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Thermal Response Testing: Results and Experiences from a Ground Source Heat Pump Test Facility with Multiple Boreholes

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Abstract

This paper presents a summary of the results of various thermal response tests performed on nine adjacent 80-m-deep boreholes. Over forty tests with durations between 48 and 320 hours have been performed during the last 3 years. All nine boreholes were tested under similar conditions to check random uncertainties between tests. Several tests with diverse conditions were then performed to study sensitivity of test results to test variables and to quantify uncertainty in test results. Some of the tests were also repeated to ascertain reproducibility of the results. The paper also presents experimental measurements of borehole annulus temperatures during a test and recovery times of boreholes after a test.

Keywords – thermal response test; borehole; ground thermal conductivity; borehole thermal resistance; geothermal; ground-source heat pump

1. Introduction

In-situ thermal response tests (TRTs) are often performed to estimate ground thermal conductivity and borehole thermal resistance values. The estimated properties are used as design inputs to determine size and configuration of the borehole field. Thermal response testing, first presented by Mogensen [1], has been an active research area for nearly three decades, and many test evaluation methods have been developed [2, 3, 4, 5]. Methods have included sensitivity analysis to study the effect of various uncertainties on test results [2, 6, 7] and the influence of advection and natural convection in groundwater-filled boreholes [3, 8, 9, 10]. More recently, local variations of ground conductivity and borehole resistance values along the borehole depth have been investigated [11]. Despite widespread interest, little is known on the accuracy, uncertainty, and sensitivity of the tests, and these areas call for more study.

In 2009 the division of Building Services Engineering at Chalmers University of Technology established a ground-source heat pump (GSHP) test facility to experimentally study various aspects of thermal response testing. To date, over forty tests have been conducted. This paper presents a summary of the test results and addresses various aspects of the accuracy and uncertainty of the tests in detail, including random errors between tests, repeatability and reproducibility of tests, sensitivities of test results, and development of borehole annulus temperatures during a test.

2. Experimental Setup

The ground heat exchanger of the experimental setup consists of nine vertical boreholes drilled in a 3×3 square configuration. The distance between adjacent boreholes is approximately 4 m. Each borehole has a diameter of 110 mm and an active length of approximately 80 m. A single U-tube of outer diameter 40 mm and inner diameter 35.4 mm is inserted in each borehole. The circulating fluid in the U-tubes is a 29.5% (v/v) ethanol solution in water. The spacing between two legs of the U-tube and between the U-tube legs and the borehole boundary is not controlled. The boreholes are not grouted and are instead filled naturally with groundwater. Figure 1 shows the geometry and the layout of the laboratory boreholes.

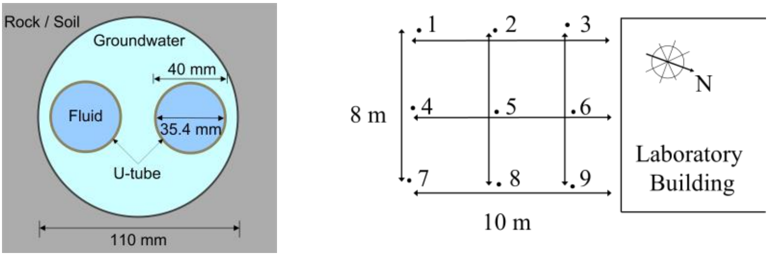


Fig. 1 Geometry and layout of the laboratory boreholes.

The experimental setup can be used to perform TRTs in both heat injection or extraction modes. All tests reported in this paper were conducted in heat injection mode using a variable capacity electric heater. Figure 2 shows the schematic diagram of the experimental setup. A high-precision power meter is used to measure the power input to the electric heater. The accuracy of the power meter is 0.15% of the reading plus 0.025% of the full scale, resulting in a total accuracy better than 1%. Each borehole has a dedicated variable speed pump and a balancing valve to control the flow of circulating fluid. The circulation pumps have a nominal power of less than 100 W. The flow rate of the circulating fluid in a specific borehole is measured over the balancing valve by using a laboratory-grade differential pressure sensor. A vortex flow meter is also installed before the electric heater to measure the flow rate. Temperature measurements are taken at multiple instances using Pt100 immersion sensors. The temperature sensors have an accuracy of higher than ±0.4 K for the range of temperatures encountered in this study. All measured data are recorded for any interval over 10 seconds by using a computerized data capture and acquisition system. Further details of the laboratory setup can be found in reference [12].

