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**Title:** Thermal response testing of compromised borehole heat exchangers

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**Abstract**

The results of five thermal response tests (TRT's) are presented. Three of the tests were carried out consecutively on the same borehole to illustrate the importance of allowing artificially imposed thermal gradients to dissipate prior to commencement or re-commencement of a test following testing issues. The two remaining tests were carried out on separate boreholes to confirm the results obtained by the first (uncompromised) of the initial three tests. The testing regime demonstrates the necessity for careful performance of TRT's and shows the variation in costs / required borehole length which may occur if testing problems occur on site.

**Keywords:** Geothermal energy, ground source energy, thermal response test, renewable energy, site investigation

**Notation:**

F	flow meter
H	BHE depth (m)
Q	heating power (W)
$R_b$	borehole thermal resistance (mK/W)
$r_b$	borehole radius (m)
t	time from test commencement (s)
$T_0$	initial ground temperature ( $^{\circ}\text{C}$ )
T1	BHE injected fluid temperature ( $^{\circ}\text{C}$ )
T2	BHE return fluid temperature ( $^{\circ}\text{C}$ )
T3	air temperature inside TRT rig housing ( $^{\circ}\text{C}$ )
T4	air temperature outside TRT rig housing ( $^{\circ}\text{C}$ )
TRT	thermal response test / testing
$\alpha$	thermal diffusivity ( $\text{m}^2/\text{s}$ )
$\gamma$	Euler's constant (0.5772)
$\lambda$	ground thermal conductivity (W/mK)

## **1. Introduction**

State of the art design tools are essential for accurate dimensioning of ground source (also known as geothermal) energy systems [1]. It is vital that accurate design of these systems is carried out so as to build upon the geothermal energy industry confidence that has been established in many countries throughout the world to-date. One of the primary tasks of the design process is to determine the length of heat exchanger piping required to extract or reject the quantity of heat demanded by a particular development [2]. An essential pre-requisite required in order to use the sophisticated design tools is provision of accurate site thermal characterisation data. Thermal response testing is currently accepted as the most appropriate method for accurately determining critical design parameters such as thermal conductivity, borehole thermal resistance and the initial temperature of the geological formation, which are required for the accurate design of medium to large scale ground source energy systems. This paper presents and compares the results obtained from five short-duration thermal response tests carried out on the same site, three of which are carried out consecutively on a single borehole. A modelling exercise is carried out using a borehole heat exchanger design tool in order to investigate the effects of the variation in site thermal parameters measured by the various thermal response tests.

## **2. Development Description**

The site works described in this paper were carried out on the construction site of a new healthcare facility in Norfolk in the United Kingdom. When complete, the development will provide facilities for approximately 40 intensive care beds alongside facilities for training, education, academic research and clinical care. A low temperature hot water under-floor distribution network will be installed in order to allow a ground source energy system to achieve the required design temperatures throughout the design life of the building and in order to optimize the operational performance of the heat pump by providing a low-temperature high-volume heat distribution network, rather than a conventional high-temperature low-volume system (e.g. standard radiators). The design flow temperature of the under-floor system will be 45 °C, with a specified maximum water velocity flow rate of 1.5 m/s. The ground source heat pump system will provide the lead heating and cooling requirements of the entire development. A gas fired boiler will be installed to provide peak heating loads where required and full

system back up which may be required during heat pump system maintenance or during possible failure events. The hot water requirements of the development will be served by the installation of a number of flat plate solar thermal collectors which will work in tandem with insulated heat storage vessels.

### **3. The Thermal Response Testing Process**

Thermal response tests are used to investigate the potential for a site to accommodate a closed loop ground source energy installation and should be considered an essential component of the design feasibility process for any medium to large scale closed loop ground source heating / cooling infrastructure installation [3-5]. The results from thermal response tests can be manipulated to provide information in relation to the:

- thermal conductivity of the geological formation into which the borehole heat exchanger (BHE) is installed (denoted  $\lambda$ , W/mK);
- borehole thermal resistance (caused primarily by the thermal transfer properties of the material used to backfill the borehole (i.e. the contact material between the borehole heat exchanger piping and the borehole wall), thermal short-circuiting between down-flow and up-flow pipes of the borehole heat exchanger and thermal resistance associated with transfer of heat from the borehole backfill material, through the pipe wall, to the carrier fluid - denoted  $R_b$ , mK/W);
- initial 'at rest' ground temperature (denoted  $T_0$ , °C);
- and can also provide an indication as to whether or not significant groundwater flow exists across the borehole heat exchanger, the existence of such a flow can have important design implications and result in the necessity to complete a complex and complicated system design in some cases [6, 7].

