AN OVERVIEW OF THE RESULTS OF *IN-SITU* THERMAL RESPONSE TESTING IN THE UK

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ABSTRACT

The results of 26 *in-situ* UK thermal response tests, derived from two test-rigs operated by Kensa Engineering and Geowarmth Heat Pumps, have been analysed. Derived values of thermal conductivity yield a median of 2.70 W/m/K, with 25% and 75% percentiles of 1.90 and 3.72 W/m/K. The lowest values are derived from Northern Irish basalt (1.1 W/m/K) and English Mercia Mudstone Rocks (1.49 W/m/K), while the highest (>8 W/m/K) are from Sherwood Sandstone and Coal Measures strata where advective heat transport with groundwater flow is believed to have led to an elevated apparent conductivity. Borehole thermal resistance exhibits 25%-ile, median and 75%-ile values of 0.09, 0.11 and 0.14 Km/W. Undisturbed ground temperature exhibits 25%-ile, median and 75%-ile values of 11.5, 12.6 and 13.3°C.

1. INTRODUCTION

This paper presents a statistical summary of the results of 26 *in-situ* thermal response tests carried out in “closed loop” boreholes in the United Kingdom since April 2005 by Geowarmth Heat Pumps Ltd. and Kensa Engineering Ltd. The two test rigs were designed and manufactured by Kensa, with subsequent modifications being made to one rig by Geowarmth. They are similar in construction and both utilise a standard concept as follows:

- a carrier fluid (typically water) is circulated through a closed loop of pipe installed in a borehole, at a rate designed to achieve transient-turbulent or fully turbulent flow. The fluid flow rate (*F*) is continuously logged using an in-line flowmeter.
- a heat source applies a constant heat power input to the circulating fluid. In the case of the Kensa rig, the heat source is an array of electrical resistance immersion heaters. In the case of the Geowarmth rig, the heat source is one/two liquid petroleum gas burners.

- the temperature of the carrier fluid entering (T_{down}) and existing (T_{up}) the borehole loop is logged at regular intervals.

At any given time, the heat input power (*P*) is calculated using the formula:

$$P = (T_{down} - T_{up}) \times F \times VHC$$

where *VHC* is the volumetric heat capacity of the carrier fluid (water), calculated using a temperature-sensitive algorithm. The power can be verified against the rated capacity of the heaters (in the Kensa rig) and is typically found to correspond to the rated power of the heater plus a small increment of heat deriving from the circulation pump (typically 100 - 300 W).

The tests were typically analysed using a line source solution (Ingersoll et al. 1954, Banks 2008) in an Excel spreadsheet environment. This mode of analysis requires a constant power input (or, at least, a series of constant power steps); thus, in the few tests where a constant power input could not be maintained, Shonder & Beck's (2000) Geothermal Properties Measurements (gpm) computer-based parameter estimation software was applied.

In many of the tests, the fluid was kept circulating after the heaters were switched off to perform a "thermal recovery test", during which the carrier fluid temperature returns to its original condition, with no heat input other than a minor contribution from the circulation pump. By utilising an appropriate negative step-function, this thermal recovery portion could be utilised to provide a verification of the thermal conductivity derived from the heating portion of the test.

2. THE TESTS

The tests which were carried out were all intended to comply with the guidelines laid down by ASHRAE (2002), the IGSHPA (2007) and the IEA (Sanner et al. 2005). The duration of the heating portion of the test varied from 39 hrs to 93.9 hrs , while the median duration was 66.4 hours. Heat delivery rates (watts per metre of borehole) varied from 40 to 95 W/m, with a median of 59 W/m. Carrier fluid flow rates varied from 6 to 38 L/min (median: 17 L/min).