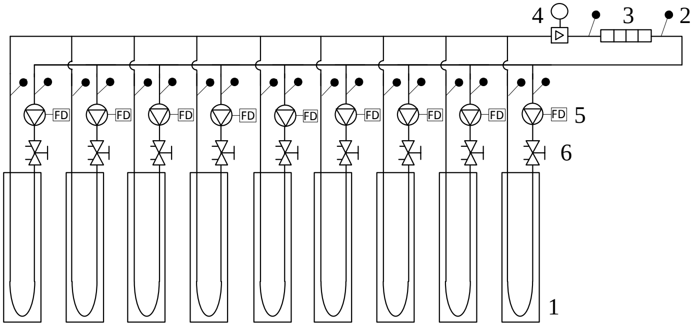


Fig. 2 Schematic of the experimental setup. 1: borehole field; 2: temperature sensor; 3: electric heater; 4: vortex flow meter; 5: circulating pump with frequency drive; 6: balancing valve.

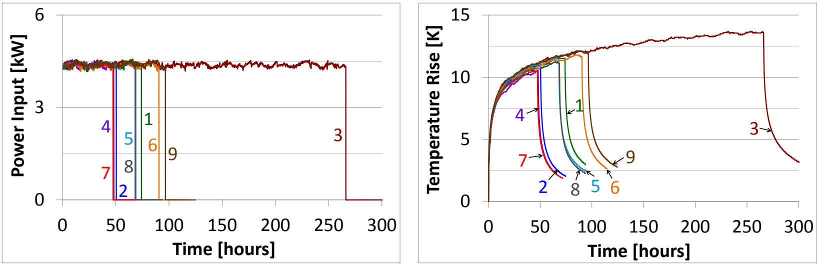
3. Evaluation of Tests

Thermal response tests can be evaluated using direct or parameter estimation-based methods. Direct methods assume average injection rates during a test, whereas methods based on a parameter estimation approach account for variations in input power instead of using an average mean value. The tests reported in this paper were evaluated using direct and parameter estimation-based approaches of the line-source solution [13]. The direct approach is based on an approximation of the line-source solution [2]. The ground thermal conductivity is determined from the line-source approximation by using the slope of the experimentally measured mean fluid temperature line plotted against logarithmic time. Borehole thermal resistance is then estimated as a ratio of the temperature difference between the experimentally measured mean fluid temperature and the borehole wall temperature calculated from the line-source approximation to the heat transfer rate per unit length of the borehole [1, 14].

When using the line-source-based parameter estimation approach, variations in input power are accounted for by considering stepwise constant heat pulses. Circulating fluid temperature is first simulated using initial guess values of ground thermal conductivity and borehole thermal resistance. The guess values are then optimized by minimizing the error between simulated and experimentally measured mean fluid temperatures to obtain the final estimations of ground thermal conductivity and borehole thermal resistance.

4. First Round of Testing

During the first round each of nine laboratory boreholes was tested under similar conditions of power input and flow rate. Tests were performed for times between 48 and 260 hours. The power level used for the tests was approximately 4.5 kW. The chosen power level resulted in a heat injection rate of approximately 55 W/m, which is in accordance with ASHRAE [15] recommendations. The flow from the circulation pumps was set to ensure turbulent flow in the ground loop. Readings of the fluid temperatures, power input, and flow were taken at regular intervals of 3 to 5 minutes. Figure 3 shows the power levels used for the first round of testing (3a) and the resulting mean fluid temperatures (3b) for nine laboratory boreholes.



(a) (b)

Fig. 3 Power inputs and mean fluid temperatures for the first round of testing of nine laboratory boreholes.

