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MEASUREMENT OF GROUNDWATER FLOW

USING AN IN-SITU THERMAL PROBE

Technical Completion Report
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TECHNICAL COMPLETION REPORT
Project A-042-NMEX

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ABSTRACT

A thermal probe for the in-situ measurement of groundwater flow in a borehole was constructed and calibrated in a horizontal position. The probe is a long slender metal rod having a heat source along its entire length and a temperature sensor at its midpoint. When a constant quantity of heat is applied to the probe, the rise in temperature is inversely related to the rate of water flow passed the probe.

Full-scale calibration of the probe was considered necessary because theoretical studies oversimplify the interaction between the heated probe and the horizontal flow of groundwater. The apparatus for calibration consists of a central sand-filled chamber having a horizontal hole lined with well-screen in its center. The central chamber is hydrologically connected to two taller water-filled chambers that are used to control the rate of water flow.

Over 40 calibrations of the thermal probe were made, but most of these tests were used to perfect experimental techniques. However, 8 of the calibration runs were considered sufficiently accurate to construct preliminary Master Curves. These curves show that if temperature differences of 0.1° Centrigade can be measured at the end of a two hour test, the probe is capable of distinguishing changes in rate of water flow of $5 \cdot 10^{-4}$ $cm^3/sec/cm^2$.

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INTRODUCTION

In the past few years there has been an increased concern over the need for water. Considerable work has been done in locating and evaluating new supplies. In the evaluation of groundwater potential, a most important parameter is the rate of flow of subsurface water. The purpose of the present research has been to construct and calibrate a thermal probe for the in-situ measurement of the horizontal component of groundwater flow.

The thermal probe is a long slender rod (about 112 cm. long and 3.8 cm. in diameter) which contains a heat source and a temperature sensor. The probe has been designed for use in boreholes and water wells. When a constant quantity of heat is added to the instrument, the rate of increase in the temperature of the probe is inversely related to the rate of water flow past the probe. The device will hopefully provide a method of determining the rate of flow of groundwater which is less time consuming and less expensive than today's more commonly used methods. The calibration data of the thermal probe suggests that the rate of flow of water can be determined in as little time as two hours after the probe has obtained an equilibrium temperature with its surroundings. The time required to reach equilibrium depends upon the initial difference between the temperatures of the probe and the water whose rate of flow is to be determined.

One may also determine the horizontal rate of flow at different depths in an aquifer with the thermal probe, a distinct advantage over other techniques for determining groundwater flow rates. Hopefully the device may find applicability in such engineering problems as the determination of seepage around dam sites.

THEORY

The initial theory for the use of the thermal probe as an instrument for the measurement of rates of flow of water in boreholes was given by Jaeger (1940, 1956). Jaeger considered the following problem:

> "An infinite solid region of thermal conductivity K, specific heat C, and density d, is bounded internally by an infinite circular cylinder of radius a, which contains a well-stirred perfect thermal conducting fluid of specific heat C, and mass M per unit length. A mass of the fluid is removed from the cylinder per unit time per unit length and replaced with the same material at temperature V_o. A constant quantity of heat Q is added to the fluid per unit time per unit length."

We have obtained theoretical curves determined by the numerical integration of Jaeger's solution to the above mentioned problem (Figures 1 and 2). In Figure 1 the chosen radius of the hole is 2.54 cm. while in Figure 2 the chosen radius of the hole is 5.08 cm. These curves suggest that the radius of the hole is an important consideration in the above problem. It would appear from these curves that differentiation between flow rates may be somewhat easier in a smaller diameter borehole.

The above problem was modified to consider the case in which the borehole had two perfect conductors of different specific heats (the water and the probe), and only the water was interchanged. The resultant curves (Figure 3) appear to represent the experimental data somewhat more closly than the curves in Figures 1 and 2, mainly in the sense that differentiation of flow rates becomes more difficult.