	Heat power input		**Flow rate**	**Duration (heating)**	**Depth of BHE**	**Diameter of borehole**
	kW	W/m	L/min	hr	m	mm
Mean	5.43	62	19.1	63.3	88	137
Median	5.40	59	16.6	66.4	95	141
25%-ile	4.92	52	15.0	50.6	75	125
75%-ile	6.37	72	21.1	71.6	100	159
Minimum	1.09	40	5.8	39.0	16	40
Maximum	11.41	95	37.5	93.9	150	200

Table 1. Properties of the 26 thermal response tests considered in this paper and of the tested boreholes (borehole diameter and installed depth of borehole heat exchanger [BHE])

3. THE BOREHOLES

Geographically, the locations of the tested boreholes ranged across the entire United Kingdom, from Cornwall and the Isle of Wight in the south of England, through the major cities of London, Birmingham and Manchester, to Northern Ireland and Scotland.

The depths of the tested borehole heat exchangers ranged from 16 m (a shallow co-axial heat exchanger installed by cone-penetrometer) to 150 m. The median depth was 95 m. The borehole diameters ranged from 40 mm (cone penetrometer) to 200 mm (Table 1).

Of the 26 tested boreholes:

- 10 were constructed as single “U-tubes” using 32 mm OD (26 mm ID) HDPE pipe
- 10 were constructed as single “U-tubes” using 40 mm OD (33 mm ID) HDPE pipe
- 2 were constructed using 40 mm OD coaxial pipe, installed by penetrometer / push displacement techniques
- 3 were constructed as double “U-tubes” using 32 mm OD (26 mm ID) HDPE pipe
- 1 was constructed as a single “U-tube” of unrecorded diameter

Also, of the 26 tested boreholes:

- in 20, the borehole was backfilled around the heat exchanger tube using some form of grout (typically, a “thermally enhanced” grout comprising a sand-rich mix of quartz sand and bentonite)
- in 1, the borehole was only partially backfilled with grout (incomplete grouting)
- in 3, the groundwater-filled borehole was backfilled with pea gravel, with only the topmost section being grouted / sealed.
- in the 2 boreholes where a 40 mm coaxial heat exchanger was utilised, no grout or backfill was used, on the assumption that the strata would simply collapse against the heat exchanger. In one case, this appeared to be successful (in unconsolidated sediments), while in the second, in lithified Chalk, incomplete collapse is inferred to have occurred, leading to a high value of borehole thermal resistance.

4. THE RESULTS

Prior to each test, the average undisturbed ground temperature (T_o) along the length of the borehole was determined either:

- by “dipping” the borehole heat exchanger at regular depth intervals prior to the test, using a temperature sensor on a graduated tape, and taking an average, or
- by measuring the fluid return temperature from the loop during the first 10 - 20 minutes of the test, prior to heater switch on.

The thermal conductivity (λ) was calculated from the gradient of a plot of average fluid temperature against log(time) for later time data (typically after 3 - 10 hours, depending on the borehole). The borehole thermal resistance (R_b) was calculated from the intercept of the plot, having first assumed a value for the volumetric heat capacity of the ground (Banks 2008). A statistical summary of the results is shown in Table 2.