The first-round tests were analyzed using both line-source approximation and line-source-based parameter estimation methods. Ground thermal conductivity and borehole thermal resistance estimations obtained from both the methods are given in Table 1. Ground conductivity and borehole resistance estimations from the direct line-source approximation method varied between 2.88 to 3.20 W/(m·K). Ground conductivity estimations had a mean value of 3.01 W/(m·K), and the whole range of nine boreholes fell within ±7% of this mean value. The estimations of borehole resistance from the direct line-source approximation method varied between 0.049 and 0.074 (m·K)/W. The borehole resistance values of the nine boreholes fell in a range of 0.062 (m·K)/W ±20%. Ground conductivity and borehole resistance from the line-source-based parameter estimation method varied between the extreme values of 2.92 to 3.18 W/(m·K) and 0.054 to 0.072 (m·K)/W, respectively. The average value of ground conductivity was 3.04 W/(m·K), and all estimations fell within the range of ±5% of this mean value. As with the direct line-source approximation method, borehole resistance estimations from line-source-based parameter estimation methods also exhibited larger variations. The borehole resistance estimations from the line-source-based parameter estimation fell within ±15% of the average borehole resistance value of 0.064 (m·K)/W.

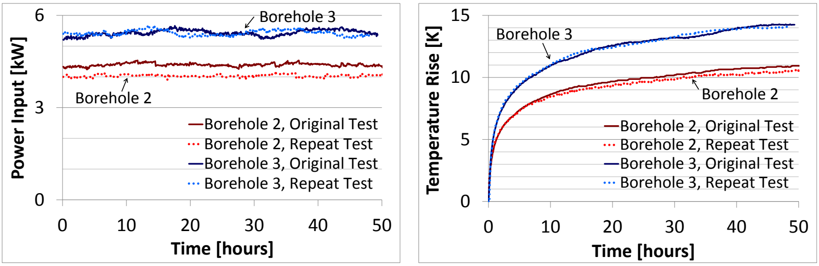
The ground conductivity and borehole resistance estimations from the line-source approximation method exhibited slightly larger variations than those from the line-source-based parameter estimation method. This can be ascribed to the use of an overall average injection rate by the line-source approximation method rather than using stepwise constant injection rates. The larger variations in thermal resistance values of the nine boreholes from both methods can be explained partly by the fact that the test boreholes were not grouted and that the spacing of the U-tube in the borehole was not controlled. Hence, each borehole had a different degree of thermal contact between the U-tube and the surrounding ground and a different level of thermal short-circuiting between two legs of the U-tube, resulting in different values of effective borehole thermal resistance. The effects of various test and parameter uncertainties on TRT results and their subsequent impact on the design of borehole systems have been studied in detail [6, 7].

Table 1. Ground conductivity and borehole resistance estimations from direct line-source and line-source-based parameter estimation methods for the first round of testing.

Borehole	Duration [hours]	Ground conductivity [W/(m·K)]		Borehole resistance [(m·K)/W]	
		Direct	Parameter estimation	Direct	Parameter estimation
1	75	2.88	3.01	0.059	0.063
2	50	3.06	3.01	0.064	0.062
3	267	3.04	2.92	0.074	0.068
4	48	2.81	2.98	0.049	0.054
5	68	2.98	3.01	0.064	0.065
6	91	2.89	3.01	0.063	0.068
7	48	3.19	3.10	0.064	0.061
8	69	3.20	3.12	0.065	0.062
9	98	3.12	3.18	0.069	0.072

5. Repeatability of Tests

Repeating an in-situ response test several weeks after an original test is generally not a viable option because of financial, time-related, or access difficulty issues, among other practical reasons. Hence there is relatively little information and research available on repeatability of tests. In order to bridge this knowledge gap, many of the tests conducted in our lab have been repeated to investigate the reproducibility of the test results.



(a) (b)

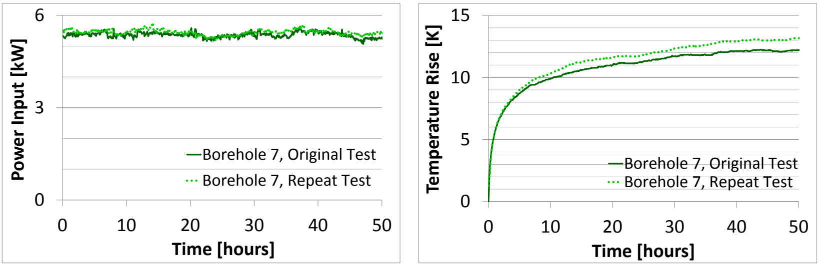
Fig. 4 Power and mean fluid temperatures for original and repeat tests on boreholes 2 and 3.

Table 2. Estimated thermal properties for original and repeat tests using the direct line-source approximation method.

