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DESIGN, CONSTRUCTION AND MAINTENANCE OF UTES WELLS AND BOREHOLES

Thermal Response Test for BTES Applications

State of the Art 2001

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Contents

ABSTRACT

Proper design of borehole heat exchangers (BHE) for commercial and institutional buildings utilizing ground source heat pump systems requires a good estimate of the thermal conductivity of the ground in order to avoid significantly over-sizing or under-sizing 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 *in situ* at a specific location using what is sometimes referred to as a thermal response test. In a thermal response test, a constant heat injection or extraction is imposed on a test borehole. The resulting temperature response can be 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 been utilized in a number of countries.

Within the framework of the International Energy Agency (IEA), and the Implementing Agreement on Energy Storage through Energy Conservation (ECES), the international co-operation project Annex 13 covers aspects of test drilling, well and borehole design, construction and maintenance of wells and boreholes for UTES applications. This report is the result of the work within the Annex 13 Subtask A2 “Thermal Response Test for UTES Applications”, and describes the current status of the equipment, analysis methodologies, and test experiences of thermal response testing worldwide until December 2001. It also suggests areas of further research and development.

ACKNOWLEDGEMENTS

This state-of-the-art report is the result of the work done within IEA ECES Annex 13, Subtask A2, an international co-operation project within the framework of the International Energy Agency (IEA). Annex 13 covers aspects of test drilling, well and borehole design, construction and maintenance of wells and boreholes for UTES applications and was approved in December 1997.

The aim of Annex 13 Subtask A is to define how to gain information of the underground properties by test drilling, and this report serves to summarise the state-of–the-art of thermal response test for BTES applications.

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NOMENCLATURE

Symbols

a = diffusivity (λ/c)

E_1 = Exponential function

G = cylindrical source function

J_0, J_1, Y_0, Y_1 = Bessel functions

k = slope

$p = r/r_o$

q = heat flow (W/m)

r = radius (m)

r_b = borehole radius (m)

r_o = reference radius (m)

R_b = Borehole thermal resistance (K/(W/m))

t = time (s)

T_b = Borehole wall temperature (°C)

T_f = fluid temperature (°C)

T_o = Undisturbed ground temperature (°C)

T^q = Ground temperature change due to a power pulse (°C)

z = Fourier's number = at/r^2

γ = Euler's constant = 0.5772…

λ = ground thermal conductivity (W/m K)

Subscript

f = fluid

1. INTRODUCTION

Underground Thermal Energy Storage (UTES) is a reliable, sustainable and energy-saving technology for cooling and heating of buildings and industrial processes and is now widely spread in the World. In the past 20 years, various applications of UTES have been constructed. Within the IEA Implementing Agreement, Energy Conservation through Energy Storage (ECES) programme, 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 borehole heat exchanger (BHE) are the two most important design parameters for BTES systems. The 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.

1.1 Historical context of thermal response test

Mogensen (1983) first presented the thermal response test as a method to determine the *in situ* values of ground thermal conductivity and thermal resistance in BHE systems. He suggested a system with a chilled heat carrier fluid being circulated through a BHE system at constant heat extraction (or cooling) rate, while the outlet fluid temperature from the BHE was continuously recorded. The temperature data over time can then be used for determining the ground thermal conductivity and borehole thermal resistance. Mogensen's method was used to evaluate existing BHE systems at several occasions, e.g. Mogensen (1985), Eskilson (1987), Nordell (1994), Hellström (1994).

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 and reported by Eklöf and Gehlin (1996). At the same time a similar device was developed at Oklahoma State University as reported by Austin (1998). Both apparati are based on Mogensen's concept but with a heater instead of a chiller.

Similar test units were later developed in other countries. In the U.S.A., several commercial units have been developed which fit into small (airliner-transportable) shipping containers. In the Netherlands, a large (housed in a sea shipping container) thermal response test measurement unit was later constructed (IF Technology and Groenholland, 1999). The Dutch version uses a heat pump for heating or cooling of the heat carrier fluid.

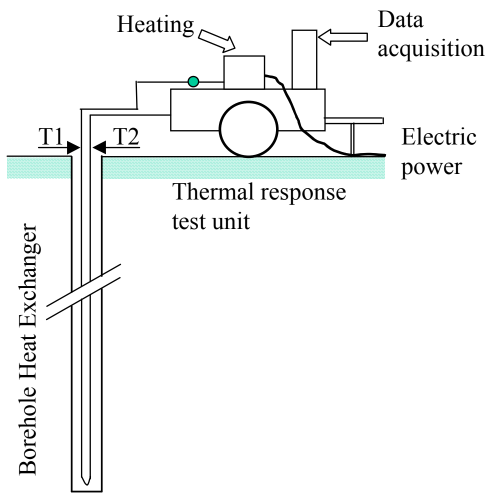


Figure 1: Thermal response test set-up

1.2 Objective and scope

This state of the art report gives a summary of known thermal response testing activities in the world and the state-of-the-art of the technology until December 2001. Mainly eight countries (Sweden, Canada, Germany, Netherlands, Norway, Turkey, United Kingdom, and the U.S.A) have developed the technique. Recently also France and Switzerland have taken up using the method. The report describes the various thermal response test facilities, test procedures, analysis methods, and test experience. Areas of future research and development are highlighted.

2. MEASUREMENT EQUIPMENT

This section describes the measurement equipment utilized in each country. As several countries utilize adapted Swedish equipment, the Swedish equipment is described first. Equipment of the other countries is described in alphabetical order. In all cases, the test apparatus injects or extracts heat into/from the borehole by circulating a heated or cooled fluid and measure its temperature response. A constant heat transfer rate is desirable, as the most commonly used analysis procedures depend on this. The units differ in heating and cooling power, type of instrumentation, size and mobility. Features of the response test apparati are summarized in Appendix 1.

2.1 Description of equipment by country

2.1.1 Sweden

The mobile thermal response test equipment, TED, was constructed at Luleå University of Technology in 1995-96 (Eklöf and Gehlin 1996; Gehlin and Nordell 1997). The equipment was set up on a small covered trailer and consists of a purge tank holding 85 litres (22.45 gallons) of fluid, a 1 kW (3,400 Btu/hr) pump circulating the heat carrier fluid through the borehole, an in-line electric resistance heater, and instrumentation. The heater has step-wise adjustable power rates in the range of 3-12 kW (10,200-41,000 Btu/hr). Fluid temperatures are measured at the inlet and outlet of the borehole by thermocouples. The fluid temperatures, ambient air temperature, air temperature inside trailer, and power rate are recorded at an optional pre-set time interval.

Figure 2: The Swedish response test rig (TED). Photo: Peter Olsson.

2.1.2 Canada

Environment Canada in Halifax had a response test apparatus built in 1999-2000, based on experience from Sweden and U.S.A. (Cruickshanks et al., 2000). The apparatus consists of a covered, climate-controlled trailer fitted with an 0.75 kW (2,600 Btu/hr) in-line pump, 3 kW (10,200 Btu/hr) in-line electrical water heater, data logger/computer, 2 temperature sensors, 2 pressure gauges, air-bleed valve, etc.

Figure 3: The Canadian response test rig. Photo: Environment Canada.

2.1.3 Germany

In Germany, the response test method was established in 1999. One test rig is operated by Landtechnik Weihenstephan (LTW) and another at UBeG GbR in Wetzlar (Sanner et al., 2000). A third response test device is run by Aetna Energiesysteme GmbH in Wildau (Sanner et al 2001). The construction of the German test equipment is based on the Swedish TED. The Landtechnik Weihenstephan rig consists of two portable containers, and the UbeG rig consists of a frame with the heating equipment and a control cupboard. Both rigs are mounted on a light trailer. The Aetna test rig is also mounted on a trailer. It uses a heat pump instead of a heater and may be operated both in heating and cooling mode (Brandt 2001).