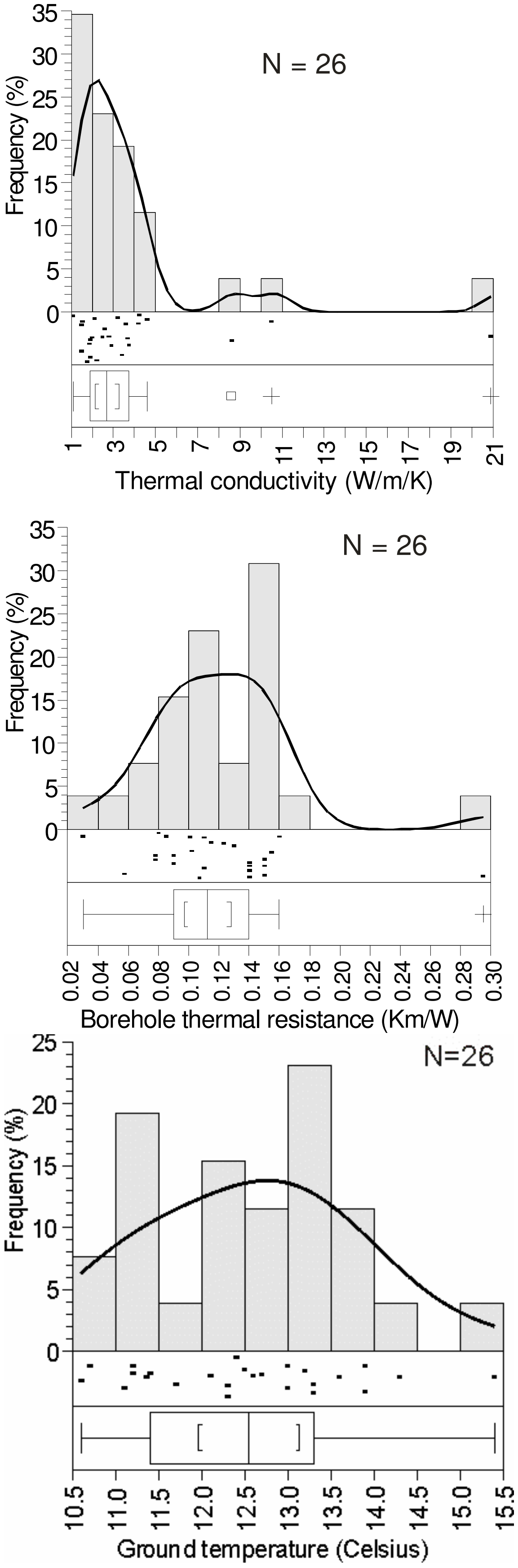

Figure 1. Histograms of the frequency distribution of (top) ground thermal conductivity, (middle) borehole thermal resistance and (bottom) average undisturbed ground temperature in the 26 tests. Below the histogram in each case are (i) a density plot and (ii) a standard boxplot (with a vertical line showing the median, the box showing the interquartile range, the “whiskers” showing the extraquartile range and squares/crosses showing near/far outliers

Analysis of the tests included an estimate of the limit of confidence on the derived values. The median limit of confidence on thermal conductivity was ± 8.4%, the median limit of confidence on borehole thermal resistance was ± 13%, while that on undisturbed temperature was typically 0.5°C. Note that the level of confidence cited in line-source analyses of thermal response tests typically reaches around 10% (Gehlin 2002, Signorelli et al. 2007). Zervantonakis & Reuss (2006) cite typical levels of confidence of 9% in λ, and 14% in R_b.

	λ	R_b	T_o		λ ± LoC	R_b ± LoC
	W/m/K	Km/W	°C			
Mean	3.87	0.12	12.55	Mean	10.3%	19.2%
Median	2.70	0.11	12.55	Median	8.4%	13.0%
25%-ile	1.90	0.09	11.48	25%-ile	7.0%	10.7%
75%-ile	3.72	0.14	13.28	75%-ile	11.2%	17.6%
Minimum	1.10	0.03	10.60	Minimum	5.0%	7.7%
Maximum	20.90	0.30	15.40	Maximum	23.8%	91.3%

Table 2. Results of the 26 thermal response tests considered in this paper (LoC = limit of confidence on best estimate, ± either side of central value)

