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RECOVERY TIMES AFTER THERMAL RESPONSE TESTS ON VERTICAL BOREHOLE HEAT EXCHANGERS

JAVED S.(1), CLAESSON J.(1), BEIER RA.(2)
(1) Chalmers University of Technology, Gothenburg, SE 41296, Sweden
saqib.javed@chalmers.se
(2) Oklahoma State University, Stillwater, OK 74078, United States

ABSTRACT

The design of a ground source heat pump system requires accurate knowledge of properties, such as ground thermal conductivity and borehole thermal resistance. These properties are often determined using an *in-situ* thermal response test of a pilot borehole. These tests are sometimes interrupted by unexpected circumstances and occasionally a retest is required. For a retest to be conducted, the ground temperature must return to within 0.1-0.3 K of the initial undisturbed ground temperature. This paper addresses the issue of borehole retesting and reports on a systematic series of thermal response tests conducted to study the times needed for the ground temperature to return to within 0.3 K of the pre-test ground temperature. Tests were conducted using various heat injection rates and different time durations. Following a test, the development of ground temperature was studied for up to 2-3 months. A mathematical model was used to validate the experimentally measured ground temperatures and to extend the results to other testing conditions.

1. INTRODUCTION

Today, ground source heat pump (GSHP) systems are increasingly used to meet the heating and cooling requirements of commercial and residential buildings. These systems often use vertical boreholes to exchange heat with the ground. The heat transfer between the borehole heat exchanger and the ground depends upon thermal properties, such as ground thermal conductivity and borehole thermal resistance. For medium- to large-sized systems, ground thermal conductivity and borehole thermal resistance values are generally determined from an *in-situ* thermal response test. In a typical thermal response test, a known amount of heat is injected into a pilot borehole. Electric heaters are commonly used to inject heat into the ground by heating the circulating fluid. The heated fluid is circulated through the borehole for a minimum of 48 hours. Inlet and exit fluid temperatures are measured at regular intervals. Other measurements include the flow rate of the fluid, the power input to the electric heater and the circulating pump, and the ambient temperature. The measurements are then analyzed using a mathematical heat transfer model to estimate ground thermal conductivity and borehole thermal resistance values.

Thermal response tests are sometimes affected by problems that can create detrimental effects on the ground thermal conductivity and the borehole thermal resistance estimations. These issues include such problems as power outage, equipment failure and fluid leakage among other unexpected circumstances. Occasionally, it is possible to swiftly rectify the problem and to continue the test. These tests can be evaluated using the mathematical models developed by Beier and Smith (2005) and Beier (2008). These models have specifically been developed to analyze interrupted thermal response tests by eliminating the effects of power interruptions during the test. However, if the problem cannot be resolved quickly, or if it is caused by equipment malfunctioning or a data logging failure, conducting a retest might be indispensable. In research settings, the retesting of boreholes is also needed in order to perform experimental parametric analysis and to investigate the repeatability and reproducibility of the thermal response test results.

A review of literature yields little guidelines for conducting retesting of boreholes. Kavanaugh et al. (2001) have carried out the only experimental study on that topic. Their work provided the basis for the present ASHRAE (2007) recommendations on borehole retesting. Kavanaugh et al. (2001) observed errors in the range of 5-12% for retests conducted with a ground temperature that was 1.1 K higher than the initial undisturbed ground temperature. Based on their findings, they concluded that, before a retest is conducted, the ground temperature should be within 0.3 K of the initial undisturbed ground temperature. After a 48-hour test, a minimum recovery time of 10-14 days is suggested to allow the ground temperature to return to within 0.3 K of the undisturbed value. For shorter test durations, the recovery time can be reduced proportionally up to a minimum of 24 hours (Martin and Kavanaugh, 2002). The existing literature provides general guidelines on borehole retesting but does not specifically address the effects of ground formation, heat injection rates, and test duration on the recovery times after a thermal response test. These factors are critical in borehole retesting as they significantly affect the development of ground temperature after a thermal response test. The existing recommendations on borehole retesting are based on experimental investigations and are limited to specific experimental conditions. In order to extend these results to other test conditions, the results should first be validated using a mathematical model. After validation, the recovery times for other test conditions can be simulated using the mathematical model.