Analysis of the data collected during a test allows ground source system designers to confirm estimated parameters used during the feasibility and full design stages of a project which leads to an optimisation of system sizing and layout whereby building heating & cooling loads are met, while the initial capital installation cost and the running costs of the system are minimised.

Most thermal response testing rigs operate by applying a known quantity of heat energy to a borehole heat exchanger pipe over a number of hours. The temperature development (or temperature response) of the heat carrier fluid circulating within the borehole heat exchanger pipe over the duration of the test is monitored by recording the injected and return temperatures at fixed time steps. Fig. 1 shows the layout of the University College Dublin (UCD) TRT rig. Water is circulated in an anticlockwise direction from the circulating pump, through electric resistance heaters of known electrical rating, by the injected fluid temperature sensor located at the point of fluid exit from the rig housing (denoted 'T1' in Fig. 1), around the borehole heat exchanger infrastructure which is installed in the sub-surface, until it reaches the return fluid temperature sensor ('T2' in Fig. 1). A flow meter (denoted 'F') is also included on the UCD TRT rig in order to verify that turbulent flow is maintained throughout the test, which is important in the context of heat transfer efficiency and replicating standard heat-pump operating conditions. Two air temperature sensors (denoted 'T3' and 'T4' in Fig. 1) are also included on the UCD rig so that the operative can confirm that excessive heat loss from the carrier fluid to the atmosphere is not occurring during the test, and therefore the 'known' heat injection rate value (based on either measurement of electrical energy required to run the heaters or by using heaters of known electrical rating) can be applied to subsequent calculations and analysis with increased confidence.

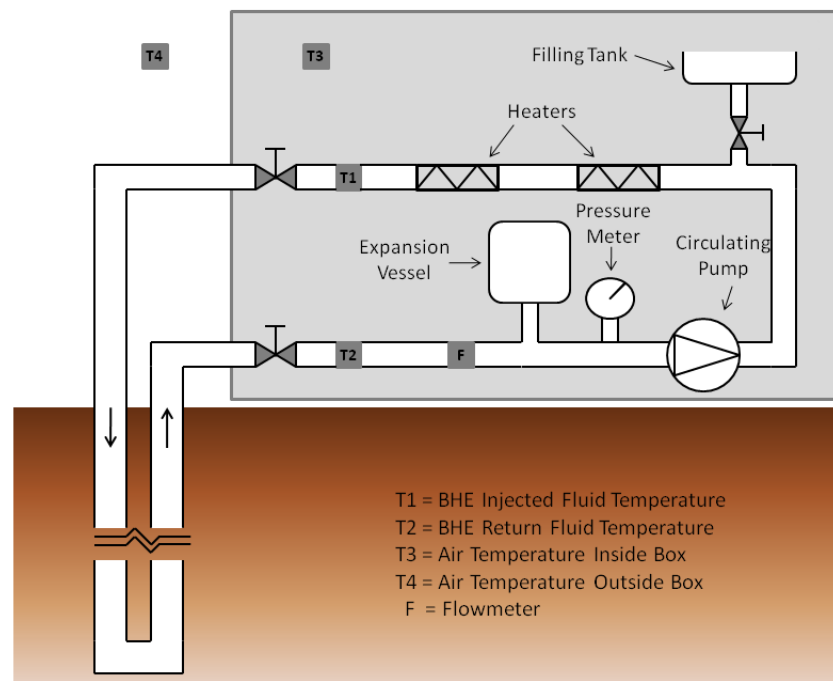


Figure 1. Thermal response testing rig layout

Test results can be evaluated using a number of differing methods which are described in detail in many previous publications [3, 8-10]. The most widely used evaluation theory is the analytical line source method which is developed from Kelvin's line source theory such that Equation 1 may be written, where  $Q$  is injected heat power (W),  $H$  is the depth of the borehole heat exchanger (m) being tested,  $k$  is the slope of the line on a plot of average temperature vs.  $\ln(\text{time})$  based on the data collected during the TRT subject to the lower time criterion shown in Equation 2, where  $r_b$  is the borehole radius (m),  $t$  is time (s) and  $\alpha$  is thermal diffusivity ( $\text{m}^2/\text{s}$ ). For a detailed explanation of the theory behind the analytical line source method readers should refer to Ingersoll & Plass [11], Florides & Kalogirou [12] or Hemmingway & Long [13].

