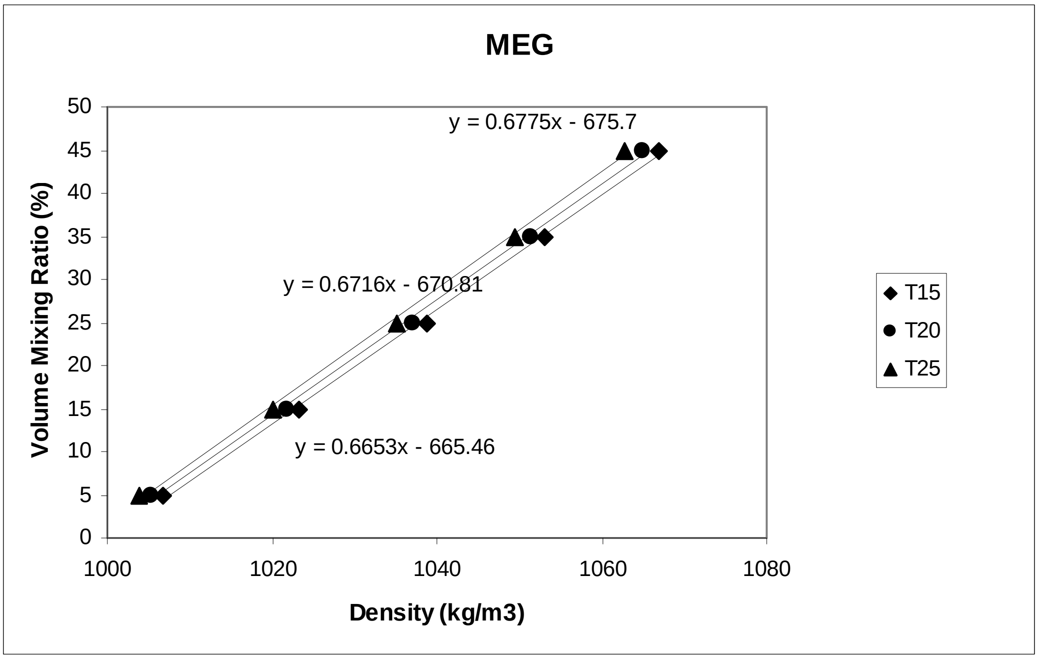
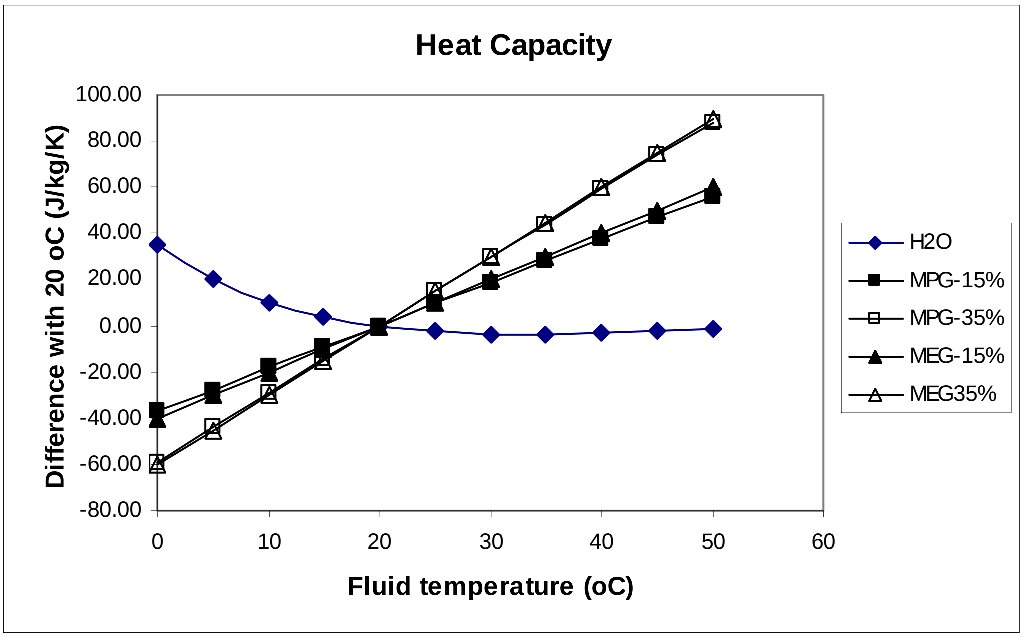
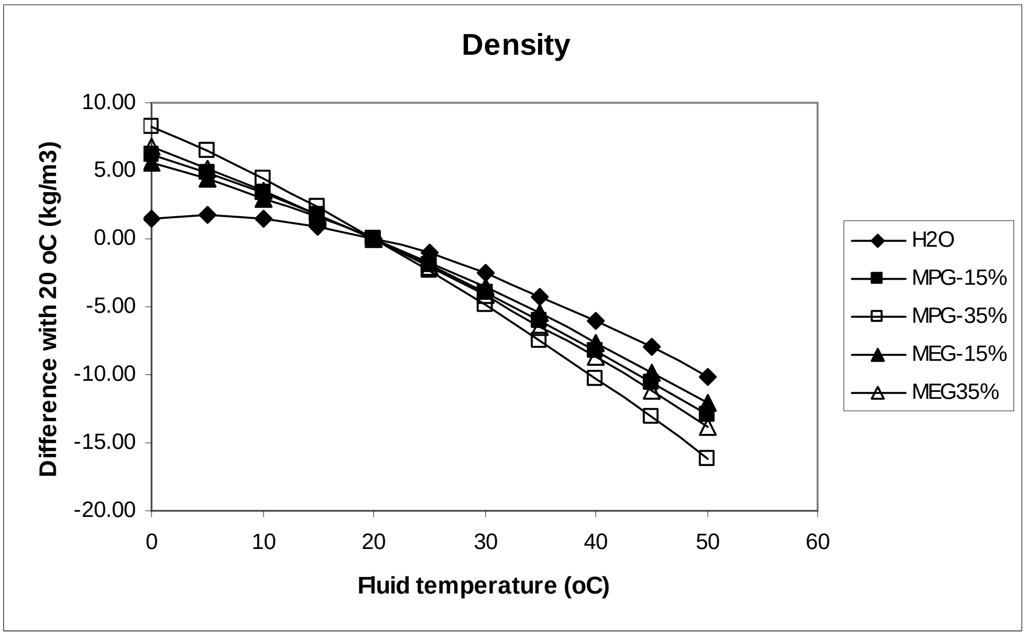

MEG
Volume Mixing Ratio (%)
Density (kg/m3)
y = 0.6775x - 675.7
y = 0.6716x - 670.81
y = 0.6653x - 665.46
T15
T20
T25
0
5
10
15
20
25
30
35
40
45
50
1000
1020
1040
1060
1080

Figure 3. Absolute difference between the fluid properties at different temperatures and taken at 20 °C. Heat capacity (top) and density (bottom).