Figure 4: The German (UbeG) thermal response test rig.

Photo: UBeG GbR, Wetzlar

Figure 5: The German (Landtechnik Weihenstephan) thermal response test rig. Photo: Landtechnik Weihenstephan

2.1.4 Netherlands

GroenHolland B.V. in Netherlands built their large response test rig in a sea shipping container (van Gelder et al., 1999, Witte et al. 2000). It is operated with a reversible heat pump, and thus can be run in either heating or cooling mode. The heat pump generates a supply of warm or cold fluid, which is used to maintain a certain temperature difference between fluid entering and leaving the borehole. By selecting an appropriate temperature difference and flow rate, any energy load between 50 and 4500 W (170-15,350 Btu/hr) can be applied. The test rig may be used for response tests on single or multiple boreholes.

Figure 6: The Dutch response test unit with cooling and heating mode. Photo: Groenholland.

2.1.5 Norway

Since 1998, a thermal response test apparatus fabricated by the same firm that built the Swedish apparatus, has been used by a company ("Geoenergi") in Norway. It has the same operation and construction (but a different Norwegian electrical system). It is described by NGU (2000) and Skarphagen and Stene (1999).

Figure 7: The Norwegian response test rig (TED-model).

Photo: Geoenergi.

2.1.6 Switzerland

Switzerland has two mobile test rigs in operation since 1998 (Eugster 2002) for measurements of boreholes and energy piles. The EPFL rig has a three-step heater unit with variable fluid flow. The EKZ has a two step in-line electric heater and a fixed fluid flow rate.

2.1.7 Turkey

In late 2000, the Centre for Environmental Research at Çukurova University in Adana took over one of the two Swedish test rigs. Slight alterations of the apparatus had to be made to adapt to Turkish standards.

Figure 8: The Turkish response test rig was built in Sweden and is of the TED-model. Photo: Bekir Turgut.

2.1.8 United Kingdom

A British version of thermal response test apparatus was constructed by GeoSciences, Falmouth, Cornwall (Curtis, 2001) in the summer of 1999. The unit is mounted on a small two-wheeled cart for easy transportation. Two 3 kW (10,200 Btu/hr) electric flow heaters can be used to give two different levels of heat injection. A variable speed pump delivers flow rates between 0.25 l/s (4 GPM) and 1 l/s (16 GPM). The electrical power input is measured, and a flow meter combined with two platinum RTD temperature sensors is used to estimate injected heat.

Figure 9: The response test facility in United Kingdom in operation. Photo: Geoscience

2.1.9 U.S.A.

There are a number of response test devices in operation in U.S.A. The first one described in the literature, developed at Oklahoma State University in 1995, is housed in a trailer that is towed to the site and contains everything needed to perform a test – the apparatus, two generators, and a purge tank containing 300 litres (80 gallons) of water. The heating elements are rated 1, 1.5 and 2 kW (3,400; 5,100; 6,800 Btu/hr). By use of a power controller on one of the heating elements, the power can be adjusted continuously between 0 and 4.5 kW (15,300 Btu/hr). Temperatures are measured with two high accuracy thermistors immersed in the circulating fluid, and the flow rate is measured using an in-line flow meter. A typical flow rate of approximately 0.2 l/s (3 GPM) is used.

The power consumption of the heaters and the circulating pumps is measured by a watt transducer. Data is collected every 2.5 minutes. Injected power, the inlet/outlet fluid temperatures and the volumetric flow rate are downloaded to an on-board computer. A detailed description of the test apparatus is available in Austin (1998).

In addition, several commercial thermal response test devices have been developed. An Oklahoma company, Ewbanks and Associates, have developed a number of test rigs, starting with a version mounted on a trailer, and progressing to versions that fit in airline-shippable crates. Another Oklahoma company, Tri-Sun has developed a unit that fits in a medium-sized suitcase. A utility in Nebraska (Spilker 1998) has developed one unit and other commercial units have been fabricated by companies in Texas and Tennessee.

Figure 10: The Oklahoma State University Test Trailer. Photo: Jeffrey Spitler

Figure 11: The suit-case response test set-up of Ewbanks, USA. Photo: Signhild Gehlin.

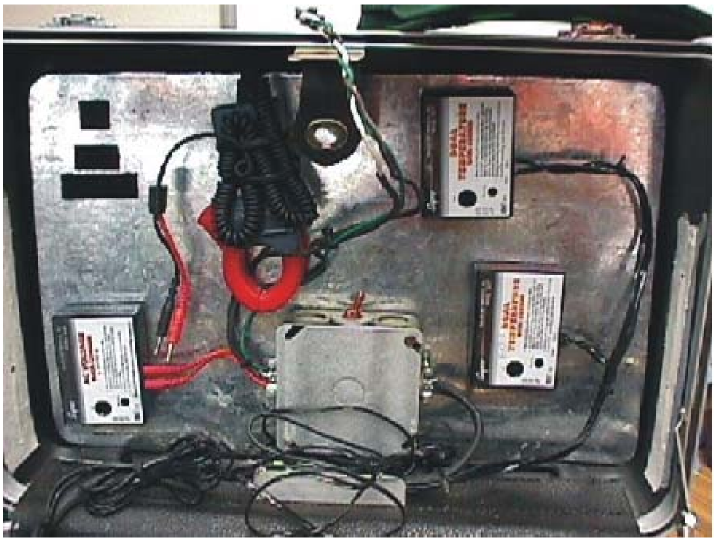


Figure 12: Suitcase Unit Fabricated by TriSun Construction, Oklahoma, USA.
Photo: Jeffrey Spitler

2.1.10 Other Countries

Three other countries are in the process of taking thermal response test units in use. France has shown recent interest in a test facility in their communication with Switzerland and technology transfer has been discussed. The Japanese company GEO-E has prepared a test rig, similar to the Swiss EKZ-unit. Totally six response test units have been built in Japan during the recent years. Measurements have been performed in Japan and China.

3. OPERATIONAL EXPERIENCE

3.1. Running the test

3.1.1 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 response test 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.

The test procedure normally starts with determining the undisturbed ground temperature (see below) and then the heat/cold injection starts. The temperature development of the circulating brine is recorded at a set time interval, normally in the range 2-10 minutes. The test proceeds for several hours (see below) until steady-state conditions are obtained. 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.

3.1.2 Determining undisturbed ground temperature

For some analysis procedures, estimates of the ground thermal conductivity depend on the undisturbed ground temperature, which must be determined before the response test has started. The undisturbed ground temperature may possibly also be determined after the ground has reach thermal equilibrium after the test. This will however take several days.

The geothermal gradient is a factor that cannot be neglected, and causes the undisturbed ground temperature to increase with depth. The temperature gradient varies globally, but is normally in the range 0.5-3 K per 100 meter (0.3-1.6 F per 100 ft). Eskilson (1987) showed that for BTES applications, it is not necessary to consider the temperature variation along the borehole. The mean temperature along the borehole may be used as a homogeneous undisturbed ground temperature around the borehole.

The undisturbed ground temperature may be determined in two ways. One commonly used method is to circulate the fluid through the borehole for about half an hour before the heater is switched on for the test. The collected temperature data is used to decide the average borehole temperature. One problem with this method is that the circulation pump will inject some heat into the system, which thus induces an increased temperature increase. Another method, which may be more reliable, is to lower a thermocouple down the water-filled U-tube before the measurement has started. The temperature is measured every few meters along the U-pipe. The temperatures are used to calculate an arithmetic mean borehole temperature.