$$\lambda = Q / 4\pi kH \quad (1)$$

$$t > r_b^2 / \alpha \quad (2)$$

There is currently no Irish or UK standard methodology for the performance of thermal response tests, however tests are typically carried out in general accordance with the methodology developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers [14], the International Ground Source Heat Pump Association [15] or the guidelines developed by the working group of Annex 13 "wells and boreholes" of the Implementing Agreement on Energy Conservation through Energy Storage of the International Energy Agency (IEA) [16], all of which are broadly similar. The test results presented in this paper are carried out in general accordance with all the previous methodologies, however the length of the tests carried out by the UCD TRT rig are carried out over a shorter time period than that recommended in the above mentioned methodologies due to technical difficulties experienced on-site (and also so that data relating to the re-commencement of thermal response tests could be gathered). The minimum test duration suggested in the previous methodologies, however, are provided to account for the fact that the ground conditions, borehole construction, borehole diameter and backfill materials can vary from site to site and project to project. The suggested minimum test duration is therefore not a technical testing or evaluation condition but an attempt to standardise test durations across the breadth of possible site and project conditions. The technical testing / evaluation limitations relating to thermal response testing and analysis using the analytical line source method are described in Equation 2, which describes the lower time criterion which must be applied to the results of thermal response test data in order to analyse it using the

analytical line source method. It indicates the quantity of 'initial testing data' which must be disregarded prior to applying the line source method. Calculation of the quantity of data which must be disregarded so that analysis using the line source method remains valid in the case of the boreholes on which the five thermal response tests in this paper are performed indicates that 1.65 hours of data must be disregarded. This calculation is based on a borehole radius ( $r_b$ ) of 70 mm and thermal diffusivity value ( $\alpha$ ) of  $8.27 \times 10^{-7} \text{ m}^2/\text{s}$ .

This suggests that the test period durations of the various thermal response tests presented (5.5, 6.5, 15.0, 16.0 and 50 hours) provide a sufficient quantity of data to exclude the initial 1.65 hours and evaluate the remaining data using the line source method. This is further evidenced due to the fact that the steady state conditions required for the evaluation of thermal response test data using the analytical line source method appear to have been achieved, verified by the straight line shown on a graph of temperature development versus the natural logarithm of time (Fig. 3) for each of the tests. The apparent achievement of steady state conditions is further substantiated by reviewing the results from the various tests, which show that the measured value of thermal conductivity obtained by the first (uncompromised) thermal response test by the UCD TRT rig (TRT 1) equals the value obtained from the test carried out using the successful third party thermal response testing rig (denoted third party A).

#### **4. Experimental Set Up**

The three thermal response tests performed using the UCD TRT Rig (denoted TRT 1, TRT 2 & TRT 3 in this paper) were carried out consecutively on the same borehole heat exchanger. TRT 1 ran for 5.5 hours, TRT 2 started 4.5 hours after the completion of TRT 1 and ran for 16.0 hours while TRT 3 started 4.5 hours after the completion of TRT 2 and ran for 6.5 hours. This subsequent re-testing of the same BHE meant that the natural thermal gradients of the ground surrounding the BHE were compromised for TRT 2 and TRT 3, caused by the heat energy applied in the previous respective tests. The heater power (9 kW), heat carrier fluid (water), pipe configuration (single U), pipe depth (201 m), pipe outer diameter (40 mm), pipe wall thickness (3.7 mm), pipe material (polyethylene), borehole diameter (140 mm), BHE pipe spacing from pipe centre to pipe centre (approximately 70 mm) and borehole backfill material (pea gravel) were identical for all three tests. Two thermal



response tests were carried out by a third party on the site (denoted Third party A & Third party B in this paper) on two additional boreholes. The previously outlined 'constant parameters' relating to the UCD TRT Rig tests are identical in the case of the third party tests with the exception of the heater power which was set to 9.8 kW. A full data set of the results obtained during the 'Third party B' thermal response test was made available to the authors, the details of which are included on subsequent Figures where appropriate. The data relating to the 'Third party A' test was not available to the authors due to commercial sensitivities, but in any case the calculated value of thermal conductivity resulting from the data analysis is known to be 1.9 W/mK. Table 1 outlines the test parameters which varied with each test. A reduction in flow rate is observed during TRT 1 and TRT 2. The flow reduced slightly as each of the tests progressed and this may be due to thermal expansion of the borehole heat exchanger piping as the testing progressed. This resulted in a gradual reduction in the pressure of the circulating carrier fluid as the tests progressed, until eventually there was not enough pressure at the intake side of the circulation pump to continue circulation. This issue will be solved for subsequent thermal response tests using the UCD TRT rig by retro-fitting a pressurisation pump. Addition of the pressurisation pump will allow the circulating carrier fluid to be pressurised to between one and two bar at test commencement stage, so that there is sufficient 'excess pressure' to counteract the reduction in fluid pressure caused by the thermal expansion of the heat exchanger pipes. It is also possible that the circulation issues was experienced due to either a small leak in the closed loop system, resulting in entrained air in the system leading to an air lock or due to air within the closed loop system which eventually rose to the circulation pump to create an air lock and therefore stop the flow. No fluid leakage was observed on site.