Once the mixing ratio is known the heat capacity at a specific temperature can be found, assuming the variations in properties of the actual product and the manufacturers data can be ignored, the error in estimated heat capacity as a function of the error in mixing ratio can be calculated. At a bulk temperature of 20 °C the heat capacity of MPG changes at a rate of 12

(J/kgK)/% for MPG and 15.8 (J/kgK)/%, with an error of 1% of mixing ratio this results in an estimated error of heat capacity of 0.3% (MPG) and 0.4% (MEG).

The properties of the fluid are used especially for the calculation of the thermal power, if the fluid properties are taken at a fixed arbitrary constant fluid temperature an additional error will be introduced as the fluid temperature changes during the TRT. To estimate this error we will examine the variation of density and heat capacity with temperature. Figure 3 shows the absolute differences between the fluid properties density and heat capacity at different temperatures compared with the values at 20 ^{o}C, for water, a 15% and 35% mix of MPG or MEG. The maximum absolute error for the heat capacity is about 90 J/kgK for both MPG and MED at 35% mixing ratio and 50 ^{o}C bulk temperature (about 2%). Difference in density is -16.2 kg/m^3 (MPG) and -13.8 kg/m^3 (MEG) at 50 ^{o}C bulk temperature (about 1.5%). A summary of the maximum errors associated with the errors in mixing ratio estimate and variation of parameters with fluid temperature during the test, for density and heat capacity, is given in table 5. Overall error ranges are small and can be minimized by calculating the power rate at every time step using the temperature-corrected fluid properties.

Table 5. Estimated error range in fluid properties when taken at fixed temperature for water, MPG and MEG, values compared with the values at 20 ^{o}C.

Fluid	Property	Relative	Absolute
Water	Density	1.00%	-10.2
Water	Heat capacity	0.83%	35.0
MPG	Density	1.56%	-16.2
MPG	Heat capacity	2.32%	88.0
MEG	Density	1.31%	-13.8
MEG	Heat capacity	2.51%	90.0

The volumetric heat capacity of the ground (C) is usually not measured but estimated from the geological profile by calculating the weighted average of reference values (with the soil layer thickness as weight). An estimate of the error range in this parameter is not easy to define, but in a range for heat capacity of 2.0 - 3.4 MJ/m^3/K an error range of about ± 0.20 - 0.51 MJ/m^{3}K (a 10-15% error) seems reasonably conservative. A new method (Bruno et al 2011) allows the estimation of the heat capacity together with the borehole resisistance. However, the conditional estimation procedure needs limit values and the error range for the heat capacity in the limit range used becomes the error standard deviation.

The active length of the borehole heat exchanger (H). Any TRT should measure the actual active depth of the borehole heat exchanger. With a typical measuring tape a precision of centimeters or even millimeters can be achieved, but it may be accurate only to 20 - 50 centimeters. Calibration of the tape measure should not be forgotten, as the measure used will introduce systematic error in the results (of all tests performed). Moreover, the error will affect results also depending on the length of the loop installed, a 1 meter error on a 20 meter loop will give a much larger error in specific heat rate than the same error on a 100 meter deep loop. Also, when a borehole is not correctly backfilled it may cave-in during the test altering the active length as well as introducing other disturbances.

With the borehole radius (r_o) we need to consider the measurement error as well as the probable variation of the borehole radius over the whole borehole length. In practice the bore-hole radius will not often be actually measured, but estimated based on drilling rod diameter. Typical borehole radius lies between 0.08 - 0.012 m, with a precision of 0.015 - 0.025 m. It has to be kept in mind however that careless drilling may produce much bigger deviations from the borehole radius (caving).

To calculate the final error we need the **slope coefficient and intercept** of the regression equation. Although these are strictly speaking, according to the classification, model errors, I include a general description of the error now as they will be needed further on.

The error of the regression coefficient cannot be known beforehand as it depends on the time-temperature evolution of the experiment realization. Assuming that the fundamental assumptions of the linear regression hold, the precision of the intercept *m* and slope coefficient *k* can be expressed by their standard deviation. Using the standard deviation of the regression coefficient, the 95% confidence interval can be calculated by: ± 1.96[1] * stdev(*k*).

Typical values for the standard deviation of the regression slope are 0.001 - 0.010 K/ln(s), yielding a 95% confidence interval of 0.002 to 0.020 K/ln(s). The intercept shows typical standard deviations of 0.05 - 0.10 K, yielding confidence intervals of 0.10 - 0.20 K.

3.3 Propagation errors (combination)

In the error calculations I give some examples based on fairly typical values of parameters and individual parameter errors, these values are listed in table 6. In the error equations it is assumed that the individual terms are independent.

Table 6. Reference values for the error ranges of the different measured variables and parameters used for the calculation of the combined errors.

Parameter	Error range		Reference value
	Absolute	Reference	
q_v, volume flow (m^3/hr)	±0.005	0.33%	1.5
ρ, density of medium (kg/m3)	±10.0	1.00%	1000
c, heat capacity of medium (J/(kgK)	±80.0	2.00%	4000
Tin, injection fluid temperature (oC)	±0.15	-	25

[1] *The multiplier is taken from the T distribution and depends on the significance level chosen and the degrees of freedom. As the number of observations (n) in a TRT is large (>> 100) and the degrees of freedom equals n - 2, 1.96 for the 95% and 2.576 for the 99% confidence intervals can be used. Assuming, amongst others, that the errors are distributed normally around the regression line*

Tret, return fluid temperature (oC)	±0.15	-	20
ΔT, temperature difference (K)	±0.212	4.25%	5
Tf, average fluid temperature (oC)	±0.106	*0.53*	-
Tg, far field temperature (oC)	±0.034	0.23%	15
H, loop length (m)	±1.0	1.00%	100
t, time (s)	±4.38 10^{-4}	-	-
r_o, borehole radius (m)	±0.020	26.00%	0.10
C, vol. heat capacity of ground (MJ/(m^3K)	±0.5	20%	2.4
k, slope coefficient	±0.010	1.50%	0.75
m, intercept	±0.100	0.52%	19.5

First some parameters are considered that are made up of either a combination of measurements (temperature difference, average fluid temperature) or are made up of a sequence of measurements (such as average undisturbed ground temperature).