This paper addresses the borehole retesting issues and reports on a systematic series of tests that have been conducted on different boreholes to determine the recovery times after a thermal response test. The tests have been conducted using various heat injection rates and different time durations. The development of ground temperatures after the thermal response tests has been studied experimentally. Next, the experimentally measured ground temperatures have been validated using a mathematical model. The results from the mathematical model are in close agreement with the experimental measurements. Finally, the results have been extended for other test conditions and recommendations on recovery times after a thermal response test have been made for different cases using the mathematical model.

2. EXPERIMENTAL INVESTIGATION OF GROUND TEMPERATURES

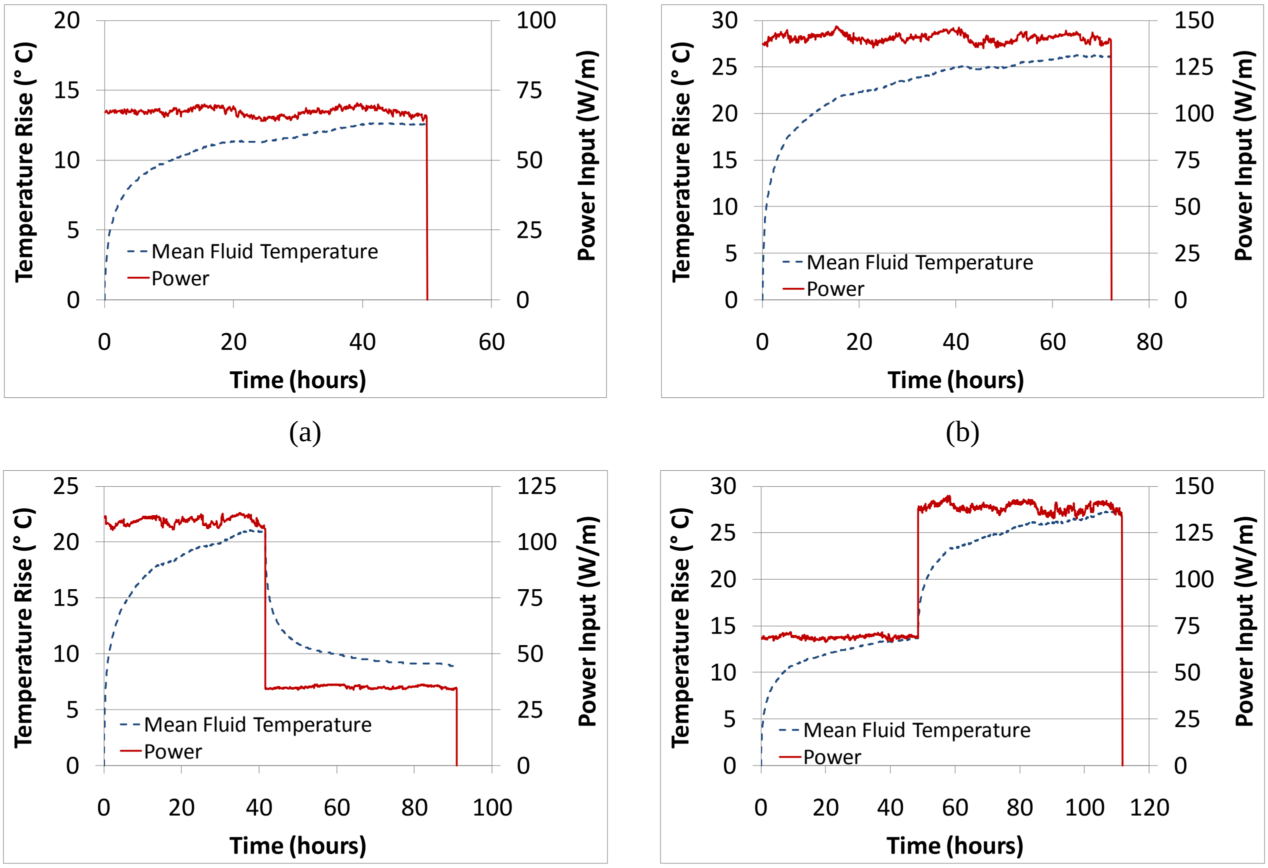
Despite its long acceptance as a standard method to estimate ground thermal properties, a clear consensus has not been found with regard to test duration and heat injection during the tests. ASHRAE (2007) suggests 36-48-hour tests with heat injection rates of 50-80 W/m. However, in practice it is common to conduct considerably longer tests with heat injection rates exceeding this range (Javed et al., 2011). A growing practice of conducting multi-injection rate tests to study the influence of groundwater flow on the estimated ground thermal conductivity values also exists (Gustafsson and Westerlund, 2010). A series of thermal response tests were planned and conducted to investigate the effects of the test duration and the heat injection rate of an earlier thermal response test on the required recovery time before conducting a retest.