Table 1. *Test set up*

Parameter	TRT1	TRT 2	TRT 3	Third party A	Third party B
Flow rate (L/min)	34 to 27	34 to 28	34	Not available	25
Test duration	5.5 hrs	16.0 hrs	6.5 hrs	15.0 hrs	50.0 hrs
Initial temperature	11.7 °C	13.1 °C	17.0 °C	Not available	11.0 °C

## 5. TRT Results

The average temperature development (i.e. the mean of the injected & return flow) profiles measured during the three UCD thermal response tests are shown in Fig. 2 (a). The importance of measuring the initial ground temperature and ensuring it is in the range expected is illustrated by the fact that all

three profiles are broadly similar in shape even though the initial ground temperature at the commencement of each test differ. Closer visual inspection and comparison of the three profiles on Fig. 2 (a) reveals that although they are similar in shape, the slope of the latter stages of TRT 2 is slightly less than that of TRT 1 and the slope of TRT 3 is slightly less than that of TRT 2. Had the results of only one of the TRT's carried out (whether it be TRT 1 where ground temperature conditions were undisturbed or TRT 2 or TRT 3 where the initial ground temperature was compromised by the artificial thermal influence of the previous tests) been plotted on a graph similar to that shown in Fig. 2 (a), rather than the three profiles superimposed on one graph, it is likely that a TRT operative would accept the results as being correct because the shape of the temperature development profile is similar to what would generally be expected for a thermal response test. This would result in the calculation of thermal properties which are not a true reflection of those present at the site. The effect of artificial thermal influence on the BHE illustrates the importance of ensuring that ground in the vicinity of a test is not thermally altered shortly before or during a thermal response test. In this case the thermal interference applied to the ground surrounding the BHE was caused by carrying out three consecutive thermal response tests on a single borehole over a short time period, however there are several other potential causes of thermal interference. The borehole drilling process produces thermal gradients which must be allowed to dissipate prior to commencement of a TRT, grouting of the borehole can generate a thermal influence (e.g. heat produced by hydration of a cement-based grout) which must be mitigated against by time delay and also drilling additional boreholes in the vicinity of a thermal response test have been shown to interfere with test results.

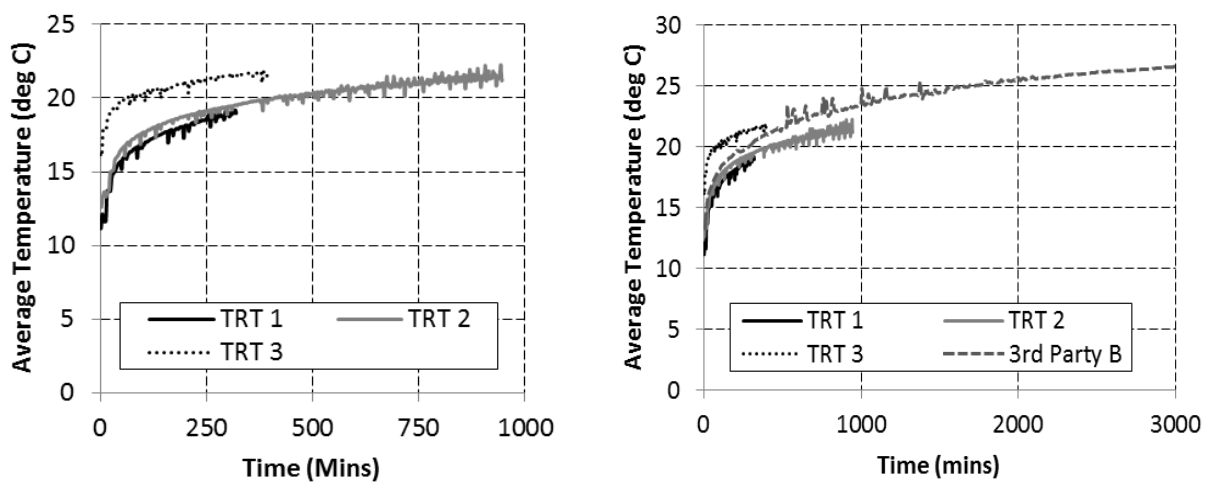


Figure 2. Average temperature development of (a) 3 UCD TRT's & (b) 3 UCD & third party B TRT's

The temperature development profile of the third party B thermal response test is superimposed on Fig. 2 (a) to form Fig. 2 (b), again a broadly similar average temperature development curve is observed to those obtained from the UCD TRT results. All five TRT data sets were processed in similar fashion using the analytical line source method described earlier in this paper. For clarity of presentation, only the UCD TRT data is presented on the graphs which follow – results from the analysis all five data sets are presented in the next paragraph and in Table 2.