The error in the calculated temperature difference depends on the error in the individual sensors, these are combined:

$$\delta\Delta T_f = \sqrt{(\delta T_{ret})^2 + (\delta T_{in})^2} \qquad 10$$

With a typical sensor error of 0.15K (at 0 °C) this becomes:

$$\delta\Delta T_f = \sqrt{(0.15)^2 + (0.15)^2} = 0.212K \qquad 11$$

At a bulk temperature of 50 °C the error increases to 0.354K.

Here it is assumed that the difference between injection and return temperature is constant (which in a TRT it should be). This may not be always true, for instance during the start of the heat injection or extraction pulse or due to variations in power. In those cases it may be needed to take into consideration the plug-flow travel time (time lag) and calculate the temperature differences taking into account an appropriate time lag.

Average fluid temperature (T_f). The error standard deviation of the arithmetical mean of fluid temperature is calculated by:

$$\delta T_f = \frac{\sqrt{(\delta T_{ret})^2 + (\delta T_{in})^2}}{2} \qquad 12$$

With a typical sensor error of 0.15K (at 0 °C) this becomes:

$$\delta T_f = \frac{\sqrt{(0.15)^2 + (0.15)^2}}{2} = 0.106K \qquad 13$$

At a bulk temperature of 50 °C the error increases to 0.177K.

The error standard deviation of the log mean difference and p-linear average depend also on the undisturbed ground temperature, so I will discuss that first.

In the ideal situation the undisturbed ground temperature is measured by lowering a sensor into the borehole heat exchanger, after this has reached temperature equilibrium with its surroundings, and temperature measurements are taken at regular intervals. Other methods to measure the vertical ground temperature profile exist and may introduce other errors, but these will not be discussed here.

If we only consider the error standard deviation in the measurements and how they add up to the total error in average ground temperature, the estimate of the error standard deviation is:

$$\delta T_g = \frac{\sqrt{\sum_{d=1}^{n} (\delta T_g(d))^2}}{n} \qquad 14$$

Measuring every 5 meters in a 100 meter deep borehole heat exchanger results in an error of 0.034K (using an error of 0.15K for the individual measurements).

To define the errors in the LMD and PLIN averages we need to use the general procedure by taking the partial derivatives as the parameters are not independent. The equations for the combination error standard deviations are:

$$\delta T_f = \sqrt{\left(\frac{\Delta T_f}{\Delta T_g}\delta T_g\right)^2 + \left(\frac{\Delta T_f}{\Delta T_{in}}\delta T_{in}\right)^2 + \left(\frac{\Delta T_f}{\Delta T_{out}}\delta T_{out}\right)^2} \qquad 15$$

The formulas for the error standard deviation of the LMD and PLIN averages are the same, but of course the equation for generating the different solutions (T_f) are not. The final results are:

LMD error

$$\delta T_f = \sqrt{\left(\frac{0.006}{0.150}0.034\right)^2 + \left(\frac{0.101}{0.250}0.150\right)^2 + \left(\frac{0.129}{0.200}0.150\right)^2} = 0.114K$$

PLIN error (with p = -0.9):

$$\delta T_f = \sqrt{\left(\frac{0.011}{-0.150}0.034\right)^2 + \left(\frac{-0.08}{-0.250}0.150\right)^2 + \left(\frac{-0.154}{-0.200}0.150\right)^2} = 0.125K$$

Of course, these errors should be calculated for every time step of an experiment realization and then added again, as the error of the average fluid temperature depends on the Tin and Tout measurements that vary during the experiment. For more precise calculation the dependence of the sensor error on the actual fluid temperature should be taken into account as well.

Now we proceed to the error range of the **thermal power rate Q**. The thermal power rate is calculated by:

$$Q = q_v \rho c \Delta T_f \qquad 16$$

The composite error range on the thermal power rate is given by:

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta q_v}{q_v}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta c}{c}\right)^2 + \left(\frac{\delta \Delta T_f}{\Delta T_f}\right)^2} \qquad 17$$

Using the error range and reference values in table (6), with a reference power rate of 30GJ, we obtain:

$$\delta Q = Q * \sqrt{\left(\frac{0.005}{1.5}\right)^2 + \left(\frac{10}{1000}\right)^2 + \left(\frac{80}{4000}\right)^2 + \left(\frac{0.212}{5}\right)^2} = 30 * 0.048 = 1.44 MJ (400W)$$

With an heat rate of 30GJ (8.33 kW) the error range is ± 1.44 MJ (400 Watt) or 4.8%. The largest contribution to the error is the measurement of ΔT, effort should be made to achieve as accurate a calibration as possible.

It is important to note that in the power rate there may be another error which is unknown: the pressure loss in the pipe is of course due to the conversion of kinetic energy to friction (heat), as this heat is not measured by the temperature sensors it introduces a bias in the test.

3.4 Error of parameters of interest (combination)

Having defined the measurement errors and errors in other parameters, the error of the final result (estimate of the parameters of interest, thermal conductivity and borehole resistance) depends on how all errors are combined to the final error of the estimate. Error propagation is calculated using the standard rules of combining errors in quadrature. The example calculations use the reference values given in Table 6.

The estimate of **thermal conductivity (λ_{trt})** is obtained by:

$$\lambda_{TRT} = \frac{q_v \rho c \Delta T}{4 \pi H k} \qquad 18$$

And the composite fractional error range can be approximated by:

$$\frac{\delta \lambda_{TRT}}{\lambda_{TRT}} = \sqrt{\left(\frac{\delta q_v}{q_v}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta c}{c}\right)^2 + \left(\frac{\delta \Delta T}{\Delta T}\right)^2 + \left(\frac{\delta H}{H}\right)^2 + \left(\frac{\delta k}{k}\right)^2} \qquad 19$$

Using the individual errors and reference values as above, and assuming a value for the thermal conductivity of 2.5, we obtain:

$$\delta\lambda_{TRT} = \lambda_{TRT} * \sqrt{\left(\frac{0.005}{1.5}\right)^2 + \left(\frac{10}{1000}\right)^2 + \left(\frac{80}{4000}\right)^2 + \left(\frac{0.212}{5}\right)^2 + \left(\frac{1}{100}\right)^2 + \left(\frac{0.01}{0.75}\right)^2}$$

= 0.051 * 2.5 = 0.127 W/mK which is about 5.1%.