Borehole #	Ground conductivity [W/(m·K)]		Borehole resistance [(m·K)/W]	
	Original test	Repeat test	Original test	Repeat test
Borehole 2	3.06	3.05	0.064	0.069
Borehole 3	2.80	2.83	0.058	0.059

Figure 4 presents original and repeated tests performed on boreholes 2 and 3. Two 50-hour tests were performed on borehole 3 under similar conditions. The power input for both the tests was approximately 5.6 kW. After the first test, the borehole was allowed to recover for 2 weeks in accordance with published recommendations [15, 16] before repeating the test. It can be seen from Figure 4 that the power input and the temperature response of the borehole for the two tests were similar. Table 2 presents ground conductivity and borehole resistance estimations for the two tests from direct line-source approximation method. Thermal properties estimated from two separate tests performed 2 weeks apart were almost identical.

Figure 4 also shows two tests performed on borehole 2. In this case the interval between the original and the repeat tests was over 3 years. The borehole was at an undisturbed state at the start of both tests. The tests were performed under similar conditions except that the input power of 4.1 kW used for the repeat test was marginally lower than the 4.6 kW used for the first test. As seen from Table 2, the evaluation of the two tests performed on borehole 2 gave nearly similar estimations of ground conductivity and borehole resistance despite being conducted 3 years apart.



(a) (b)

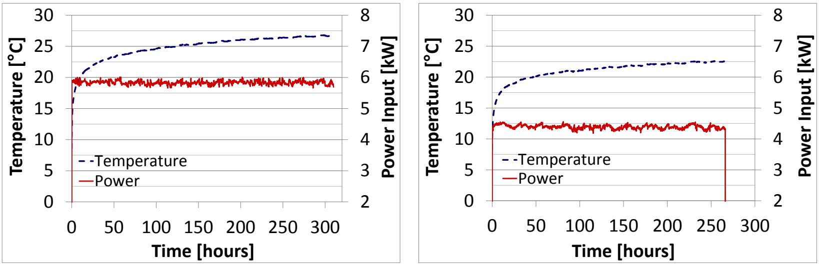
Fig. 5 Power and mean fluid temperatures for two similar tests performed on borehole 7.

Figure 5 shows two tests performed on borehole 7. The repeat test was performed 1 year after the original test. However, at the time of the repeat test the borehole was still recovering from another test. As can be seen from

Figure 5, the temperature response of the repeat test performed on a disturbed borehole was different from the original test performed on the undisturbed borehole despite both tests having similar levels of input power. Evaluation of these two tests gave significantly different results. The three cases of boreholes 2, 3, and 7 suggest that TRTs are repeatable and their results are reproducible if the surrounding ground is allowed to recover to the undisturbed state before performing a retest.

6. Long-Duration Tests

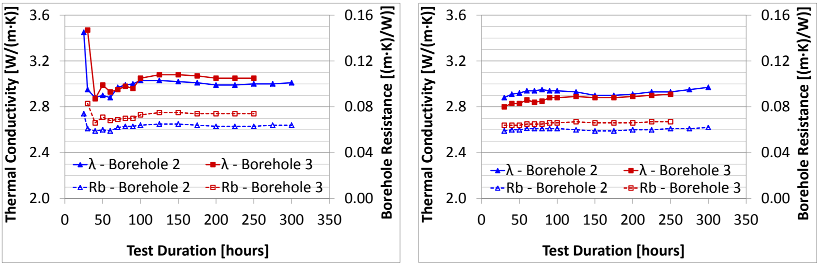
Duration of a TRT remains a topic of considerable interest. A longer test duration provides more accurate and reliable evaluation of tests as it allows the borehole heat transfer to reach a quasi-steady state and also because it reduces statistical errors associated with power and thermal fluctuations. On the other hand, the quest to make TRTs commercially more viable has led to tests with shorter durations. A number of extended tests were conducted on laboratory boreholes to check the sensitivity of tests to the length of test duration. Figure 6 shows tests performed on boreholes 2 and 3, which were both tested for over 250 hours.



(a) (b)

Fig. 6 Long-duration tests performed on (a) borehole 2 and (b) borehole 3.