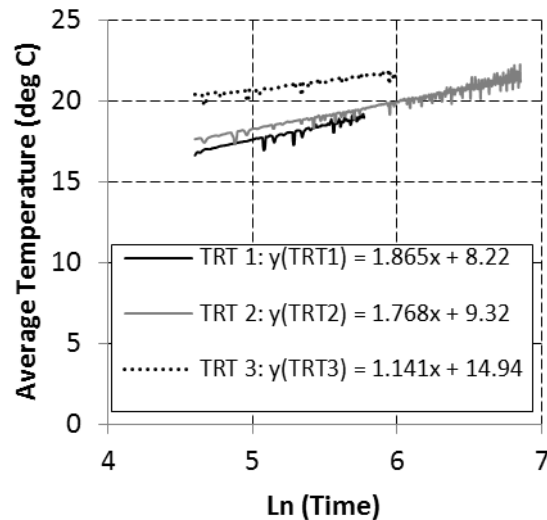


Figure 3. Average temperature vs.  $\ln(\text{Time})$  with 'early data' removed

A graph of average temperature development vs. the natural logarithm of time with the 'early data' removed (i.e. the data shown in Fig. 2 (a) representing the temperature development during the early stages of the TRT prior to the achievement of stable heat flow as described by Equation 2 in the ground is removed) is shown on Fig. 3. In the case of the three UCD TRT's all parameters in Equation 1 are identical except for 'k' – as the slope of each line in Fig. 3 differs. This results in the calculation of thermal conductivity values for TRT 1 of 1.9 W/mK, TRT 2 of 2.0 W/mK and for TRT 3 of 3.0 W/mK. The conductivity values resulting from TRT 1 and TRT 2 fall within the expected range of thermal conductivity values for the formation, which is estimated to be in the region of 1.25 to 2.33 W/mK [17-19]. The reason for the increase in thermal conductivity value calculated for TRT 2 and TRT 3 relative to TRT 1 is due to the thermal interference caused by the preceding thermal response test(s). The third party A TRT resulted in a calculated thermal conductivity value of 1.9 W/mK which is within the range expected for the formation and concurs with the value obtained by the uncompromised UCD thermal response test (TRT 1). For an unknown reason the third party B TRT resulted in a lower than

expected calculated thermal conductivity value of 1.5 W/mK. While the precise reason for this lower value being obtained is unknown, variation in the results from thermal response tests could be caused by for example: instrumentation failure, poor construction of a borehole heat exchanger (e.g. only partial grouting of the borehole, resulting in poor thermal contact with the surrounding ground formation and therefore a lower apparent thermal conductivity) or local variations in geology across a site. All the measured thermal conductivity results are included in the modelling exercise presented later in this paper in order to illustrate the importance of allowing artificially imposed thermal gradients to dissipate prior to commencement of a TRT and also of careful planning, attentive operation and scientifically rigorous analysis of data collected during thermal response tests.

Fig. 4 shows the difference between the air temperature measured inside and outside the UCD TRT rig housing during TRT 1, TRT 2 and TRT 3. Positive temperature difference values indicate a higher air temperature value within the rig housing than that measured outside the rig housing while negative temperature values indicate a lower temperature value within the rig housing. Differences in the measured temperature are due to both a small amount of heat loss from the closed TRT circuit into the rig housing and also due to isolation of the temperature sensor located within the rig housing and the one located outside, by the rig housing itself. The fact that both positive and negative temperature differences are observed (rather than positive alone or negative alone) indicates that a significant portion of the temperature difference is likely due to isolation of the internal temperature sensor from external temperature conditions (wind, sun, rain etc.) by the rig housing. The recorded temperature differences are small and therefore only a small amount of heat energy is being lost from the system.