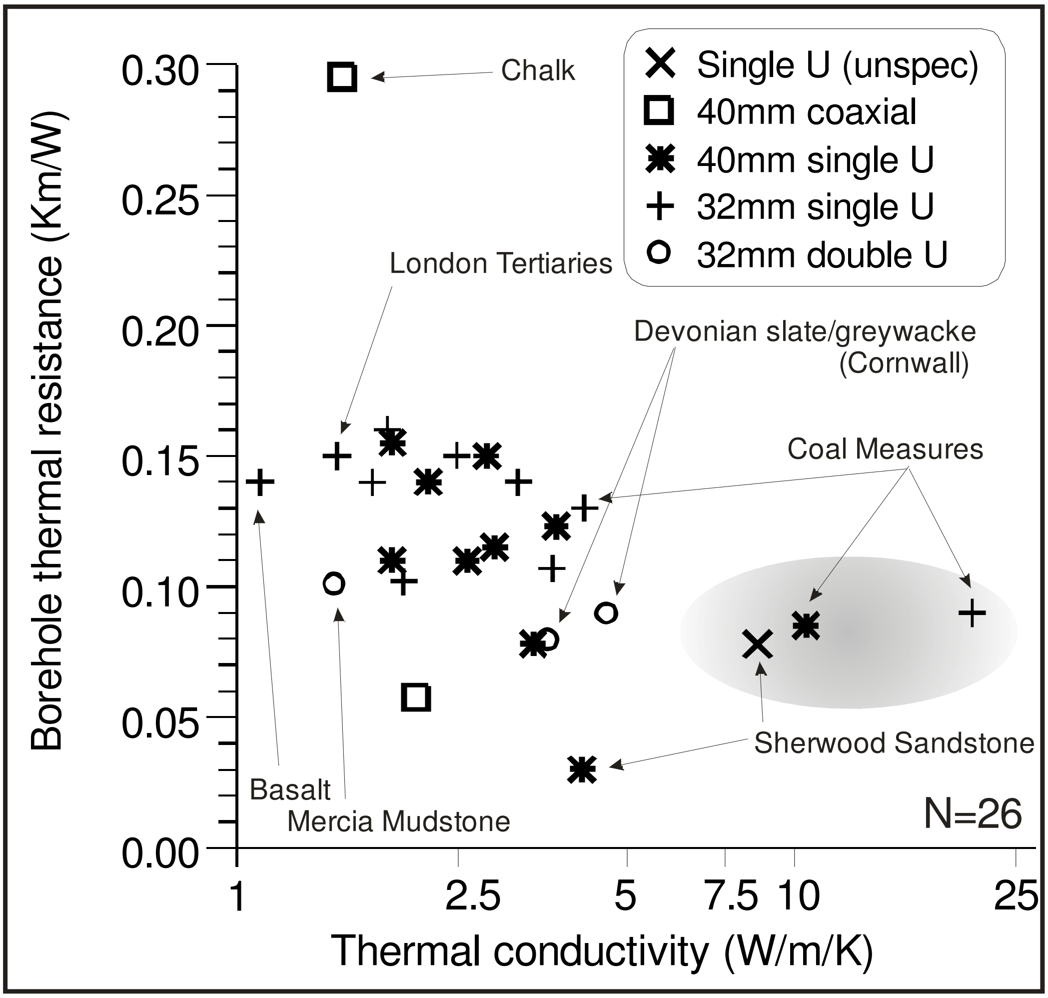

Figure 2. Cross-plot of borehole thermal resistance (R_b) against thermal conductivity (λ) for the 26 analysed tests. The shaded ellipse indicates tests where advection of heat with groundwater flow is believed to have affected results

5. THERMAL CONDUCTIVITY OF THE GROUND

Figure 2 shows the distribution of recorded thermal conductivities plotted against borehole thermal resistance. The bulk of thermal conductivities fall in the range 1.5 to 3 W/m/K, with the lowest values being derived from Northern Irish basalts (1.1 W/m/K) and Triassic Mercia Mudstone strata (1.49 W/m/K). Relatively high values of >3.5 W/m/K were derived from Devonian slates/greywackes from Cornwall, the Sherwood Sandstone and the Carboniferous Coal Measures. Three anomalously high values in the range 8 - 21 W/m/K were derived from the Sherwood Sandstone and the Carboniferous Coal Measures strata and are inferred to be enhanced due to additional heat transfer by advection with groundwater (or even mine water) throughflow.