The largest contribution to the total error (calculated as the contribution to the sum of squares) is the temperature difference (70%) followed by the fluid heat capacity (15.5%) and error on the slope of the regression coefficient (6.9%).

The **borehole resistance (Rb)** is given by:

$$R_b = \frac{H}{Q}\left(m - T_g\right) + \left[\frac{1}{4\pi\lambda}\left[\ln\left(\frac{4\frac{\lambda}{C}}{r_0^2}\right) - \gamma\right]\right] \qquad 20$$

Unfortunately, the definition of the composite error for is not so easy[2]. need to apply a more general procedure and derive the partial derivatives, the uncertainty of the estimate of borehole resistance δRb is then defined as:

$$\partial R_b = \sqrt{\left(\frac{\Delta R_b}{\Delta H}\delta H\right)^2 + \left(\frac{\Delta R_b}{\Delta Q}\delta Q\right)^2 + \left(\frac{\Delta R_b}{\Delta m}\delta m\right)^2 + \left(\frac{\Delta R_b}{\Delta T_g}\delta T_g\right)^2 + \left(\frac{\Delta R_b}{\Delta\lambda}\delta\lambda\right)^2 + \left(\frac{\Delta R_b}{\Delta C}\delta C\right)^2 + \left(\frac{\Delta R_b}{\Delta r_o}\partial r_o\right)^2} \qquad 21$$

Calculating the partial derivatives as before, using a spreadsheet and the typical values of table 6, we obtain:

[2] Although the u ncertainty in the first part of the equantion, $\frac{H}{Q}\left(m - T_g\right)$, can be expressed using the simple rules for addition, multiplication and division the second part cannot be expressed as a set of independent functions. For brevity sake I have included the full formula using partial derivatives.

$\delta R_b =$

$$\sqrt{\left(\frac{-0.0003}{1.2}1\right)^2+\left(\frac{0.0003}{83.3}400\right)^2+\left(\frac{0.0019}{0.135}0.15\right)^2+\left(\frac{-0.0023}{0.158}0.034\right)^2+\left(\frac{-0.0030}{0.025}0.213\right)^2+\left(\frac{0.0003}{24000}0.5\right)^2+\left(\frac{0.00064}{0.001}0.01\right)^2} = 0.027K/(W/m)$$

The total error of Rb in this example is 11.5%. By far the largest contribution to the error is the thermal conductivity, accounting for 93% of the total error. The borehole radius is the second largest (5.8%) followed by the intercept of the regression coefficient (0.66%).

3.5 Model errors

The first consideration is if and to what extent the estimator (3) is a good estimator of the true ground thermal conductivity of the ground volume that is tested (if the true thermal conductivity of the tested ground volume is a good estimator of the reservoir thermal conductivity is another question) and (4) of borehole resistance. This depends on a number of assumptions that are not always possible to test, including (Witte, 2009):

1. The heat transport in the ground is by conduction only
2. The thermal conductivity in the tested ground volume is isotropic and constant in time and space.
3. There is no axial heat transport
4. There is no effect of heat capacity in the borehole
5. The borehole heat exchanger is accurately approximated by a line source
6. There is, after an initial transient state, a steady state borehole resistance
7. The power flux is constant

Some examples of processes that invalidate the above assumptions are: groundwater flow (1), variations in geology and associated thermal conductivities of composite materials, for instance inclusions like clay lenses or gravel beds (2), changing phreatic water table (2, 3, 6), large temperature changes at the surface or due to geothermal gradients (3), large radius boreholes or boreholes filled with high-capacity backfilling (4), short boreholes (5) and fluctuations in power output (7).

Even if all fundamental assumptions hold, there is still a difference between the ILS and the true model. The logarithmic term in the ILS model (1) is only an approximation of the exponential integral. The error is given by (Hëllstrom 1981):

$$\frac{at}{r_0^2} \qquad 21$$

The relative error is < 10% when this value is < 5 and < 2.5% when this value < 20.

The coefficients of the linear regression of slope (k) and intercept (m) are in fact also model errors. The least squares linear regression method that is normally used to obtain estimates of these coefficients also makes definite assumptions about the data, especially: that the relationship is linear, that the errors are normally distributed, uncorrelated and independent, have zero mean and have constant variance. In the case of a TRT there may be nonlinearity introduced by power drift or by changes in ambient conditions (either as a drift or as cyclic effects). Moreover, the errors are not uncorrelated but are auto-correlated in time, therefore the standard deviation of the regression coefficients are not correct estimators of the error. The linear regression model should always be checked for lack of fit and significance of coefficients.

Also the fact that the regression is carried out with log-time, but the sampling takes place at fixed time intervals, introduces a possible error source. The density of observation points will increase as the TRT test time increases, giving relatively more weight to later times. This effect can be mitigated by resampling (or applying appropriate weights to) the data in such a way that the relative data-density does not change. A possible resampling scheme would be to resample the data with constant spacing between observations on the log-time scale (e.g. every 0.15 units) and calculating the required spacing of the sampled data points by taking the inverse of the logarithm. For example, suppose we have 75 hours of data with a sampling frequency of 60 seconds. The logarithmic scale ranges from 4 (first data point) to 12.51. In total there will be 4500 data points, which we can resample on a equidistant log scale by selecting subsequent data points at a distance (in seconds) of e^{lstep} where *lstep* is the value on the log-scale (between 4 and 12.5) with a constant increase yielding 56 equidistant data points. This procedure could be repeated, selecting random starting points, in a bootstrap procedure (Effron and Tibshirani, 1993) to obtain estimates of the standard error of the regression coefficients using all data. Alternatively, e^{lstep} can be used as weights in the regression equation.

The regression should of course still be checked for lack of fit.