The thermal response tests, conducted to investigate the recovery times after borehole retesting, covered a wide range of conditions. The first test (see Figure 1a), was planned in accordance with ASHRAE (2007) recommendations. The test was conducted for approximately 48-hours with a mean heat injection rate of 67 W/m. For the second test (see Figure 1b), a higher injection rate of approximately 140 W/m was used. The test duration was also increased to 72 hours. The third and fourth tests were conducted with multiple injection rates. In the third test (see Figure 1c), a higher injection rate of 105 W/m was used for first 42 hours of the testing period, followed by a lower injection rate of 35 W/m for the next 50 hours. For the fourth test (see Figure 1d), the order of the heat injection was reversed. A lower injection rate of 70 W/m was used for the first 48 hours followed by a higher injection rate of 140 W/m for the next 64 hours.

Before conducting the tests, undisturbed ground temperature measurements were taken for all boreholes. The pre-test undisturbed ground temperature was calculated by monitoring the fluid temperatures exiting the U-tube at the start-up of the circulation pump. The fluid was kept in the U-tube for a number of days and was in thermal equilibrium with the surrounding ground. The average temperature of the fluid exiting the U-tube at start-up provides an accurate estimation of the undisturbed ground temperature. For the tests reported upon in this paper, the undisturbed ground temperature measurements were between 8.5 and 8.7 °C. Because the tests were conducted over a period of 6-7 months, the measurements of undisturbed ground temperature showed slight variations due to seasonal changes in the shallow ground temperatures. The next step was to evaluate the thermal response tests to obtain an estimation of ground thermal conductivity. When simulating development of ground temperatures after a thermal response test, a ground conductivity estimation is required by the mathematical model presented in next section. The understudy ground formation has a relatively high thermal conductivity value of approximately 3.0 W/(m·K).

After a thermal response test, the development of ground temperatures, over time, was measured regularly. The measurements were taken every 2-5 days for two weeks after the test was initially conducted and every

7-10 days thereafter. The ground temperature measurements were taken using the same procedure described above. The measurements were taken until the ground temperature returned to approximately 0.1 K of its initial undisturbed value. Figure 3 shows the development of ground temperatures, measured experimentally, for the thermal response tests seen in Figure 1. The straight horizontal lines in Figure 3 represent the temperature values of 0.3 K above the undisturbed ground temperatures. According to ASHRAE (2007), the ground temperature must be allowed to return to this temperature level before a retest can be conducted. In the case of the first thermal response test (Figure 1a), the recovery time needed for the ground temperature to return to 0.3 K of its initial undisturbed value is approximately 10 days. This test was conducted in accordance with ASHRAE (2007) recommendations and the results, shown in Figure 3a, are in agreement with the findings of Kavanaugh et al (2001). For the second thermal response test, shown in Figure 1b, the time it took for the ground temperatures to return to within 0.3 K of the initial undisturbed value increased from 10 days to between 35-40 days as the test duration was extended from 48 to 72 hours. Furthermore, the heat injection rate was approximately doubled from 67 to 140 W/m. Figure 3b shows the ground temperature measurements for this case. Figure 3c shows the recovery times after the thermal response test of Figure 1c. This test was conducted using injection rates of 105 W/m for the first 42 hours and 35 W/m for the next 50 hours. After this test was conducted, it took the ground temperature between 20-25 days to return to 0.3 K of its initial undisturbed value. Finally, in the case of the thermal response test seen in Figure 1d, a recovery time of 40 days was required before the ground temperature returned to 0.3 K of its undisturbed value. This test was conducted using a heat injection rate of 70 W/m for the first 48 hours followed by a higher injection rate of 140 W/m for the next 64 hours.



(a)

(b)

(c)

(d)

Figure 1. Thermal response test cases.