Figure 7a presents ground conductivity and borehole resistance estimations using the direct line-source approximation method for different durations of tests performed on boreholes 2 and 3. Ground conductivity and borehole resistance estimations converged after approximately 100 hours. For durations between 50 to 100 hours, a maximum absolute deviation of around 6% was demonstrated. The deviation was significantly higher for test durations shorter than 50 hours. Figure 7b shows estimations of ground conductivity and borehole resistance for boreholes 2 and 3 from the line-source-based parameter estimation method for various test durations between 30 and 300 hours. Ground conductivity and borehole resistance estimations remained nearly constant for tests longer than 50 hours; estimated values remained consistent even for shorter test durations.

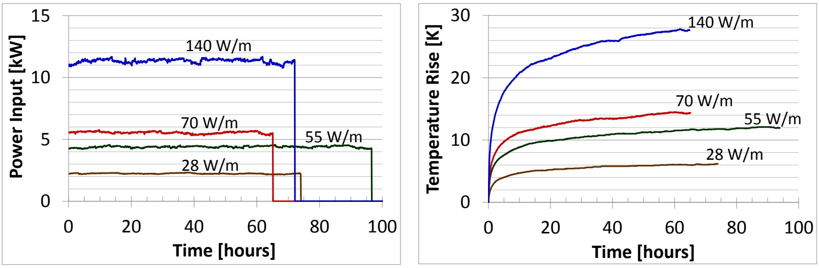


(a) (b)

Fig. 7 Ground conductivity (λ) and borehole resistance (Rb) for different test lengths from (a) direct line-source approximation and (b) line-source-based parameter estimation methods.

7. Tests with Different Heat Injection Rates

For groundwater-filled boreholes, the choice of input power or heat injection rate influences the estimations of thermal properties from a test. This is because a larger heat injection rate increases the convective heat transport in the borehole, which consequently decreases the borehole resistance. The effects of natural convection in groundwater-filled boreholes on the TRT results were studied using a series of investigations.



(a) (b)

Fig. 8 Power inputs and mean fluid temperatures for tests performed on borehole 9.

Figure 8 shows various tests conducted on borehole 9. The tests were conducted using different heat injection rates between 25 and 140 W/m. The ground thermal conductivity and borehole thermal resistance estimations obtained for these tests from the direct line-source approximation method are shown in Figure 9. As seen from the figure, larger injection rates resulted in lower borehole resistance estimations, whereas ground conductivity estimations remained nearly constant. The estimation of borehole resistance decreased by approximately 23% between two tests with 2.2 kW (28 W/m) and 4.4 kW (55 W/m). Between tests with 5.5 kW (70 W/m) and 11 kW (140 W/m), the borehole resistance estimation decreased by 25%.

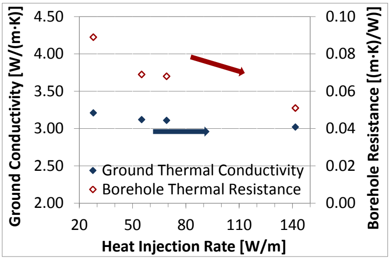
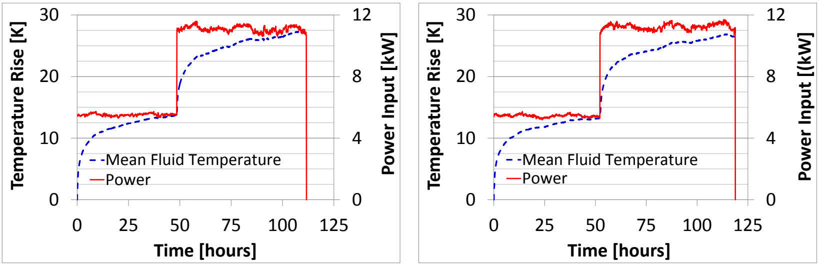


Fig. 9 Ground conductivity and borehole resistance estimations for tests with different heat injection rates performed on borehole 9.

8. Multiple Injection Rate Tests

The thermal response for various injection rates expected on a borehole can also be studied using tests with multiple injection rates. A number of tests with two or more step-wise constant heat injection rates were performed on the laboratory boreholes. Figure 10a and 10b show two such tests conducted on boreholes 1 and 7, respectively.



(a) (b)

Fig. 10 Tests conducted with multiple injection rates on (a) borehole 1 and (b) borehole 7.