The average fluid temperature, especially the way in which this is calculated, is also a model error in the sense that it depends on our assumptions concerning the boundary conditions of fixed temperature or fixed heat flux on the borehole wall. The ILS method of TRT really assumes constant heat flux, but that is probably not realistic. Marcotte & Pasquier (2008) show that a P-linear estimator with p -> -1 gives the best unbiased estimate of average fluid temperature.

4 Conclusions

TRT results are widely used to assess the potential for geothermal systems and to design these systems. Feasibility, cost and performance of the geothermal installations using borehole heat exchangers depends to a large extent on these parameters.

The TRT is in itself a straightforward method, albeit not easy to execute with sufficient accuracy under field conditions. Lacking in current TRT reporting is an evaluation of fundamental assumptions and error evaluation. To be able to successfully apply a TRT result in a project, a TRT report needs to include a chapter on quality control. This chapter needs to give the following information:

- Qualitative assessment of test location and test results with regard to fundamental assumptions of the TRT.
- Estimate of thermal conductivity and borehole resistance based on site geology, these can be used to select appropriate test conditions.
- Calculation (using the TRT machine characteristics and site test conditions) of the theoretical error and observed error. Explanation of any differences between these.
- Explicit choice of formula for calculation of average temperature.
- Examination of regression with regard to lack of fit and error, error of coefficients calculated with bootstrap method where resampling takes into account differences in data-densities.
- Plotting CUSUM (Cumulative SUM) charts of estimated thermal conductivity especially noting if estimates converge to a stable value.

In this paper I have given an overview of the error sources of a Thermal Response Test and have given some example calculations for typical situations. Results show a clear ranking of the magnitudes of the different individual errors in the TRT analyses. Large relative errors are found for the borehole radius (26%), soil heat capacity (20%) and measured temperature difference (4.25%). For the composite errors, for the power rate, especially the temperature difference is important. The error of the thermal conductivity estimate also depends to a large extent on the temperature difference (70%), the fluid heat capacity (15.5%) and the slope error (6.9%).

For the estimate of the borehole resistance the estimated thermal conductivity contributes over 90% to the total error, the borehole radius 5.8% and the intercept of the regression 0.66%.

Note that the error calculations are based on the estimated errors of the different parameters, if there is an issue with the accuracy the result can be quite different. For instance, the estimated undisturbed ground temperature has a small effect on the error of the borehole resistance based on the error of the individual temperature measurements. If this parameter is not measured accurately however, the contribution to the bias of the borehole resistance can be quite large.

The results also indicate a number of possibilities and areas where the error in the TRT can be decreased. A careful calibration of the temperature sensors used to calculate the temperature difference is of main importance. One of the methods to decrease error and bias in the regression line calculation is by resampling the data to obtain an even distribution of observations on the log-time scale. Also the correct choice of method to obtain the average fluid temperature is essential.

Clearly, the experimenter's choice with regard to experiment settings is important. Sometimes selecting a high flow rate is advocated, but this will affect the experiment in two ways. First of all it will decrease the temperature difference, which results in a larger relative measurement error. Moreover, the conversion of pump kinetic to thermal energy (pressure loss), which cannot be measured by the temperature sensors, will also be larger. It is therefore better to select a lower flow rate and higher temperature difference for the experiment.

Further work is needed to incorporate this analysis in a wider scope aimed at understanding the relation between a single test and repeated tests at the same location or interpreting tests performed at several locations. A more detailed and quantitative quality control protocol would need to be developed to allow tests of different test performers to be compared.

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References

Austin, III, W.A. 1998: Development of an in situ system for measurement for ground thermal properties. MSc Thesis, Oklahoma State University. 164 pp.

Bandos, T.V., Montero, Á., Fernándeza, E., Santandera J.L.G, Isidroa, J.M., Péreza, J., Fernández de Córdoba, P.J., Urchueguía, J.F.. 2009 Finite line-source model for borehole heat exchangers: effect of vertical temperature variations. Geothermics, 38: 263-270.

Bauer, D., Heidemann, W., Müller-Steinhagen, H. and Diersch, H.-J. G., 2011a. Thermal resistance and capacity models for borehole heat exchangers. International Journal of Energy Research, 35: 312–320.

Bauer, D., Heidemann, W., Diersch, H.-J.G.. 2011b. Transient 3D analysis of borehole heat exchanger modeling, Geothermics, Volume 40, Issue 4, pp 250-260.

Beier, R.A. & Smith, M.D., 2003. Removing variable heat rate effects from borehole tests. ASHRAE Transactions Vol. 109, Part 2, pp. 463-474

Beier, R.A. & Smith, M.D., 2005. Interrupted In-Situ Tests on Vertical Boreholes. ASHRAE Transactions Vol. 111, Part 1, pp. 702-713.

Bruno, R, Focaccia, S. & Tinti, F., 2011. Geostatistical modeling of a shallow geothermal reservoir for air conditioning of buildings. Proceeding of IAMG 2011 Salzburg, “Mathematical Geosciences at the Crossroads of Theory and Practice, pp. 146-163.

Carslaw, H.S., Jaeger, J.C., 1959. Conduction of heat in solids, second edition. Clarendon Press, Oxford.

Chiles, J.P. & Delfiner, P. 1999. Geostatistics: Modeling Spatial Uncertainty. Whiley, New York. 696 pp.

Effron , B. and Tibshirani, R.J. 1993. An Introduction to the Bootstrap. Chapman & Hall. 436 pp

Fujii, H., Okubo, H., Nishi, K., Itoi, R. Ohyama, K. and Shibata, K., 2009. An improved thermal response test for U-tube ground heat exchanger based on optical fiber thermometers,Geothermics,Vol.38,No.4,pp.399-406,.12.

Gehlin, S. 1998: Thermal Response Test, In-Situ Measurements of Thermal Properties in Hard Rock. Licentiate Thesis, LULEÅ University of Technology. 42 pp.

Haider Kahn, M. 2000. Modeling, simulation and optimization of ground source heat pump systems. BSc Thesis, Oklahoma State University. 218 pp.

Incropera, F.P. & Dewitt, D.P., 1985. Fundamentals of heat and mass transfer, 2nd edition. Wiley New York, 802 pp.

Ingersoll, L.R. and Plass, H.J. 1948: Theory of the Ground Pipe heat Source for the Heat Pump. Heating, Piping & Air Conditioning. July. Pp. 119 – 122.