Gehlin (2001) compares 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 collector was connected to a response test facility (the Swedish TED) and the collector fluid was circulated without heat injection for more that 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 0.1°C (0.2°F). 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 (0.7°F) 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.

3.1.3 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 for research purposes; their normal commercial tests are 50 hours in length. Austin, et al. (2000) and Witte, et al. (2002) have compared tests of different duration. Test cost is related to test length. One contractor (Wells 1999) who performs in situ tests in the Ohio area, 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.

3.2 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.

3.2.1 Heat losses or gains

Uncontrolled heat losses or gains to or from the environment due to insufficient thermal insulation cause problems (Austin 1998; 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.

3.2.2 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. A recommended solution reported in the U.S.A. (Ewbanks 1999) is to use a significantly oversized generator (e.g. a 50 kW generator for a 5 kW load), which should maintain a relatively constant power. Another 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). A third solution is to use an analysis procedure that can account for fluctuating power.

3.2.3 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 study. 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.

3.2.4 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 = 2 Btu/hr-ft-F) with a 5 m thick top-soil layer (λ = 1.5 W/m,K = 0.9 Btu/hr-ft-F) 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.

This may be further complicated by a difference in conductivity above and below the static groundwater level. The thermal response test naturally gives an aggregate value of all the layers. Some insight into the variation of conductivity with depth may be obtained by measuring the temperatures along the borehole after the test. (Witte 2001) In the case of a heat rejection test, areas of the ground with higher conductivities will have lower temperatures, and areas with lower conductivities will have higher temperatures.

3.2.5 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, the influence of regional groundwater flow is negligible.

Chiasson et al. (2000) 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 has not been thoroughly studied, and may give some explanation to field observations where groundwater flow has occurred.

3.2.6 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.

4. ANALYSIS METHODS

Currently used methods to estimate the thermal properties of the ground formation may be divided into direct methods such as the line source and cylinder source approaches and methods that use formal parameter estimation techniques. The following six methods, based on four theoretical approaches, have been reported:

1. Line source theory as used by Eklöf and Gehlin (1996), Gehlin and Nordell (1998).
2. Line source theory as used by Smith (1999a)
3. Line source theory as used by Curtis (2001).
4. Cylinder source theory (used by Kavanaugh and Rafferty 1997),
5. Parameter estimation with 1D finite difference borehole model (Shonder and Beck 1999).
6. Parameter estimation with 2D finite volume borehole model (Austin et al. 2000).

4.1 Line source

The equation for the temperature field as a function of time and radius around a line source with constant heat injection rate (Carslaw and Jaeger, 1959) may be used as an approximation of the heat injection from a BHE:

$$T^q(r,t) = \frac{q}{4\pi\lambda} \int_{\frac{r^2}{4at}}^{\infty} \frac{e^{-u}}{u} du = \frac{q}{4\pi\lambda} E_1(r^2/4at) \qquad (1)$$

With increasing time, the radius of influence will increase. Ingersoll and Plass (1948) show that the equation can be used for cylindrical heat injection ducts with an error less than 2% if

$$t > \frac{20r_b^2}{a}. \qquad (2)$$

For a normal borehole, t is in the range 10-20 hours.

E_l is the so-called exponential integral. For large values of the parameter at/r^2, E_l can be approximated with the following simple relation:

$$E_1(r^2/4at) = \ln\left(\frac{4at}{r^2}\right) - \gamma \qquad \frac{at}{r^2} \geq 5 \qquad (3)$$

where the term γ = 0.5772…. is Euler's constant. The maximum error is 2.5% for $at/r^2 \geq 20$ and 10% for $at/r^2 \geq 5$.

The measured temperature during a response test is the fluid temperature, and the relationship between the fluid temperature and the temperature at the borehole wall (T_b at r_b) is:

$$T_f^q(t) = T_b^q(t) + q \cdot R_b \qquad (4)$$

where R_b is the thermal resistance between the fluid in the pipes and the borehole wall. The index q in the temperatures denotes that it is the temperature change due to the heat pulse q. Thus the fluid temperature as a function of time can be written:

$$T_f(t) = \frac{q}{4\pi\lambda} \cdot \left(\ln\left(\frac{4at}{r^2}\right) - \gamma \right) + q \cdot R_b + T_o \quad (5)$$

where T_o is the undisturbed ground temperature.

In practice, researchers have made use of this approach in somewhat different ways although they essentially follow Mogensen (1983).

Eklöf and Gehlin (1996), Gehlin and Nordell (1998), Sanner et al. (2000) and Cruickshanks et al. (2000) apply the line source solution to determine the thermal conductivity of ground formation for underground thermal energy storage systems. The implementation is done by determining the slope of the average fluid temperature development versus the natural log of time curve:

$$T_f(t) = k \cdot \ln t + m \qquad k = \frac{q}{4\pi\lambda} \quad (6)$$

where k is the slope of the curve.

Gehlin and Eklöf (1996) recognize that it is, in practice, difficult to keep the heat injection constant during the entire test period due to unstable power supply. To account for such power variations, the heat input may be decomposed into stepwise constant heat pulses that are then superimposed in time. Thus, the average borehole temperature at any given time step is expressed as a sum of the heat input contributions from a series of past time intervals. The effective conductivity of the ground formation is then computed by considering the stepwise change in the heat injection. However, pulses of shorter duration than 2-3 hours may be neglected since the heat capacity of the borehole will buffer the effect.

The use of Equation 6 for the evaluation of the thermal conductivity may be misleading if the data series are disturbed by ambient air temperature. It also requires that an initial few hours of measurements be ignored when calculating the slope. An alternative procedure, used in Sweden (Gehlin 1998) and Norway, is a parameter estimation that adjusts the thermal conductivity of the ground and the thermal resistance between the fluid and the borehole wall. Equation 5 is used to obtain the best match to the experimentally determined temperature response. This approach indicates where data intervals are disturbed (e.g. increased temperature due to solar radiation), thus the disturbances may be observed and adjusted for in the parameter estimation. The difference between the two methods is illustrated in Figure 13.