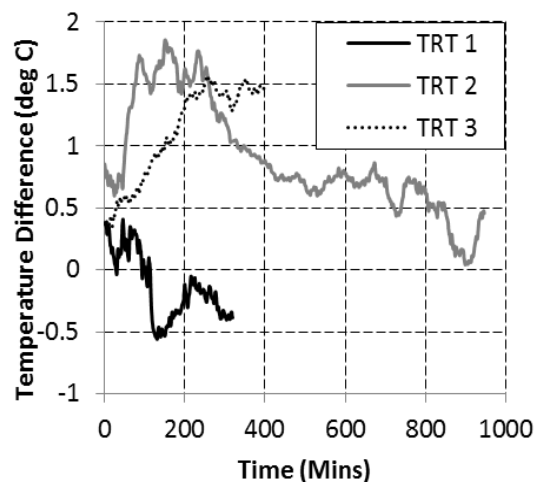


Figure 4. *Temperature difference inside / outside rig housing*

In addition to calculating the thermal conductivity of the geological formation tested, data collected during a thermal response test may be analysed to provide a figure for effective borehole thermal resistance (denoted  $R_b$ , mK/W) to take account of the thermal resistance created by the spatial dimension of the borehole heat exchanger. The effective borehole thermal resistance is calculated using Equation 3, edited from Esen and Inalli [20], where  $H$  is the borehole heat exchanger depth (m),  $Q$  is the injected heat power (W),  $T_f(t)$  is the temporal evolution of the mean fluid temperature measured during a test,  $\lambda$  is the thermal conductivity (W/mK),  $t$  is time (s),  $r_b$  is the borehole radius (m),  $\alpha$  is the thermal diffusivity (m<sup>2</sup>/s),  $T_0$  is the initial undisturbed ground temperature (°C) and  $\gamma$  is Euler's constant (0.5772).

$$R_b = (H / Q) \left[ T_f(t) - \{Q / 4\pi\lambda H\} \{ \ln(t) \} - T_0 \right] - (1 / 4\pi\lambda) \left[ \ln(4\alpha / r_b^2) - \gamma \right] \quad (3)$$

Analysis of the data obtained during the three UCD tests resulted in calculated effective borehole thermal resistance values of 0.262, 0.237 and 0.165 mK/W for the first, second and third test respectively. The reduction in effective borehole thermal resistance values for consecutive test results from the fact that each of the preceding thermal response tests elevated the temperature of the ground surrounding the borehole heat exchanger, resulting in a reduction in the amount of time required to achieve the same temperature response in each subsequent test (this is graphically illustrated in Fig. 2(a)).

## 6. Description of Model

A software program called 'Energy Earth Designer 3' (EED) has been selected to analyse the effects of the variation in site thermal parameters. The software was originally developed through collaboration between the Institute of Applied Geosciences of Justus-Liebig University, Germany and the Department of Mathematical Physics in the University of Lund, Sweden [21, 22]. The accuracy of EED has been verified by comparison against measured field data, three dimensional finite element models and in-depth parameter studies. It has established itself as one of the most commonly used ground source energy design tools used by the industry in Europe.

The model presented investigates the variation in total length of borehole heat exchanger required to supply the calculated development heating and cooling loads due to the variation in thermal parameter results measured by the five thermal response tests. This variation in length of BHE is directly related to the increase or decrease in project costs in order to illustrate the importance of accurate site thermal characterisation. It is worth noting that although a gas boiler will be installed at the development in order to provide capacity to cover peak heating loads where necessary and to provide heating during heat pump down times, the modelling exercise which follows incorporates these peak load conditions so that the ground source energy system is designed to have sufficient capacity to cater for peak load conditions when required.

## 7. Model Input Parameters

### 7. Building Energy Data

The building energy data provided in Figs 5 (a) and (b) has been interpreted from data provided by a multi-disciplinary building consultancy firm called Ingleton Wood. Fig. 5 (a) shows an approximated monthly breakdown of the space heating and cooling base load energy requirements of the proposed development in megawatt hours (MWh). Fig. 5 (b) shows a monthly breakdown of the peak heating and cooling loads in kilowatts (kW) and the associated durations of the respective peak loads. The system shows itself to have a heating dominated profile over the course of a year, as would be expected for UK / Irish climatic conditions.