Lamarche, L. & Beauchamp B., 2007. A new contribution to the finite line-source model for geothermal boreholes. Energy and Buildings, 39(2): 188-198.

Marcotte, D. & Pasquier, P. 2008. On the estimation of thermal resistance in borehole thermal conductivity test. Renewable Energy, 33(11): 2407 – 2415.

Melinder, Å (ed), 2010. Properties of secondary working fluids for indirect systems. International Insititute of Refrigeration (IIR).

Mogeson, P.1983: Fluid to Duct Wall Heat Transfer in Duct System Heat Storages. Proceedings of the International Conference on Subsurface Heat Storage in Theory and Practice. Swedish Council for Building Research.

Niven, C, 1905: On a method of finding the conductivity for heat. Proc. R. Soc. Lond. A. 76: 34-48.

Signorelli, S., Bassetti, S., Pahud, D. & Kohl, T., 2007. Numerical evaluation of thermal response tests. Geothermics, 36(2): 141-166.

Stålhane, B. & Pyk, S., 1931: Ny metod för bestämning av värmeledningskoefficienter. Teknisk Tidskrift, 28, Svenska Teknologföreningen.

Taylor, J.R., 1997 An introduction to error analysis: the study of uncertainties in physical measurements. University Science Books, 327 pp.

Van Gelder, A.J., Witte, H.J.L., Kalma, S., Snijders, A. and R.G.A. Wennekes 1999: In-situ Messungen der thermische Eigenschaften des Untergrunds durch Wärmeentzug. IN: T. Hitziger (Ed): OPET Seminar "Erdgekoppelte Wärmepumpen zum heizen und Klimatisieren von Gebäuden. 109 pp.

Witte, H.J.L. 2006. Geothermal Response Tests using controlled multi-power level heating and cooling pulses (MPL-HCP): Quantifying ground water effects on heat transport around a borehole heat exchanger. In: Stiles (ed). The Tenth International Conference on Thermal Energy Storage, Ecostock 2006 Proceedings. May 31 - June 2, 2006, Stockton College New Jersey (USA).

Witte, H.J.L. 2010. Fluid properties correlations and mixing rules (water, monopropylene glycol and ethylene glycol). Groenholland, 2010. Unpublished report.

Witte, H.J.L., A.J. van Gelder, J.D. Spitler. 2002. In Situ Measurement of Ground Thermal Conductivity: The Dutch Perspective. ASHRAE Transactions, Vol. 108., No. 1.

Henk J.L. Witte - "Error Analysis of Thermal Response Tests (Extended Version)", INNOSTOCK 2012 conference, Groenholland Geo-Energysystems, Valschermkade 26, 1059CD Amsterdam, Netherlands, Phone: 31-20-6159050, e-mail: henk.witte@groenholland.nl

J. Appendix II

DRIFT AND CONDITIONAL ESTIMATION

Ground thermal conductivity is deduced by the ILS relationship and, namely, by calculating the slope b of the linear behaviour of temperature in the space of time-log $T_f(t)=b\cdot\ln t+a$. λ_g, by knowing the power injected Q (fixed) and the borehole length H (fixed), is determined by b $b=\dfrac{Q}{4\cdot\pi\cdot\lambda_g\cdot H}$.

The drift's method proposed doesn't change the general logic of the approach, but the way of estimating b. This chapter introduces the drift's method to estimate the linear regression parameters a and b.

The drift method in theory

Given the residual model $T(t)=m(t)+Y(t)$, with the trend expressed by the theoretical relationship, the expectation of temperature increments, called drift, is

$$D(t,\Delta t)= ET\left[(t+\Delta t)-T(t)\right]= m(t+\Delta t)-m(t)= b\left(\ln(t+\Delta t)-\ln(t)\right)$$

The drift in the space of τ increments ($\Delta\tau$) is a line passing through the origin with slope b:

$$D(t,\Delta t)= b\left(\ln(t+\Delta t)-\ln(t)\right)= b\Delta\tau = D(\Delta\tau)$$

Pairs satisfying a constant lag $\Delta\tau$ must have a time distance varying with time

$$\Delta t = e^{\Delta\tau+\ln t}-t = t\left(e^{\Delta\tau+\ln t}\right)$$

Experimentally the probabilistic mean is substituted by the statistical mean of nc increments with the same increment $\Delta\tau$. In practice a discrete number of drift values are considered, corresponding to nj time-log increments $\Delta\tau_j$:

$$D(\Delta\tau_j)=E\left[T(\ln(t+\Delta t_j))-T(\ln t)\right]=E\left[T(\ln t+\Delta\tau_j)-T(\ln t)\right]\cong D^*(\Delta\tau_j)=\frac{\sum_{\alpha=1}^{nc(\Delta\tau_j)}\left[T(\ln t_\alpha+\Delta\tau_j)-T(\ln t_\alpha)\right]}{nc(\Delta\tau_j)}$$

Given the experimental drift plot $\{D^*(\Delta\tau_j)\}$, the least-squares regression can be applied in order to estimate the parameter b (Fig.a).