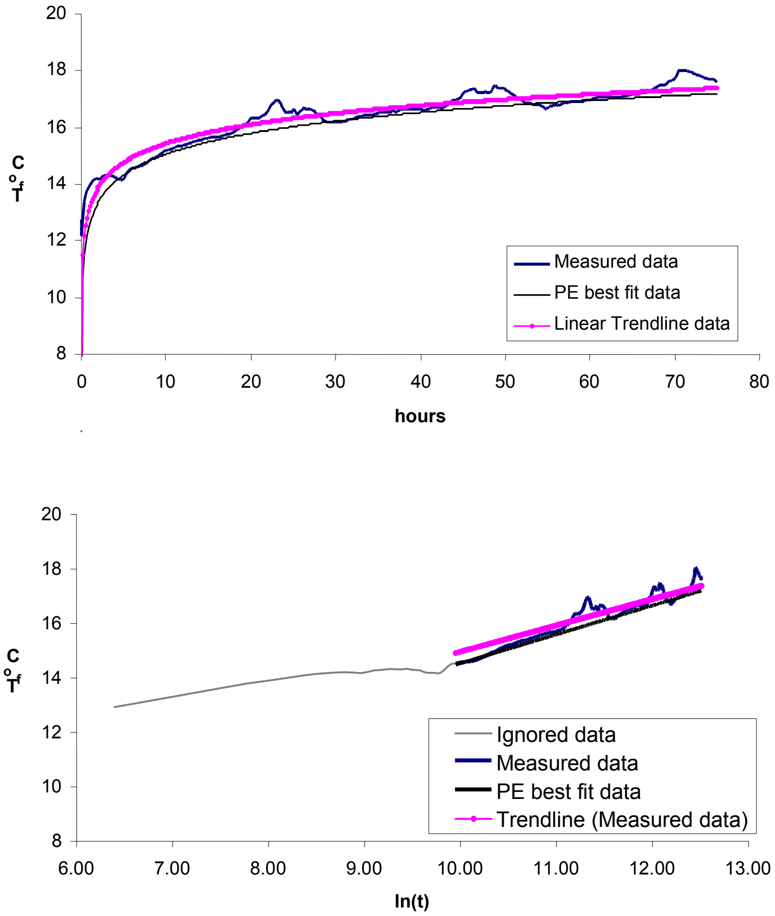


Figure 13: The two graphs show the same data sets; Measured data, Parameter estimation best fit data and Trendline data, presented versus time (upper) and linearized (lower).

Smith (1999a, 1999b) also uses the line source approach to estimate the thermal conductivity on several test boreholes at the Oklahoma State University. In Smith's (1999b) implementation, a great deal of care was applied in manually selecting time periods when the heat input and fluid flow rates were "nearly" constant. That is since even small perturbations in the power input or the fluid flow rate can, as demonstrated by Austin (1998), cause significant variations in the results

The approach to response test data analysis in the UK is to make a direct analogy of the thermal response test to a hydraulic single well test. A period of constant heat injection is followed by a period of near-zero heat injection. Two line source solutions are superposed and fit with least squares. From this, the thermal conductivity and borehole resistance can be estimated.

4.2 Cylinder source

The cylinder source model, of which the line source model is a simplified variation, may be used for approximating the BHE as an infinite cylinder with a constant heat flux. The heat exchanger pipes are normally represented by an ”equal diameter” cylinder. The cylindrical source solution for a constant heat flux is as follows:

$$T^{q}(r,t) = \frac{q}{\lambda} \cdot G(z,p) \qquad \begin{cases} z = \dfrac{at}{r^2} \\ p = \dfrac{r}{r_o} \end{cases} \tag{7}$$

where G(z,p) is the cylindrical source function as described by Ingersoll (1954):

$$G(z,p) = \frac{1}{\pi^2} \int_0^{\infty} f(\beta) d\beta \tag{8}$$

$$f(\beta) = (e^{-\beta^2 z} - 1) \cdot \frac{\left[J_0(p\beta)Y_1(\beta) - Y_0(p\beta)J_1(\beta)\right]}{\beta^2\left[J_1^2(\beta) + Y_1^2(\beta)\right]} \tag{9}$$

where J_o, J_1, Y_o, Y_1 are Bessel functions of the first and second kind.

Deerman and Kavanaugh (1991) and Kavanaugh and Rafferty (1997) suggested an iterative procedure, which uses the cylinder source method to inversely determine the ground thermal conductivity. The effective thermal conductivity (and diffusivity) of the ground formation is computed by reversing the process used to calculate the length of the ground loop heat exchanger. Based on a short-term *in situ* test, the effective thermal resistance of the ground of a daily heat pulse is compared to a value computed from the Fourier number (z) and the cylinder source function G(z,p) with assumed value for the thermal conductivity and the diffusivity of the ground formation until the ground resistance values are the same.

4.3 Parameter estimation with 1D finite difference borehole model

Shonder, et al. (1999) developed a parameter-estimation-based method which is used in combination with a 1D numerical model. This model is similar to a cylinder-source representation, in that it represents the two pipes of the U-tube as a single cylinder. However, it adds two additional features -- a thin film, that adds a resistance without heat capacity; and a layer of grout, which may have a thermal conductivity and heat capacity different from the surrounding soil, Figure 14. In addition, unlike a standard cylinder-source solution, this model accommodates time-varying heat input.

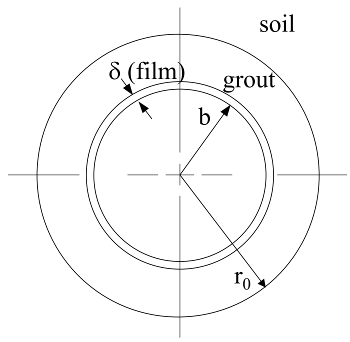
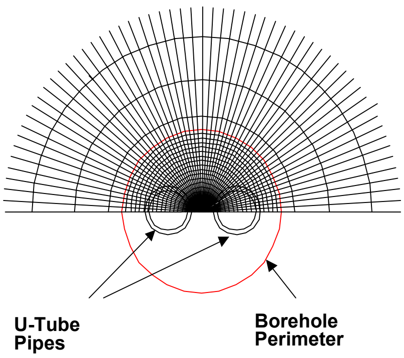


Figure 14: One-dimensional numerical model geometry for Oak Ridge National Laboratory Method (Shonder, et al. 1999)

4.4 Parameter estimation with 2D finite volume borehole model

The procedure developed by Austin, et al. (2000) utilizes a parameter estimation technique, which adjusts the thermal conductivities of the grout and ground. A numerical model is used to obtain the best possible match to the experimentally determined temperature response. These thermal conductivities are the best estimates of actual thermal conductivities.

A two-dimensional (polar coordinates) finite volume model is utilized. The inner part of the numerical domain is shown in Figure 15. For a typical borehole, a grid resolution of about 100 finite volume cells in the angular direction and about 150 to 200 cells in the radial direction is utilized. The exact grid resolution is a function of the borehole and U-tube pipe geometry and is determined by an automated parametric grid generation algorithm. The radius of the numerical domain is 3.6 m to allow for a reasonably long simulation time. The geometry of the circular U-tube pipes is approximated by "pie-sectors" over which a constant flux is assumed to be entering the numerical domain for each time step. The pie-sector approximation attempts to simulate the heat transfer conditions through a circular pipe by matching the inside perimeter of the circular pipe to the inside perimeter of the pie-sector and by establishing identical heat flux and resistance conditions near the pipe walls. The heat flux at the pipe wall is time-dependent – the heat flux is determined from experimentally-measured power input. Accordingly, the method has no problems associated with fluctuating power levels. The convection resistance due to the heat transfer fluid flow inside the U-tubes is accounted for through an adjustment on the conductivity of the pipe wall material.



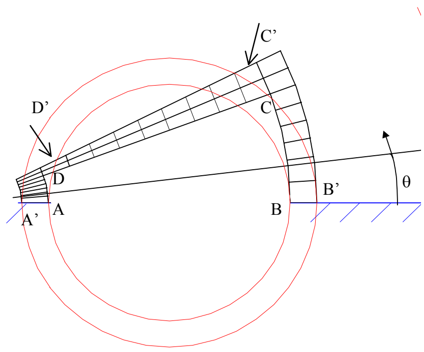


Figure 15: Numerical grid used by Austin, et al. (2000)

The parameter estimation algorithm minimizes the sum of the squares of the errors between the numerical model and the experimentally determined temperature response. A number of optimisation methods have been tested. For this problem, which involves searching along a narrow turning valley, the Nelder-Mead Simplex method with O'Neill's modifications seems to be the best method (Jain 2000).

This approach was further refined by a boundary-fitted coordinate grid, as shown in Figure 16, with the finite volume method. (Spitler, et al. 2000). However, for real-world applications, there is a point of diminishing returns here, as the down-hole geometry is not known precisely, even under the best circumstances. Spacers that force the U-tube against the borehole wall may help significantly, though.