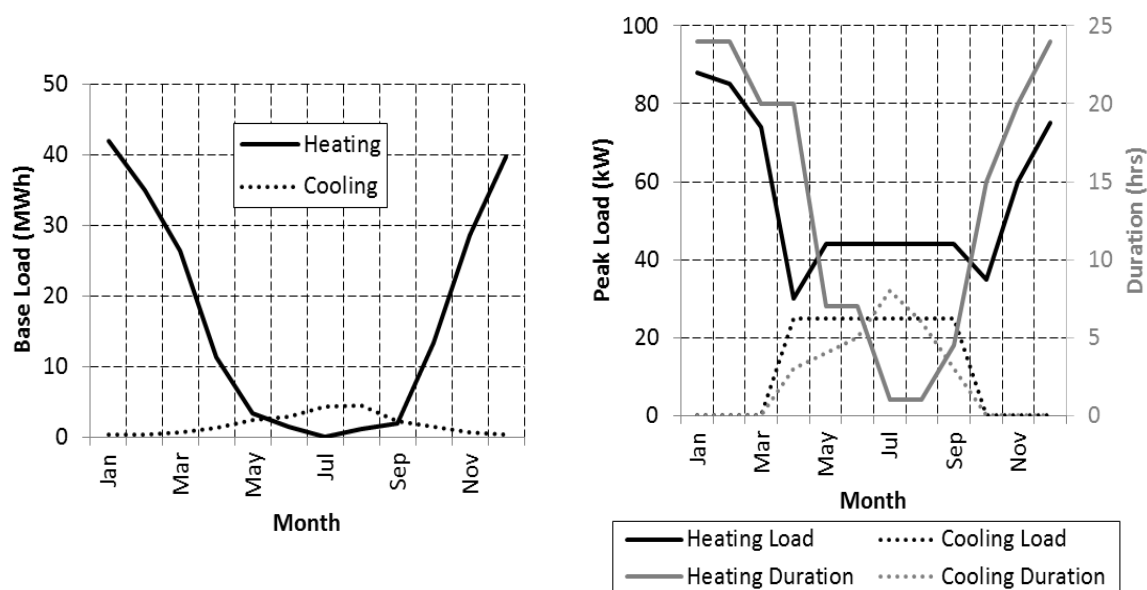


Figure 5. (a) Base heating & cooling loads and (b) peak heating & cooling loads

## 7.2 Other Input Parameters

The drillers log reveals the presence of made ground to a depth of 1 m below ground level, followed by sand and gravel to 21 m, soft fractured chalk with flint to 75 m and firm chalk with flint to a depth of 204 m. A depth-weighted average approach for calculating a pre-thermal response test estimated value for the thermal conductivity of the geological formation into which the borehole heat exchanger is installed (assuming the thermal conductivity of sand & gravel is 1.0 W/mK and of the chalk & flint is 1.8 W/mK) results in a calculated value of 1.72 W/mK. This value for thermal conductivity will be used as the 'base case' model scenario, against which the varying measured thermal conductivity values will be compared.

Some of the other important parameters included in the model (calculated by depth-weighted average where appropriate) are as follows: volumetric heat capacity 2.5 MJ/m<sup>3</sup>K; average ground surface temperature 9.5 °C and geothermal heat flux 0.05 W/m<sup>2</sup>. Heat carrier fluid properties are those commensurate with a solution of 25% monopropylenglycole and 75% water mixture, details of the borehole heat exchanger are provided in the section four earlier in this paper. A seasonal performance factor (SPF, the ratio of heat produced over the course of a season to the electrical demand required to drive the heat pump over the same period) of 3.5 has been allowed for heating and 4.5 for cooling – these figures are considered to be conservative.

## 8. Model Results

The model was set up such that the variation in length of borehole heat exchanger resulting from the change of thermal conductivity could be calculated. The model input parameters outlined in section seven of this paper were entered into the model. The resulting total borehole heat exchanger lengths required to satisfy the building thermal loads for each value of thermal conductivity are shown in Table 2 (i.e. the total quantity of sub-surface borehole heat exchanger piping which needs to be installed e.g. a required borehole length of 2,000 m may correspond, for example, to 10 x 200 m deep boreholes at the site, while a required bore length of 1,800 m may correspond to 9 x 200 m deep boreholes at the site etc.), where numbers in brackets indicate a reduction in the required borehole heat exchanger length relative to the 'base case scenario' (thermal conductivity value of 1.72 W/mK).

As expected, lower values of thermal conductivity lead to the requirement for additional borehole heat exchanger length.

Table 2. Analysis and modelling results

Parameter	Base Case	TRT	TRT 2	TRT 3	Third party A	Third party B
Thermal conductivity (W/mK)	1.72	1.9	2.0	3.0	1.9	1.5
Required bore length (m)	2,010	1,937	1,882	1,528	1,937	2,150
Additional bore length (m)	0	(73)	(128)	(482)	(73)	40

The resulting effect on borehole drilling costs is shown in Fig. 6 where a drilling cost of €70 per meter, which would be typical of drilling costs for large scale borehole systems in Ireland, has been assumed (this may be considered to be a conservative estimate of the total cost savings as additional cost savings such as reduced piping costs, reduced grouting costs and reduced ground level connection costs may also be achieved). Fig. 6 demonstrates that, in addition to providing an increased level of confidence in assumed design parameters, updating the computer model by changing the pre-TRT estimated thermal conductivity value of 1.72 W/mK to the TRT measured value of 1.9 W/mK results in a decrease in drilling costs of over €5,000, which immediately makes the thermal response test approximately cost-neutral.