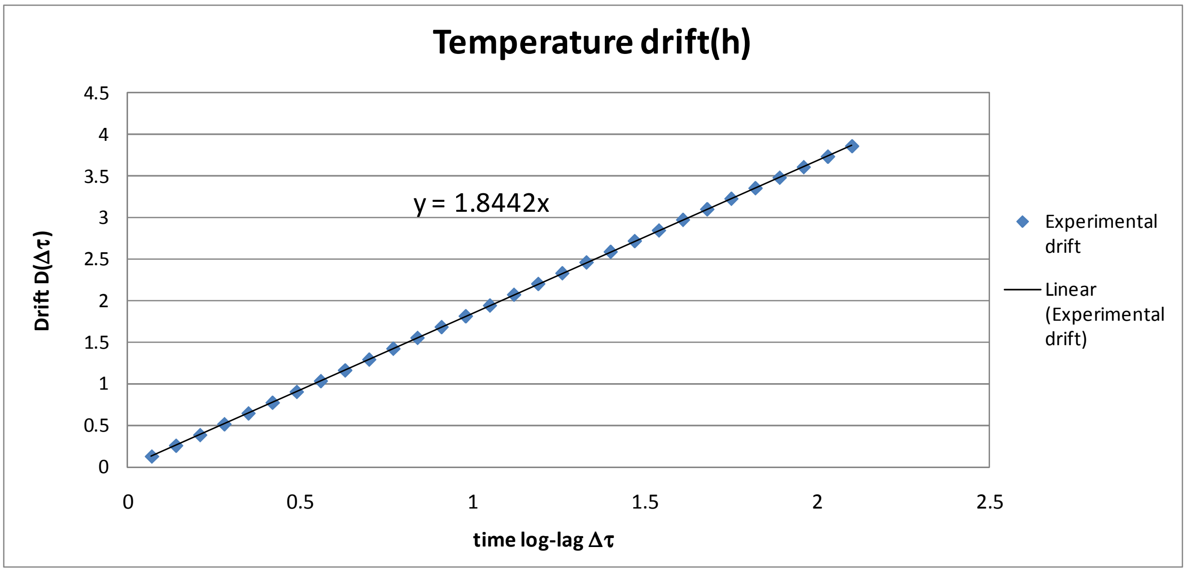

Fig. a- Linear regression on the experimental drift of temperature in the space of time-log increments

In principle the "drift method" has a couple of advantages over the classical method:

The estimation filters the intercept a, and this fact allows for a more precise estimation of the slope b;

The separation of the estimations of slope from that of the intercept allows for a better control of each regression.

The drift method in practice

The drift method splits in two phases the estimation of parameters of the mean temperature in the space {τ} of time-log:

the estimation of the slope b by regression on the experimental drift

$$b^D = \sum_{j=1}^{nj} \psi_j^b D^*(\Delta\tau_j)$$

the estimation of the intercept a, conditioned by the preceding estimate, by regression on the experimental temperature

$$a^D = \sum_{j=1}^{nj} \psi_j^a T_f(t_\alpha) + \psi_0^\alpha$$

In principle the two regressions do not have problems from the methodological point of view, but in practice some problems arise in case of TRT processing given the high number of data and their increasing density in the τ space.

The conditioning relationship between c_g and R_b

Once calculated λ_g it is then possible to calculate R_b. Normally the procedure provides first the choice of a fixed c_g and then the calculation of the borehole thermal resistance.

This calculation is performed in a deterministic way and overall by imposing a guess value of c_g that is chosen as an average for the soils involved.

But in reality ground volumetric heat capacity (c_g) can vary within a variability range (defined for example from VDI norms); we can suppose that the a priori probability distribution is symmetric (e.g. Gaussian), with the average, m_{Cg}, coincident with the medium point of the interval and with tables' average value. We can also consider that the semi-interval corresponds to $2\sigma_{Cg}$.

Borehole thermal resistance, Rb, has a variability range whose extremes, R_{bmax} and R_{bmin}, are calculated numerically on borehole parameters (thermal properties of grouting, U pipes and circulating fluid, spacing between pipes) and on work properties (drilling, grouting and pipe spacing), as variations of the average value, m_{Rb}, which is correspondent to a perfect borehole (known geometrical and thermal characteristics of it).

The attribution of a probability distribution to borehole thermal resistance requires some hypotheses. Maybe it is lawful to think at a uniform distribution with average, m_{Rb}, equal to the central value and variance equal to

$$\sigma_{Rb}^2 = \frac{(R_{b\max} - R_{b\min})^2}{12}$$

Bivariate probability distribution

Realistically the two variables are independent, considering that ground volumetric heat capacity cg is a magnitude naturally variable and borehole thermal resistance Rb is an artificial variable, resulting from a human action. Joint probability distribution is therefore the product of corresponding mono-variate distributions:

$$f(c_g, R_b) = f_C(c_g) f_R(R_b)$$

Optimality criterion, namely the choice of the couple of optimal values (c_{g0}, R_{b0}), can refer to a classical estimation frame: the choice of a correct estimator which minimizes the estimation variance.

Actually it is not a bivariate problem, but a monovariate one, because theoretical linear relation allows us to eliminate one of the variables:

$$\omega_1 \ln(c_g) + \omega_2 R_b + \omega_3 = 0$$

Optimality of one parameter implies other's optimality. Therefore it is sufficient to consider one variable that varies along the conditioning line, because this is equivalent to consider a couple of parameters conditioned from the relation.

Given a random variable with a known distribution, of which we would like to estimate the true value of the non-sampled realization, optimal value coincides with average value, because it guarantees estimation's correctness and variance's minimization. Estimation error e is given by the difference between true value X and estimated one x_o:

$$e = x_o - X$$

True not known value is a random variable; therefore also the error is a random variable. If classically estimator has to be correct and optimal, expected value of the error should be null and estimation variance should be minimized:

$$E[e] = E[x_o - X] = 0 \quad \Rightarrow \quad x_0 = E[X] = m_X$$

$$E[e^2] = \min \quad \Rightarrow \quad \frac{\partial E\left[(x_o - X)^2\right]}{\partial x_o} = 0 \quad \Rightarrow \quad E[-2(x_o - X)] = 0 \quad \Rightarrow \quad x_o = E[X]$$

Finally the problem is solved if we know probability distribution of our variable, which describes the relation between the two parameters of interest.

Conditioning relation reduces of one dimension bivariate law variability domain and identifies a sub-domain of existence of a couple of possible values for parameters based on TRT measures. New extremes, c_{gLmax}, c_{gLmin}, R_{bLmax}, R_{bLmin}, are obviously included within original existent range.

$$\left(c_{gLmax}, c_{gLmin}\right) \subseteq \left(c_{gmax}, c_{gmin}\right) \qquad \left(R_{bLmin} R_{bLmax}\right) \subseteq \left(R_{bmax}, R_{bmin}\right)$$