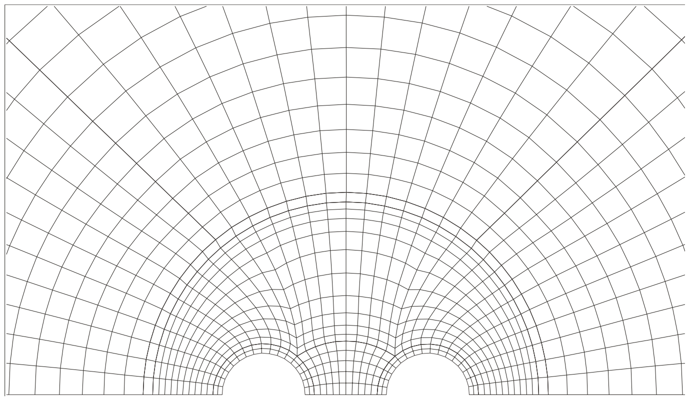


Figure 16: Boundary-fitted coordinate grid (Spitler, et al. 2000)

4.5 Discussion of models

There are a number of ways used to analyse the temperature data from thermal response tests. Analytical solutions of the line source or cylinder source theory and various numerical models mostly based on some cylinder approach. Most models also use parameter estimation to determine the ground thermal conductivity, although varying variables are used. The European countries use ground thermal conductivity and thermal resistance between heat carrier fluid and borehole wall, whereas the American models analyse for ground thermal conductivity and grout thermal conductivity. There is however an obvious correlation between the borehole thermal resistance (R_b) and the grout thermal conductivity (λ_{grout}), since the thermal resistance is a product of the heat losses in the pipe material as well as the grout and contact resistance between fluid/pipe, pipe/grout and grout/borehole wall.

The models also differ in the representation of the borehole. Line source approaches do not take into account heat capacity effects in the borehole whereas cylinder based models may do that. This effects the simulated initial temperature development in particular. The cylinder models also give possibilities in the representation of the borehole geometry and heat capacities of borehole filling, piping and heat carrier fluid. Simple cylinder models approximate the borehole to be a cylinder with a certain temperature and heat capacity. Other models use various ”equal diameter” representations of the pipes and the boreholes. The most advanced model here is the one described by Spitler et al. (2000) where the fine grid describing the borehole allows for very detailed characterisation of the materials and geometry of the borehole.

Gehlin & Hellström (2001) compared four different analysis models for evaluation of the same sets of response test data. This evaluation meant parameter estimation with the two variables λ_{ground} and R_b. Two analytical line source solutions were used; the E1 (Equation 1) model and the Line source approximation in Equation 5. An analytical cylinder source model from Carslaw and Jaeger (1959) including the effect of borehole filling heat capacity was also used and finally a two-dimensional numerical model including borehole filling heat capacity. The four models were compared with respect to test length and amount of data used in the analysis. No significant difference was found between the two line-source models. The numerical model tends to give slightly higher values of ground thermal conductivity and borehole thermal resistance than the line source, and the cylinder source even higher than that.

4.6 Error Analysis

Uncertainties in the estimated ground thermal conductivities come from several sources: random and systematic experimental error, approximations made in the analytical or numerical model, estimate of the far field temperature, and length of test. These uncertainties have been discussed by Austin (1998), Austin, et al. (2000), and Witte, et al. (2002). The overall uncertainties of the estimations made by different analysis procedures with different test equipment are on the order of ±10%. Austin (1998) has shown that error in the measurement of heat transfer rate to the borehole results in a similar percentage error in the estimation of ground thermal conductivity. Therefore, care must be taken to either measure the heat transfer rate using a temperature difference at the borehole inlet and outlet or, if the heat transfer rate is measured elsewhere, to minimize any unmeasured heat losses or gains.

Uncertainties due to approximations in the analysis procedure may be due to the assumption of constant heat transfer rate. Austin (1998) showed highly variable thermal conductivity predictions made with the line source procedure, when there were significant variations in the heat transfer rate to the borehole. In this situation, the parameter estimation procedure, which does not assume a constant heat transfer rate, can provide more accurate estimates. However, with a constant heat transfer rate, Witte, et al. (2002) have shown that the line source and parameter estimation methods may give very similar answers.

5. MEASUREMENTS

This section reports briefly on measurements made until December 2001 in the different countries. Appendix 2 summarises these measurements.

5.1 Sweden

The Swedish TED has been used in over 30 response tests. Typical for Swedish response tests is groundwater filled boreholes in granitic rock. Due to the use of groundwater filled boreholes, effects of natural convection in the borehole and local groundwater flow have been observed.

A number of measurements have been performed at Luleå University of Technology for research and evaluation of different BHE. Tests on single U-tube and double U-tube BHE, both on groundwater filled and grouted boreholes have been studied, and also tests with several power injection pulses have been performed (Gehlin 1998, Gehlin & Hellström, 2000).

Eklöf & Gehlin (1996) described measurements at two locations, where the test rig could not be connected directly to the borehole but the heat carrier fluid had to pass through several meters of horizontal piping buried in the ground. Thus the effect of the horizontal piping has been included in the measurements.

A few measurements have been performed in sedimentary rock as reported by Gehlin & Hellström (2000), where also two measurements on co-axial BHE are presented.

5.2 Canada

The first response tests in Canada were reported by Cruickshanks et al., (2000). The tests were performed on groundwater filled boreholes in mixed slate/quartzite geology.

Problems with disturbance on the temperature measurements from variations in the ambient air temperature are mentioned.

5.3 Germany

In Germany, thermal response tests have been performed on pilot boreholes for larger BHE systems since 1999. Seven response tests were reported by Sanner et al. (2000). Six of the tests are run on double U-tube BHE, the seventh on a single U-tube BHE. The geological conditions at the test site are all sedimentary. Boreholes were grouted or sand filled. Details on German measurements are also given in Sanner et al. (1999).

A response test on a sand filled borehole with suspected high groundwater flow, giving unrealistic (much too high) values of the ground thermal conductivity is mentioned in Sanner et al. (2000).

5.4 Netherlands

The thermal response test rig at GroenHolland and IF Technology has been used both for research and commercial measurements. About 20 measurements have been performed so far in the Netherlands, as well as 3 tests in Belgium and 3 in the United Kingdom (Witte 2001). Response tests on different loop configurations have been done (single borehole with single U-tube, 3 boreholes with U-tubes and horizontal piping, single concentric loop and U-tube with small shank spacing). Different loading profiles have been used and measurements have been compared during summer and winter conditions. An experiment was also performed where temperature measurements were made every 2.5 m (8 ft) along the borehole next to the loop in order to determine how the heat extraction rate per meter borehole changes as a function of soil stratigraphy and water content (Van Gelder, 1999).

A response test in Horst, the Netherlands, where the influence of groundwater flow on the determination of the ground thermal conductivity was observed, is described in a report in Dutch, from IF Technology (1999).

Witte et al. (2000) present a response test for the St. Lukes Church site in central London. Two test holes were drilled in the layered, sedimentary ground, and the ducts were grouted after the single U-tubes were inserted. A heat extraction experiment was done on one of the boreholes, and a heat injection experiment was done on the other. The estimated conductivities from the two tests matched within 4%.

5.5 Norway

Norwegian response test conditions are similar to those in Sweden. Groundwater filled boreholes in crystalline hard rock are used. The hilly landscape causes a high groundwater flow in fissures, which improves the performance of BHE. Measurements in selected wells have demonstrated that the heating capacities may be twice as high as that of “dry” wells, where heat flux is mainly due to the rock thermal properties (Skarphagen & Stene, 1999).