The experimental results indicate that the development of ground temperature after a thermal response is significantly affected by the test duration and the chosen heat injection rate. After a 48-hour thermal response test conducted using 67 W/m, the recovery time for the ground temperatures to return to 0.3 K of the initial undisturbed value is approximately 10 days. The recovery times increase significantly with increased test durations and injection rates.

3. SIMULATION OF GROUND TEMPERATURES

Experimental investigations of ground temperatures after a thermal response test are intricate and lengthy. Moreover, it is practically impossible to experimentally determine the recovery times for all probable test conditions. An alternative approach is to use a mathematical model to predict the recovery time after a specific thermal response test. However, in order to use a mathematical model, the recovery times simulated from the experimental results should first be validated against the mathematical model.

This paper uses a mathematical model, developed by Javed and Claesson (2011), to determine the recovery times after a thermal response test. The model assumes radial heat transfer in the borehole and the ground. For this model, the borehole geometry is simplified and a single pipe, instead of a U-tube, is considered. The pipe is filled with a circulating fluid with a thermal capacity C_p. The fluid temperature $T_f(t)$ represents the mean fluid temperature entering and exiting the U-tube. The thermal resistance of the pipe is R_p. The thermal resistance over the pipe results in an outer boundary pipe temperature of $T_p(t)$. The model considers the thermal conductivity and the thermal diffusivity values of both the ground and the grout. The ground thermal conductivity and the thermal diffusivity are λ and a, respectively. The grout has thermal conductivity and the thermal diffusivity of λ_b and a_b, respectively. The heat flux q_{inj} is injected into the fluid in the pipe. The heat fluxes through the pipe wall to the grout and across the borehole boundary to the surrounding ground are $q_p(t)$ and $q_b(t)$, respectively. The overall heat transfer problem, shown in Figure 2, is solved using Laplace transformations. Further details of the model can be found in the research of Javed and Claesson (2011).

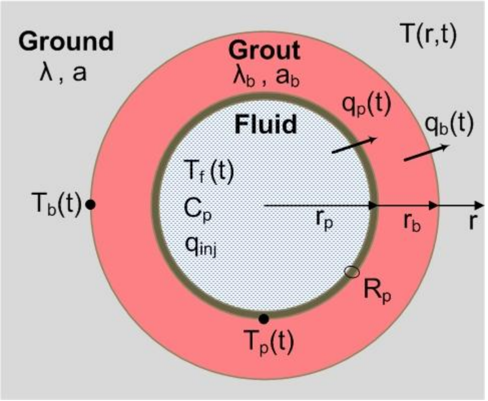
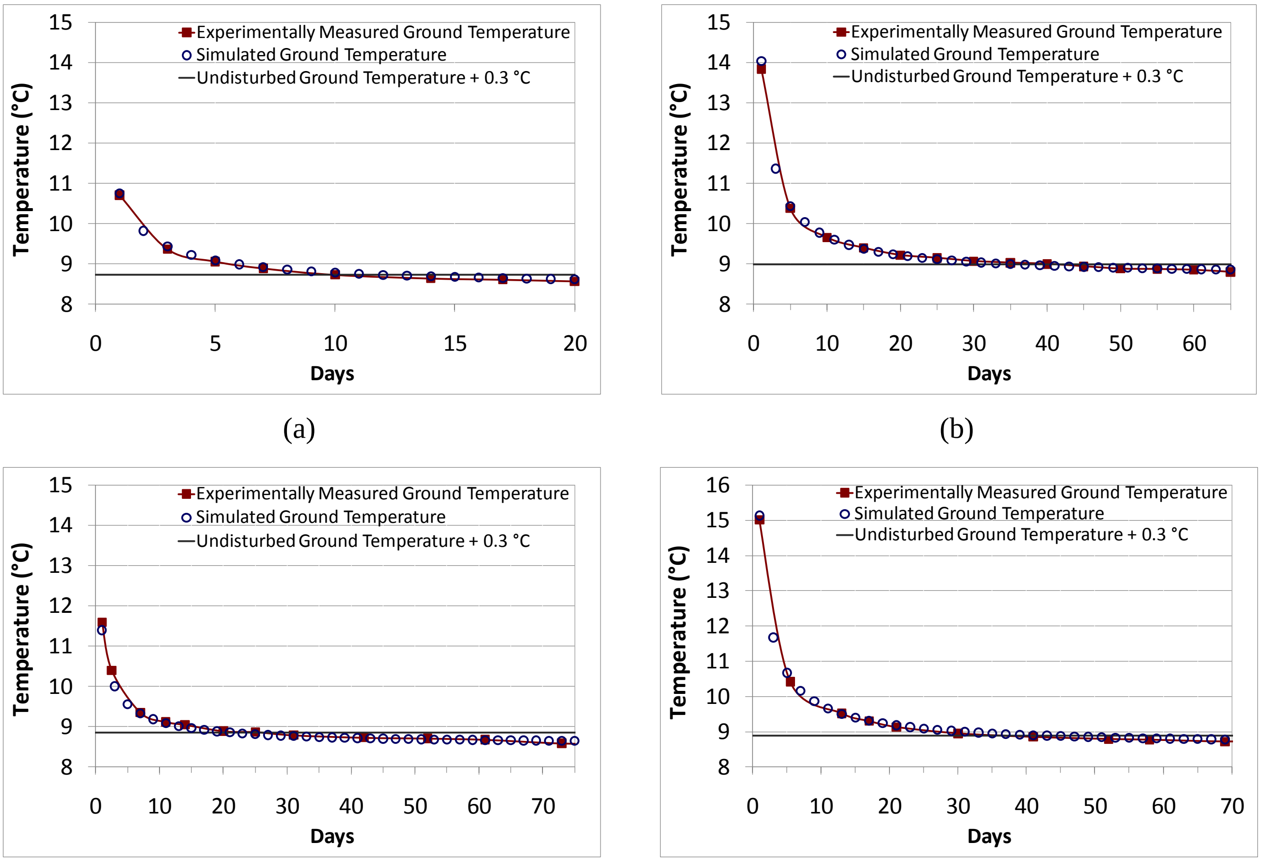