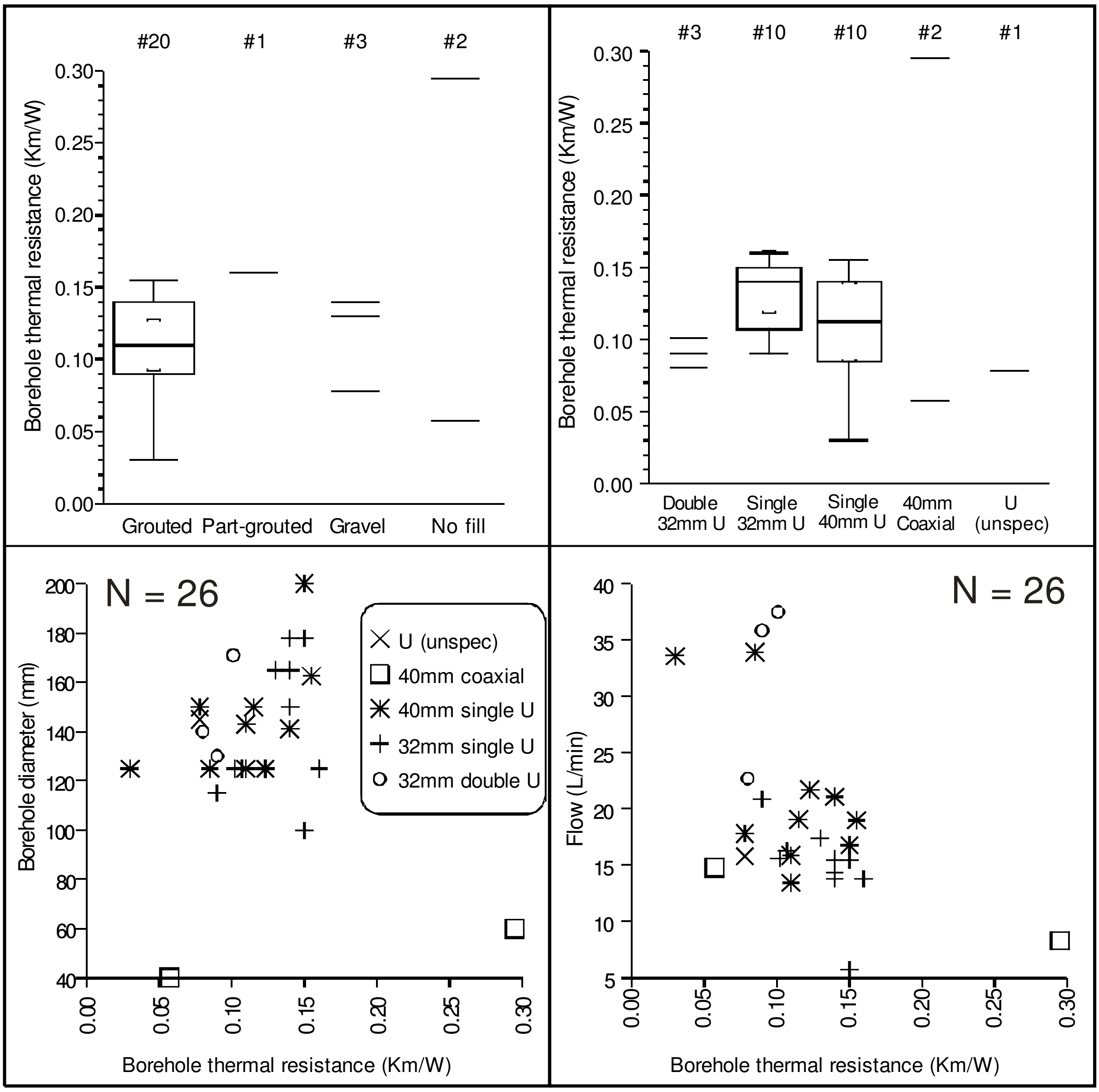

Figure 3. Statistical analysis of constructional and operational factors potentially affecting borehole thermal resistance (R_b) for the 26 analysed tests. For explanation of "boxplots", see Figure 1.