Around 30 response tests, mostly commercial, have been performed in Norway in recent years (Midttomme, 2000). The measurements have been concentrated to the Oslo area.

The National Geological Survey of Norway (NGU) and the Norwegian Water Resources and Energy Directorate (NVE) are currently developing a database of thermal conductivity in the Norwegian bedrock. The plan for the future is to combine the ground thermal conductivity database with a groundwater well database and topological data of the area, thus improving the basis for the design of BHE.

NGU has published a report on a thermal response test performed in Lorenskog, along with a thorough study of the geology in the area, as a pre-study for a hospital heating/cooling BHE system (NGU 2000).

5.6 Switzerland

Switzerland started measuring in 1998. They have so far made seven measurements, mainly on grouted double U-pipes and energy piles.

5.7 Turkey

The two first Turkish response tests were carried out in Istanbul in December 2000 (Paksoy, 2000). The option of measuring the effective average thermal properties of the ground profile surrounding a borehole, makes thermal response test especially valuable in the complex and varying geology of Turkey. Geologic formations with several sedimentary layers of very different thermal properties are common in Turkey. The test method is also used for evaluation and development of grouts from domestic material, since different types of bentonite occur naturally in many places in Turkey.

5.8 United Kingdom

Response tests in UK have been performed by GeoScience Limited and the Dutch company, Groenholland. Measurements have been made at six sites in England (Cornwall, Chesterfield, Exeter, London) and Scotland since September 1999 (Curtis, 2000). Groenholland (Witte 2001) has reported three tests. Results from tests in London are presented by Witte, et al. (2000a, 2000b).

5.9 U.S.A.

Test conditions vary widely throughout the U.S.A. and hundreds of tests have been made for commercial clients, without the results being published. This section emphasizes published test results.

Spilker (1998) reported four tests made in Nebraska with three different back fill materials in two different diameter boreholes. Thermal conductivities and borehole resistances were estimated, but not reported. Instead, the impact on a design for a specific building was reported. Required borehole depth for a 144 borehole BHE varied between 59 m (194 ft) and 88 m (289 ft). Skouby (1998) described five tests performed in South Dakota and Nebraska used to support design of ground source heat pump systems for schools. A thermal conductivity test is recommended for commercial projects with installed cooling capacities in excess of 88 kW (25 tons).

Smith and Perry (1999b) evaluated borehole grouts with the aid of thermal response tests. Remund (1999) showed results from thermal response tests that were compared with laboratory measurements. The measurements were used for evaluation of different grouts and borehole thermal resistance.

Smith (1999b) reported on 16 tests performed by the Middleton Corporation of Akron, OH. The duration of these tests were generally 12 hours, and for 7 of the tests for which the BHE were designed, the systems were reported to be operating within design parameters.

Two validation tests have been reported by Austin et al. (2000). One test was performed on a core drilled hole. The core samples were carefully preserved in sealed PVC cases and stored in climate-controlled rooms to avoid changes in the moisture content of the sample. The conductivities of 19 representative samples were then measured in a guarded hot plate apparatus (Smith 1998) to obtain an independent estimate for its thermal conductivity. The in situ test, analysed with the 2-D finite volume parameter estimation procedure, matched the independent measurement within 2%, which is considerably better than might be expected with the uncertainty of the in situ test and analysis procedure being estimated at ±10%.

Two other tests were performed using a medium-scale laboratory experiment where the geometry and thermal characteristics of a borehole are replicated under controlled conditions. The thermal conductivity of the soil material (fine quartz sand) used in the experiment was determined independently with a calibrated soil conductivity probe. Two tests were run: one with dry sand, and one where the sand was saturated. In both cases, the in situ test matched the independently measured estimates within 2%.

Shonder and Beck (1999) also used a thermal response test for validation of their 1D parameter estimation model. The data set is from the medium-scale laboratory experiment, described by Austin et al. (2000). The 1D parameter estimation model matches the independently made estimate of the thermal conductivity within 3%.

Shonder and Beck (2000) also report on three in situ tests performed in Lincoln, Nebraska, at sites where ground source heat pump systems are being used to provide heating and air conditioning for elementary schools. For these cases, operating data from one of the schools were used in conjunction with a detailed numerical model to estimate effective thermal conductivity for that site. The conductivity estimated with a 50 hour test, was within 4% of that determined from one year of operating data. Sequential conductivity estimates are made with three different methods (line source, cylinder source and the 1D finite volume parameter estimation method) for each of the three tests. The time period at which the results converge is instructive. It varies significantly from test to test and method to method. For these three tests, where the power output of the generators was fairly constant, the line source method approached the final value from below – in other words, using a shorter test, say 12 hours, would result in a conservative (low) estimate of the thermal conductivity. Presumably, this would be true for most cases, where the grout thermal conductivity is lower than the ground thermal conductivity.

However, in a fourth test, performed at an undisclosed location, two periods of significant power fluctuation two and five hours respectively occurred about 10 and 30 hours into the test. The line source methods and cylinder source methods were both applied assuming that the heat injection power was constant. Where it fluctuated, fluctuations in the conductivity estimates made by the line source and cylinder source methods are clearly observed. In this case, the thermal conductivity is over estimated by as much as 30% at the 15^{th} hour, apparently due to the power fluctuations.

5.10 Cost

The thermal response test cost varies between countries, as does the service included in the test. Brief cost estimates for a thermal response test conducted on one borehole in different countries are given in Table 1.

Table 1: Approximate costs for a thermal response test in some countries.

Country	***Cost***	***Comment***
Germany	2500 EURO	Includes test, analysis and report
Sweden	2500 EURO	Includes test, analysis and report
Norway	3800 EURO	The service is offered as a total pre-investigation including 160 m drilling, pipe fitting, measurement, analysis and preliminary dimensioning for a cost of 10700 EURO
Netherlands	3000 EURO	Test, analysis and report
USA	4000-7000 USD	Includes cost of drilling test borehole, at 2000 USD.

6. WORKSHOP AND TEST COMPARISON IN MOL, BELGIUM

On Oct. 14, 2000 a workshop was held in the Flemish Research Centre (VITO) in Mol, to discuss international experiences in thermal response testing of boreholes. It was a joint activity of the Annex 12 and Annex 13 of the IEA Energy Storage Implementing Agreement. Thermal response testing experts in Europe came together, adding up to 20 participants from 9 countries.

The Mol site also allowed making a comparison of tests with three different test devices. Three boreholes spaced only a few meters apart, in virtually identical geology, were used. The holes had been drilled for the subsurface investigations of the planned borehole thermal energy store "TESSAS". In all boreholes, each of 30.5 m (100 ft) depth, double U-pipes has been installed with different grouting material in each borehole:

- Mol-sand (re-filling of the sand produced while drilling)
- Graded sand (filling with a sand of specially optimised grain size distribution)
- Bentonite (grouting with a standard bentonite-cement-grout)

During the previous summer, thermal response tests had been conducted at all three BHE by Groenholland (NL). In the days before and during the workshop in October, tests with the LTW and UBeG equipment were done at individual boreholes.

In the following, the evaluation of the UbeG test is shown. The basic data are given in Table 2, the measured temperature curve in Figure 17.