Figure 2. Heat transfer problem considered by the mathematical model used to simulate recovery times after a thermal response test.

The mathematical model was used to simulate development of ground temperatures after a thermal response test. The ground temperatures are calculated by superposition of the temperature response with the heat injection rates used in the test. The development of ground temperature was simulated by considering actual injection rates during the test followed by a zero injection rate after the test. Figure 3 shows the simulated ground temperatures and the experimental results. As can be seen, the simulated results are in very good agreement with the experimentally measured results. The simulated results suggest that, after the thermal response test of Figure 1a, the recovery time is approximately 11 days. For this test, the experimentally-found recovery time was 10 days. For the test shown in Figure 1b, the simulated recovery time is approximately 36 days. Experimental results showed that the ground temperatures returned to 0.3 K of the undisturbed value between 35 and 40 days after the test was conducted. For the thermal response test shown in Figure 1c, the simulated recovery time is 21 days, which again is in agreement with the experimentally-found recovery time ranging between 20 and 25 days. For the thermal response test shown in Figure 1d, the simulated recovery time is 43 days, as compared to the experimentally-found recovery time of approximately 40 days.

The above-mentioned results indicate that the recovery time simulated from the mathematical model closely match the experimental values. The mathematical model can now be used to extend the experimental results and to simulate recovery time for test conditions different from those used in this investigation.



(a) (b)

(c) (d)

Figure 3. Recovery times (in days) for the ground temperature to return to 0.3 K of its pre-test values for thermal response tests shown in Figure 1.

4. EXTENDING RESULTS TO OTHER TEST CONDITIONS

As seen in Sections 2 and 3, the recovery of ground temperature after a thermal response test depends upon the test duration and the heat injection rate. In addition to these two parameters, the recovery time of the ground temperature also depends upon the thermal properties of the ground, including its thermal conductivity and volumetric heat capacity. These properties vary significantly for different ground formations. Ground conductivity can vary from 0.5 W/(m·K) for low conductivity formations to 4 W/(m·K), or higher, for high conductivity formations. To investigate the recovery times for different test conditions, ground formations shown in Table 1 are considered. For each ground formation, the simulations were conducted over the course of a 10-100-hour test period, using heat injection rates ranging from 25 to 150 W/m.

Table 1. Considered ground formations.