6. BOREHOLE THERMAL RESISTANCE

The majority of determinations of borehole thermal resistance fell in the range 0.10 to 0.15 Km/W, while a significant number of determinations of <0.10 Km/W imply rather thermally efficient boreholes (Note that Sanner et al. (2000) and Mands & Sanner (2001) cited values of borehole thermal resistance between 0.06 and 0.50 Km/W for thermal response tests in Germany. All except two of the German tests yielded values below 0.12 Km/W, however, while boreholes filled with thermally enhanced grout yielded values of 0.06 – 0.08 Km/W).

One anomalously high value of 0.3 Km/W was derived from a coaxial closed loop tube installed in a borehole in Chalk. This hole was not backfilled with grout and it is believed that incomplete collapse of the wall against the tube resulted in poor thermal contact between tube and borehole wall. In the other instance where a coaxial tube was installed in a cone penetrometer hole in unconsolidated sediments, a rather low borehole thermal resistance was determined, presumably reflecting the small effective borehole diameter and the collapse of the strata against the tube wall.

When borehole thermal resistance is plotted against various construction factors, only relatively few clear trends are noted:

- gravel filled boreholes offer no clear advantage or disadvantage relative to thermally enhanced grout.
- poor (partial) grouting is detrimental to borehole performance
- the three double "U tubes" offered a better thermal performance (around 0.1 Km/W or lower) as compared with the single "U-tubes"
- low (not fully turbulent) fluid flow rates may be associated with high borehole thermal resistance (although lack of grouting also affects one of these data points).

7. UNDISTURBED GROUND TEMPERATURE

The majority of determinations of undisturbed ground temperature fell in the range 11 to 13.5°C. The highest value of 15.4°C was from a deep (148 m) borehole in Devonian slates near the Cornubian granite batholith complex - a region of known high geothermal heat flux.

8. CONCLUSIONS

The results of 26 *in-situ* UK thermal response tests, derived from two test-rigs operated by Kensa Engineering and Geowarmth Heat Pumps, have been analysed. Derived values of thermal conductivity yield a median of 2.70 W/m/K, with 25% and 75% percentiles of 1.90 and 3.72 W/m/K. The lowest values are derived from Northern Irish basalt (1.1 W/m/K) and English Mercia Mudstone Rocks (1.49 W/m/K), while the high values are derived from Devonian slates / greywackes, the Sherwood Sandstone and the Coal Measures. The highest (>8 W/m/K) values are from Sherwood Sandstone and Coal Measures strata where advective heat transport with groundwater flow is believed to have led to an elevated apparent conductivity. Borehole thermal resistance exhibits 25%-ile, median and 75%-ile values of 0.09, 0.11 and 0.14 Km/W. Undisturbed ground temperature exhibits 25%-ile, median and 75%-ile values of 11.5, 12.6 and 13.3°C. As regards borehole thermal resistance, the data suggest that (i) gravel-filled boreholes offer no clear advantage or disadvantage relative to thermally enhanced grout, (ii) poor (partial) grouting is detrimental to borehole performance, (iii) double “U tube” construction tentatively results in better thermal performance than single “U-tubes” and (iv) low (not fully turbulent) fluid flow rates may be associated with high borehole thermal resistance. As regards co-axial heat exchangers, these can result in good thermal performance (low R_b) when installed by penetrometer techniques in unconsolidated sediments that collapse against the coaxial tube, yielding good thermal contact. Such heat exchangers are ill-advised in lithified, non-collapsing formations, unless any remaining annular space is subsequently backfilled with grout (or natural groundwater).

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