Table 2: Basic data of Thermal Response Test in Mol by UBeG

Length of borehole	30.5 m (100 ft)
Type of borehole	Polybutylene-Double-U
Borehole diameter	150 mm (6 in)
Test duration	71.8 h (11.-13-10.2000)
Extracted heat	129 kWh (440.2 kBtu)
Extraction power	1797 W (6131 Btu/hr)
Initial ground temperature (average over 30.5 m length of borehole)	12.5 °C (54.5 °F)

The regression lines for T3 and T4 are shown in Figure 18. With the slope of the lines, the thermal conductivity can be calculated:

T3 $$\lambda_{eff} = \frac{1797}{4\pi 30.5 \cdot 1.884} = 2.49$$

T4 $$\lambda_{eff} = \frac{1797}{4\pi 30.5 \cdot 1.890} = 2.48$$

The average of all sensors results in $\lambda_{eff} = 2.49$ W/m/K

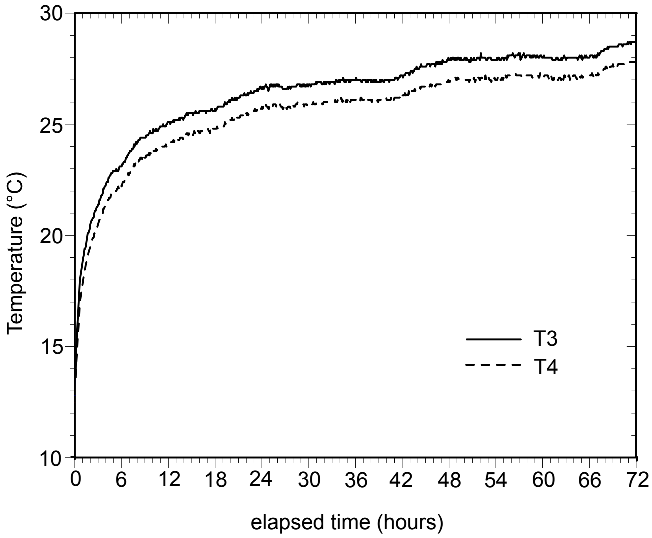


Figure 17: Measured temperature curve of UBeG test in Mol

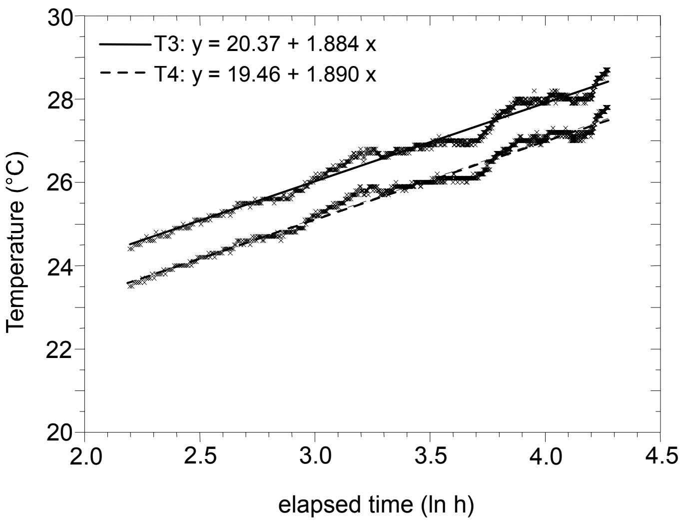


Figure 18: Measured temperatures on logarithmic time scale and regression lines for data in Figure 17.

The thermal borehole resistance R_b is calculated for several time-temperature pairs, from 12 h to 71 h. The representative value is $R_b = 0.13$ K/(W/m)

The results of the various tests (Table 3) show a thermal conductivity of the ground around 2.5 W/m/K (1.4 Btu/hr-ft). It was expected that all results for the ground thermal conductivity should give near the same answer, because the geological profile is the same for each borehole. Only the Groenholland/Bentonite test deviates somewhat; further investigation is needed to determine the cause of the anomaly. The Groenholland tests were also analysed using a parameter estimation procedure. The results are shown in Table 4. While some

Table 3: Results of comparison of Thermal Response Test in Mol, evaluation with line-source method

Grouting:	Groenholland	UBeG	LTW
Mol-sand	λ = 2.47 W/m/K r_b = 0.06 K/(W/m)	-	λ = 2.47 W/m/K r_b = 0.05 K/(W/m)
Graded sand	λ = 2.40 W/m/K r_b = 0.1 K/(W/m)	-	λ = 2.51 W/m/K r_b = ?
Bentonite	λ = 1.86 W/m/K r_b = 0.08 K/(W/m)	λ = 2.49 W/m/K r_b = 0.13 K/(W/m)	-

deviation is shown for the Bentonite test, the results agree much better using the parameter estimation procedure.

Table 4: Results of comparison of Thermal Response Test in Mol, evaluation of Groenholland data with 2-D parameter estimation model

	Mol-sand	Graded sand	Bentonite
Ground	λ = 2.51 W/m/K	λ = 2.42 W/m/K	λ = 2.20 W/m/K

7. CONCLUSIONS

7.1 General conclusions

Since the introduction of mobile thermal response tests in Sweden and the U.S.A. in 1995, the method has developed and spread rapidly in North America and Europe. With the exception of the Dutch system, all of the systems 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. The Dutch system can impose either heat injection or a heat extraction, and the power output is controlled by maintaining a constant ΔT across the ground. Also the AETNA rig has this option.

A variety of data analysis models have been developed. Various applications of the line source approach are used because of its simplicity and speed. The line source theory is the most commonly used model for evaluation of the response test data in all countries, and is dominant in Europe. The use of the cylinder source model for thermal response tests is only reported in the U.S.A, although the theory is used for design of BHE systems in both U.S.A. and Canada. Numerical models coupled with parameter-estimation techniques have been used in the U.S.A.

The issue of the duration of the test period is still discussed, and further studies are needed. The most scientifically rigorous work indicates that, with current test methods and analysis procedures, approximately 50 hours of measurements are needed to obtain an accurate estimate of the thermal conductivity. However, economic aspects of the test duration must be considered for commercial thermal response tests -- a shorter test may be "good enough" if reasonably constant heat injection can be imposed. In this case, the result may be conservative.

Thermal response tests have so far been used primarily for *in situ* determination of design data for BHE systems, but also for evaluation of grout material, heat exchanger types and groundwater effects. The method is also suitable for verification of design when the BTES system has been constructed.

7.2 Further research

This review of the state of the art elucidated some areas where further research and clarification are required. Future research is recommended in the following areas:

- Experimental methods and analysis procedures should be developed to allow shorter tests. This should improve commercial acceptance of the technology. Current limitations which increase the required test length and possible solutions include:
  - Particularly when the line-source analysis procedure is used to analyse results, any deviations from a constant heat rejection/extraction pulse cause difficulties in analysing the results. Deviations are commonly caused by fluctuations in the heat input supplied by the electric resistance heater and heat transfer from the apparatus to the environment that fluctuates with weather conditions. Possible approaches to insure more uniform heat rejection/extraction pulses include:
    - Use of higher quality power supplies or well-controlled heat injection/extraction.