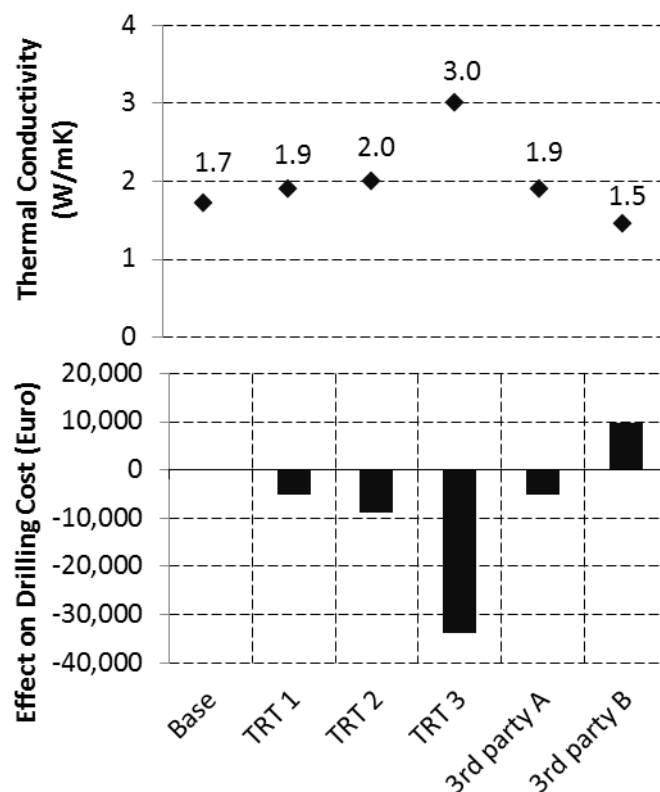


Figure 6. (a) Variation in thermal conductivity & (b) associated effect on BHE drilling costs



The earlier stated importance of allowing artificially imposed thermal gradients to dissipate prior to commencement of a TRT and also of careful planning, attentive operation and scientifically rigorous analysis of data collected during thermal response tests is reinforced by the wide spectrum of required borehole heat exchanger lengths and the associated variation in drilling costs. The largest difference in required borehole length stands at 622 meters, with an associated differential in borehole drilling cost of €43,540.

## **9. Discussion & Conclusions**

The results of five thermal response tests carried out on the same site are presented. Three of the tests were carried out consecutively on a single 200 m deep borehole using the UCD TRT rig and show an increasing trend in measured thermal conductivity values caused by the thermal interference imparted on the borehole by each previous respective test. The two remaining tests were carried out on two additional 200 m deep boreholes at the same site and result in two differing values of thermal conductivity being observed: one close to what would be expected (and which is equal to the result obtained by the 'uncompromised' UCD thermal response test) and one below what would be expected for the geological formation being tested.

Artificially imposed thermal gradients may be generated in the ground in a number of ways as follows: repetition or re-starting of thermal response tests on the same borehole due to failure or interruption of a test (e.g. generator failure, pump failure), thermal gradients generated by the drilling of the borehole on which the thermal response test is being carried out, thermal gradients created by the borehole grout (e.g. heat of hydration produced by a cementitious grout) or by drilling additional boreholes in the vicinity of test borehole while a thermal response test is being carried out. The variation in measured thermal conductivity values from each thermal response test (1.9, 2.0, 3.0, 1.9 and 1.5 W/mK) illustrates the importance of allowing these artificially imposed thermal gradients to dissipate prior to commencement of a thermal response test.

The installation and cost implications associated with the variation in measured site thermal conductivity values is assessed using a borehole heat exchanger design tool. The largest difference in required borehole length is approximately 600 meters (equivalent to the requirement to install three additional 200 m deep boreholes for the development described in this Chapter), with an associated differential in borehole drilling cost in the region of €45,000. Problems for a project can eventuate from

either oversizing or undersizing of the amount of borehole heat exchanger pipe length required to satisfy the energy loads of a development. If the quantity of heat exchanger pipe is oversized (due to the calculation of a thermal conductivity which is too low relative to the actual ground conductivity) the project will incur additional drilling and installation costs. However, if the quantity of heat exchanger pipe installed is undersized (due to the calculation of a thermal conductivity value which is too high relative to the actual ground conductivity) then the operation of the ground source heat pump will be inefficient due to increased electrical input costs. This difference in required total borehole length and associated cost illustrates the importance of careful planning, attentive operation and correct analysis of data collected during thermal response tests.

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