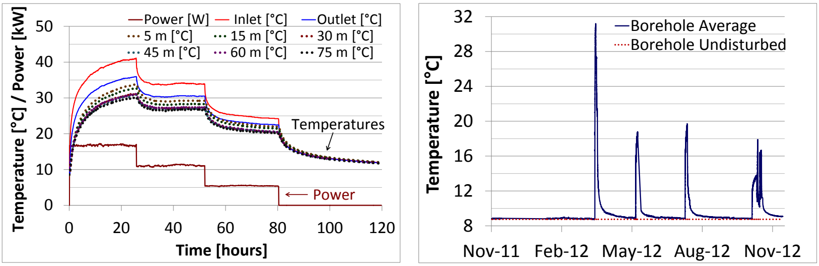
Tests with multiple injection rates cannot be evaluated using the direct line-source approximation method. Therefore, these tests were evaluated using the line-source-based parameter estimation method. Ground conductivity and borehole resistance estimations were determined for the first injection rate. The borehole resistance for the second injection rate was determined assuming no change in the ground conductivity for the second injection rate. Ground conductivity and borehole resistance estimations for tests of Figure 10 are given in Table 3. It can be seen from the table that borehole resistances for the second injection rate with a higher input power were significantly lower than borehole resistances for the first injection rate with a lower input power. The increase in power input from 5.5 to 11 kW reduced the borehole resistance estimations by approximately 23% and 30% for boreholes 1 and 7, respectively. This decrease in borehole resistance estimations is in the same range as noted earlier for borehole 9 in Figure 9.

Table 3. Estimated thermal properties for two injection rates of tests on boreholes 1 and 7.

Borehole #	Ground conductivity [W/(m·K)]		Borehole resistance [(m·K)/W]	
	1st injection rate	2nd injection rate	1st injection rate	2nd injection rate
Borehole 1	3.00	3.00	0.060	0.046
Borehole 7	3.07	3.07	0.059	0.041

9. Borehole Annulus Temperatures

When performing a test on a borehole, the most common temperature measurements are the fluid temperatures entering and leaving the borehole. For groundwater-filled boreholes additional temperature measurements in the borehole annulus can provide unique in-situ information. For laboratory boreholes temperatures in the annulus are measured along the borehole depth. Figure 11a shows these measurements for one of the tests. The temperature at the top of the borehole remained a few degrees higher than the middle and bottom of the borehole throughout the test duration. The temperature measurements in the annulus region can be used to model the internal heat transfer in groundwater-filled boreholes and to evaluate the thermal resistance between the U-tube and the surrounding ground. A study to estimate convection coefficients on the U-tube and borehole wall using the annulus temperatures is currently being undertaken. The annulus temperatures are also being used to study the required recovery times for a borehole to return to the undisturbed state after a test.



(a) (b)

Fig. 11 (a) Circulating fluid temperatures and annulus temperatures along the borehole depth for a multi-injection rate test. (b) Average annulus temperatures of a borehole.

Figure 11b shows a series of tests performed on one of the laboratory boreholes between November 2011 and November 2012. Tests with different heat inputs were performed for different time durations. After a test, the development of borehole annulus temperatures was measured until the temperature returned to the undisturbed state. For the dense rock formation of the laboratory boreholes, the recovery time following a standard 50-hour test with a heat injection rate of 50–75 W/m was between 2 to 3 weeks. The recovery times were directly proportional to the test duration and heat injection rate used for the test. This means that increasing (or decreasing) the test duration or the injection rate twofold will double (or half) the borehole recovery time. Recovery times for various sets of ground formation, heat injection rates, and test durations have been published [16].

10. Conclusions

In this paper research findings from over forty TRT results performed on a field of nine boreholes were presented. Results from initial tests conducted on each of the nine boreholes under similar conditions suggest variations of approximately ±5% and ±15% around mean values of ground conductivity and borehole resistance, respectively. Tests shorter than 50 hours and evaluated using the simple line-source approximation method gave substantially inaccurate results. For groundwater-filled boreholes, tests with higher power input resulted in significantly lower borehole resistance estimations. Temperature measurements in borehole annulus indicated a recovery time of 2–3 weeks after a 50-hour test with an injection rate of 50–70 W/m. Tests repeated under identical conditions gave reproducible results.

11. References

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