        - Reduction of heat leakage and influence of solar radiation by better thermal insulation of the equipment.
    - For boreholes with significant amounts of low-conductivity grout between the U-tube and borehole wall, the thermal response in the early hours depends much more on the grout rather than the surrounding ground. Any installation procedure that reduces the resistance of the borehole will allow the thermal response to more quickly approach the line-source response for the surrounding ground. Hence, the line-source analysis procedure will be feasible at an earlier time and allow shorter tests. One approach would be to use spacer clips and/or thermally-enhanced grout. (In an analogous manner, the same approach should allow parameter-estimation procedures to more quickly differentiate between the effects of the grout and the ground on the thermal response, allowing shorter tests.
    - Current recommendations for tests on the order of 50 hours or more are based on a range of different geological conditions, test apparati with varying power quality, etc. The development of analysis procedures which can be run in real-time and also used to determine when the test results are conclusive would allow some tests to be run for significantly shorter periods. A preliminary investigation of this carried out by Jain (1999) showed that required test lengths, for some cases, could be as short as ten hours, when an online parameter estimation method was run with an heuristic convergence algorithm. It might also be possible to apply a simpler criterion based on the quality (uniformity) of the heat rejection/extraction pulse.
- Alternatively, test apparati might be developed which do not require test personnel on site. This might allow longer tests to be more acceptable. Based on the Dutch approach, this might involve systems enclosed in large (theft-resistant) containers with telemetry and large, high-quality, reliable, well-maintained diesel generators, where stable net supplied electricity is not available.
- Validations to date have been made primarily by comparisons to cored samples. Ultimately, the best confirmation of the method's validity will probably involve comparison of data from long-term operation with predictions made based on a thermal response test. As suitable measured data are extremely rare, future work is necessary to collect such data. (At the least, such data should be continuously and accurately measured from the beginning of the system operation.). More comparisons between response tests and drill core data may be of interest for studies of special geological situations and of groundwater influence.
- There are some phenomena that can have a significant effect on test results, but have only been given preliminary consideration. These areas in which further research would be useful include:
    - The minimum required elapsed time after drilling and grouting before a thermal response test should be started is not well understood. Further work to establish guidelines would be useful.
    - The analysis procedures all assume that there is no groundwater flow. Practical guidance and analysis procedures (coupled conductive models) should be developed also for situations where significant groundwater flow occurs.
    - The issue of groundwater influence is of interest both for the estimation of the ground thermal conductivity and for the borehole thermal resistance. Since the convective effects of groundwater are temperature dependent, it may be necessary

to study the effect of heating versus cooling mode during the response test when measuring a groundwater filled borehole.

    - Study the effect of superimposed sinusoidal power fluctuations (e.g. variation of ambient temperature) and stepwise thermal load (effect of convection, effect of stops etc), as well as evaluation of decline period in borehole following thermal load period may give information about the variation of thermal resistance and effective thermal conductivity for water filled boreholes.

- Many of the systems built to date have been more-or-less experimental in nature – designed and fabricated by researchers and/or constructed without the benefit of any previous operational experience. Consequently, the systems have not always been as reliable and robust as might be desired. Additional efforts to develop more reliable and robust equipment for performing thermal response test are needed.

- Another potential application of thermal response testing is verification of the design and installation. If applied to a ground heat exchanger that has been installed, it may be possible to determine whether or not the ground heat exchanger will perform as planned. In order to realize this application, it will be necessary to include the effects of horizontal connecting pipes in the analysis procedure.

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Appendix 1 Summary of Experimental Apparati State of the Art December 2001

Reporting Country	Canada	Germany[1]	Netherlands	Norway	Sweden	Switzerland[2]	Turkey	United Kingdom	U.S.A.[3]
References	Cruickshanks, et al. (2000)	Sanner (2001)	Witte, et al. (2001)	Helgesen (2002)	Gehlin and Hellström (2000)	Eugster (2002)	Paksoy (2000)	Curtis (2001)	Austin, et al. (2000)
Configuration	Trailer	Trailer	Container	Trailer	Trailer	mobile	Trailer	Cart, 2-wheel	Trailer
Heat Injection (kW)	3.2	1-6	0.05-4.5	3-12	3-11	3-9	3-12	3-6	0-4.5
Heat Extraction(kW)	--	--	0.05-4.5	--	--	--	--	--	--
Power Control	None	Manual, six levels	Continuously variable with controlled ΔT	Manual, four levels	Manual, three levels	semi-manual, three levels	Manual, four levels	Manual, two levels.	Manual, continuously variable rate.
Flow Rate (L/s)	0.75 (est.)	0.28	0.14-0.83	0.5-1.0	0.5-1.0	variable	0.5-1.0	0.25-1	0.2 (typical)
Circulating Fluid	Water / Prop. Glycol	Water	Water Water/glycol	Water / Prop. Glycol	Water / Prop. Glycol	Water	Water	Water	Water
Temperature sensors	Not reported.	PT100	PT100	Thermocouples	Thermocouples	PT100	Thermocouples	Thermistors	Thermistors
Reported accuracy: temperature sensors	Not reported.	Not reported	±0.07 K	±0.2 K	±0.2 K	0.1	±0.2 K	±0.1 K	±0.1 K
Power sensor	Not reported.	Not reported	Not reported	Watt transducer	Watt transducer	not reported	Watt transducer	kWh meter (pulse output)	Watt transducer
Reported accuracy: power measurement	Not reported.	Not reported	Not reported	±2%	±2%	not reported	±2%	Not reported	±1.5%
Flow sensor	Estimated from ΔP.	Not reported	MagMaster	Volumetric flow meter	none	not reported	Volumetric flow meter	Electromag-netic	Volumetric flow meter
Reported accuracy: flow sensor	Not reported.	Not reported	0.2-0.9 %	±3%	--	not reported	±3%	Not reported	±2%

[1] There are three known test units in Germany; only one (UBeG) is described in this column.

[2] There are two known test units in Switzerland; only one (EPFL) is described in this column.

[3] There are a number of test units in the USA; the one described in this column is the only one for which specifications are published.

Appendix 2. Summary of Measurements State of the Art December 2001

Reporting Country	Canada	Germany	Netherlands	Norway	Sweden	Switzerland	Turkey	United Kingdom	U.S.A.
First year of operation	2000	1999	1999	1998	1996	1998	2000	1999	1995
Number of test rigs	1	3	1	1	1	2	1	1	>10
Total number of tests	2	> Ca. 35[4]	Ca. 20[5]	Ca. 50	Ca. 35	7	2	Ca. 6	>300
Measured ground types	Hard rock, Slate	Unconsolidated sediments (sand, silt etc.), Sediments (Marl, Shale etc.)	Clay, sand, peat, shale, mudstone, sandstone, chalk	Hard rock, Shale	Hard rock, Shale, Sedimentary	Molasse sediments	Sedimentary	Hard rock, shales, clays, mudstones, coal bearing measures, limestone	Sedimentary, clay, shale
Measured BHE Backfill material	Groundwater	Grout, Sand	Groundwater Bentonite grout, sand, ground material, bentonite/cement grout	Groundwater	Groundwater, Sand	Grout (BHE)	Groundwater	High solids bentonite	Bentonite grout, thermally enhanced grout, pea gravel, sand
Measured BHE types	Single U-tube	Single U-tube, double U-tube Energy piles	Single and double U-tube, concentric	Single U-tube	Single U-tube, double U-tube, concentric	Double U-pipe , Energy piles (EP)	Single U-tube	Single U-pipe with geoclips	Single U-tube, double U-tube.
Typical borehole depth	55-91 m	26-117 m (min. pile 7 m, max 250 m)	30-100 m	120-200 m	100-150 m	150-300 m (BHE) < 30 m (EP)	150 m	50-70 m	60-120 m
Typical borehole diameter	150-164 mm	150-160 mm	50-300 mm	115-140 mm	110-115 mm	150 mm (BHE) ~240 mm (EP)	150-200 mm	125-150 mm	85-150 mm

[4] UBEG and AETNA ca. 15 tests each from 1999 to 2002

[5] Tests performed in Netherlands, Belgium and UK