Formation	**Ground Thermal Conductivity** (W/(m·K))	**Volumetric Heat Capacity** (kJ/(m^3·K))
Soil, dry	1.0	1800
Clay, moist	1.6	2400
Rock, average	2.4	2400
Sand, saturated	2.4	2600
Rock, dense	3.4	2600

Table 2. Recovery times (in days) for the ground temperature to return to 0.3 K of pre-test values for various test conditions.

Test Duration (Hours)	**Heat Injection Rate** (W/m)	**Recovery Times After a Thermal Response Test** (Days)			
		Soil, dry	**Clay, moist**	**Sand, saturated / Rock, average**	**Rock, dense**
10	*25*	3	2	1	1
	50	6	4	3	2
	75	9	5	4	3
	100	11	7	5	4
	150	17	11	7	5
25	*25*	7	4	3	2
	50	14	9	6	4
	75	21	13	9	6
	100	28	17	11	8
	150	41	26	17	12
50	*25*	13	8	5	4
	50	27	17	11	8
	75	41	25	17	12
	100	55	34	22	16
	150	82	51	34	24
75	*25*	20	12	8	5
	50	40	25	16	11
	75	61	38	25	17
	100	82	51	33	23
	150	123	77	51	36
100	*25*	26	16	10	7
	50	54	33	21	15
	75	81	50	33	23
	100	109	68	44	31
	150	164	102	67	47

The simulation results from the mathematical model, under different test conditions, are shown in Table 2. For a high conductivity formation (i.e., dense rock), the ground temperature takes 8-12 days to return to 0.3 K of its pre-test value after a 50-hour thermal response test conducted in accordance with ASHRAE (2007) recommendations, using injection rates of 50-75 W/m. For medium conductivity formations of saturated sand and average rock, the recovery time after a similar thermal response test is 11-17 days. The recovery time increases to 17-25 days and 27-41 days for low conductivity formations of moist clay and dry soil, respectively. These results show the significance of ground formation and its thermal properties upon the post-thermal response test recovery times. The results also suggest that, for low to medium conductivity formations, the ground temperatures do not return to 0.3 K of the initial undisturbed values within 10-14 days, as suggested by ASHRAE (2007). Therefore, the existing guidelines on recovery times for low and medium conductivity formations should be revised.

In addition to the ground thermal properties, the recovery times after a thermal response test are also significantly influenced by the test duration. As discussed above, the recovery times for a 50 hour test with a heat injection rate of 50-75 W/m are 8-12 days for a dense rock formation. For shorter test durations of 10 and 25 hours, these recovery times are reduced to 2-3 days and 4-6 days, respectively. For longer test durations of 75 and 100-hours, the recovery times increase to 11-17 days and 15-23 days. As can be noticed, the changes in the recovery time are directly proportional to the changes in the test duration. This means that for a specific ground formation and a fixed heat injection rate, increasing the test duration twofold will double the recovery times. This is true for all ground formations with any fixed heat injection rate.

The effects of the heat injection rate on ground temperature recovery times are similar to the effects of test duration. For a particular test duration, the recovery times increase proportionally with an increase in the injection rates. Consider the case of a 50-hour thermal response test conducted on average rock formation with an injection rate of 50 W/m. The recovery time for this test is approximately 11 days, as seen from Table 2. Decreasing the heat injection rate from 50 to 25 W/m also reduces the recovery time to 5 days, i.e., approximately half of the previously noted 11 days. If the injection rate is increased twofold to 100 W/m, the recovery time is also doubled to 22 days.

5. CONCLUSIONS

This paper reported on the recovery time requirements of ground temperatures after a thermal response test. A series of thermal response tests, with varying test durations and heat injection rates, were conducted. After the tests, the ground temperature was experimentally measured until it returned to 0.1 K of its pre-test value. The experimental measurements show that the return of the ground temperature to pre-test conditions can take significantly longer than suggested by existing guidelines. The experimental measurements were then validated using a mathematical model. The results from the mathematical model were in close agreement with the experimentally measured temperatures. Finally, the results were extended to different test conditions and recovery times for various sets of ground formations, heat injection rates, and thermal test durations. The results indicated that the existing recommendation on recovery times for low to medium conductivity formations needs to be revised. The results also showed that the required recovery times are strongly related to the thermal response test duration and the heat injection rate.

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