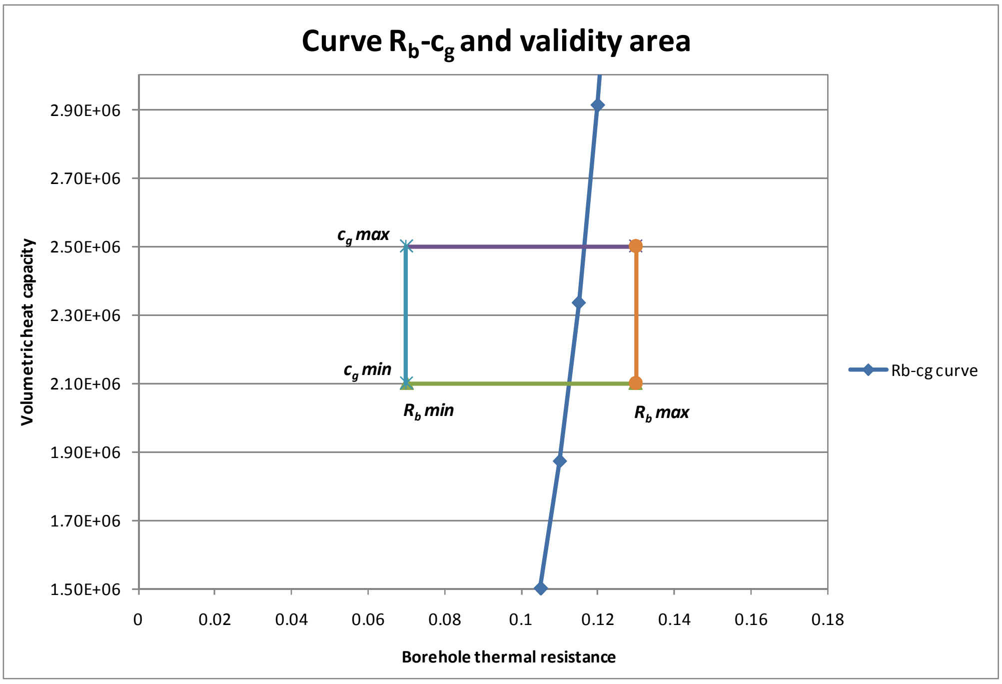

Fig.b - Curve validity area: through the intersection between the curve and the domain we obtain a smaller validity area

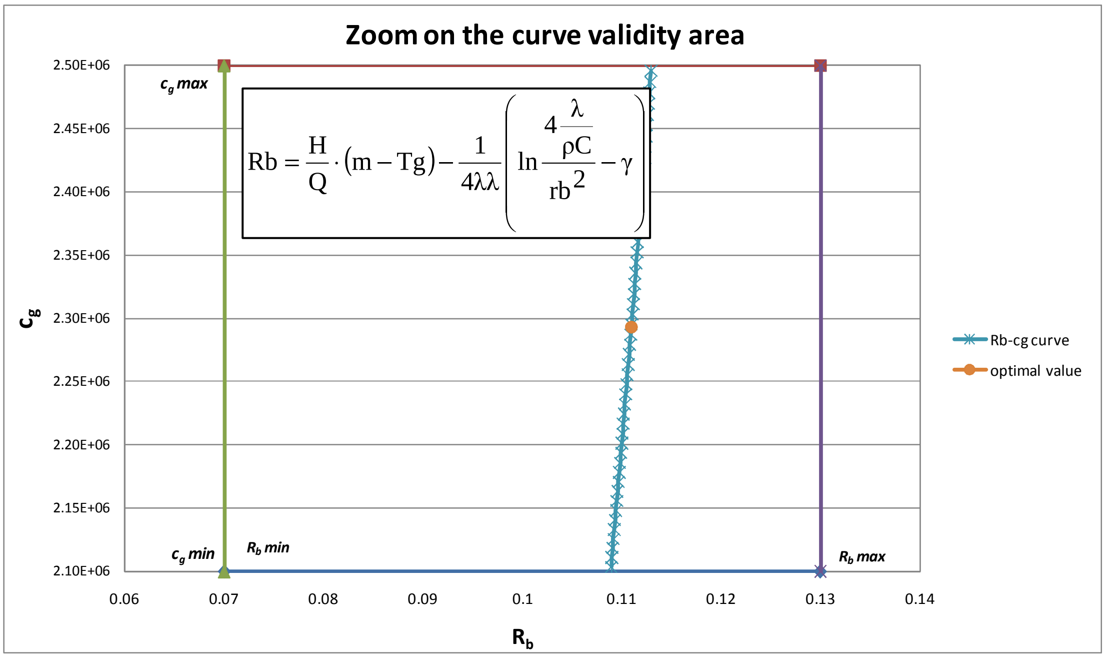

Fig.c - Zoom on the validity area of R_b-c_g curve and R_b equation

The sub-domain, which derives from the conditioning relation, identifies a conditional probability distribution.

We call L the sub-domain defined from the conditioning relation. Here follows the equation of conditional distribution:

$$f(c_g, R_b \mid c_g, R_b \in L) = \frac{f(c_g, R_b)}{F(c_g, R_b \in L)} = \frac{f_C(c_g) f_R(R_b)}{[F_C(c_{gL\,\max}) - F_C(c_{gL\,\min})][F_R(R_{bL\,\max}) - F_R(R_{bL\,\min})]}$$

where bivariate law respects probability's axioms. Practically

$$F(c_{g\max}, R_{b\max}) \cong 1 \qquad F(c_{gL\min}, R_{bL\min}) \cong 0$$

Optimal value results therefore

$$c_{g0} = E[c \mid c, R \in L] = \int_{c_{L\,\min}}^{c_{L\,\max}} c\, f(c, R \mid c, R \in L)\, dc$$

Substituting Rb:

$$az_1 c_g + az_2 R_b + az_3 = 0 \quad \Rightarrow \quad R_b = \frac{-az_1 c_g - az_3}{z_2}$$

$$c_{g0} = \int_{c_{gL\min}}^{c_{gL\max}} c \; f\left(c_g, R_b \mid c_g, R_b \in L\right) dc = \frac{\int_{c_{L\min}}^{c_{L\max}} c_g \, f_C\left(c_g\right) f_R\left(\frac{-z_1 c_g - z_3}{z_2}\right) dc}{\left[F_C\left(c_{gL\max}\right) - F_C\left(c_{gL\min}\right)\right]\left[F_R\left(R_{bL\max}\right) - F_R\left(R_{bL\min}\right)\right]}$$

Alternatively we can solve everything in R_b:

$$R_{b0} = \int_{R_{L\min}}^{R_{L\max}} R_b \; f\left(c_g, R_b \mid c_g, R_b \in L\right) dR = \frac{\int_{R_{L\min}}^{R_{L\max}} R_b \, f_C\left(\frac{-z_2 R_b - z_3}{a_1}\right) f_R\left(R_b\right) dR}{\left[F_C\left(c_{gL\max}\right) - F_C\left(c_{gL\min}\right)\right]\left[F_R\left(R_{bL\max}\right) - F_R\left(R_{bL\min}\right)\right]}$$