Although Figures 1, 2, and 3 give some indication of the response of the probe with time under different flow rates, we believe the theory

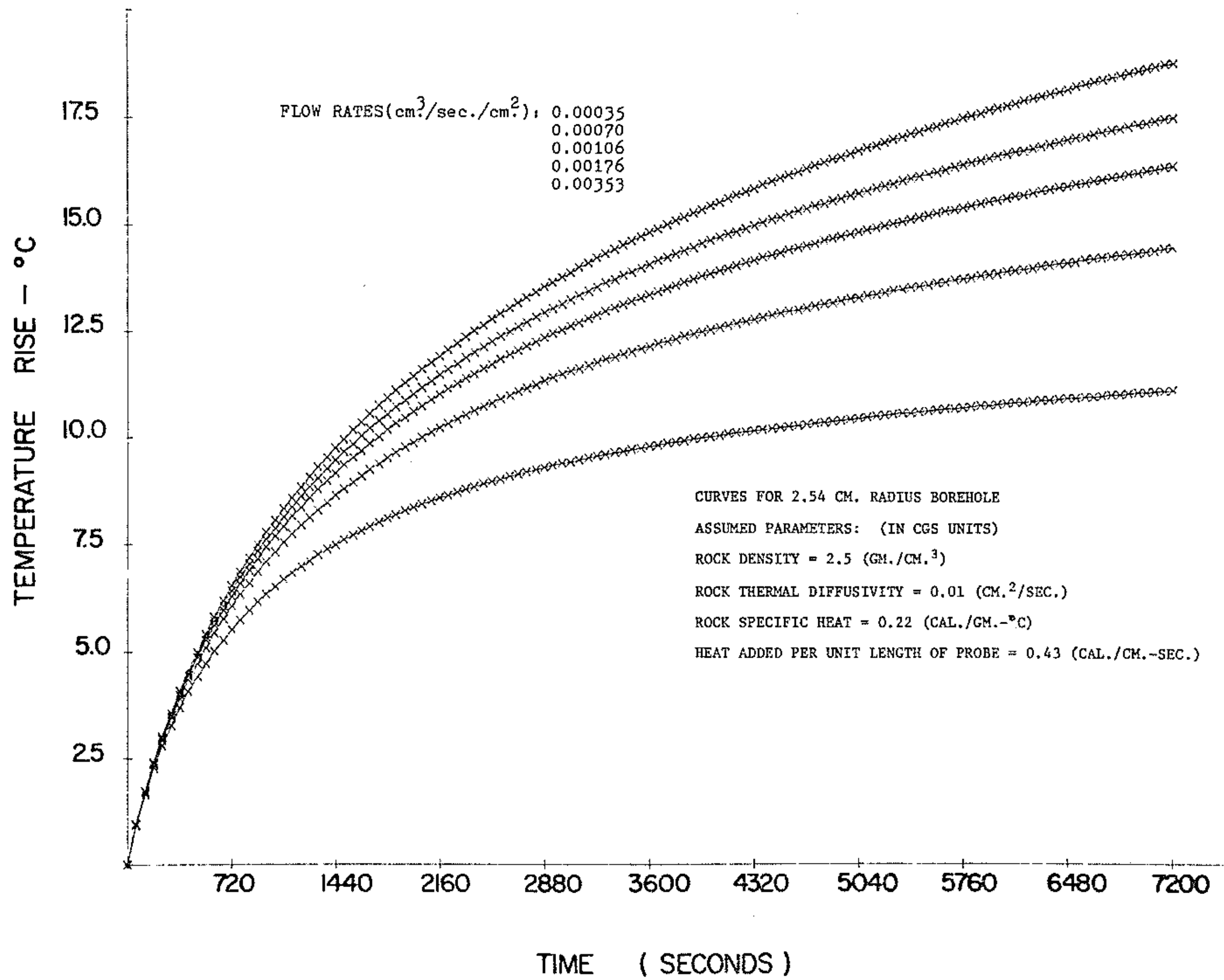

Figure 1. Theoretical curves of the temperature increase of the probe versus time for several flow rates and a 2.54 cm borehole radius.

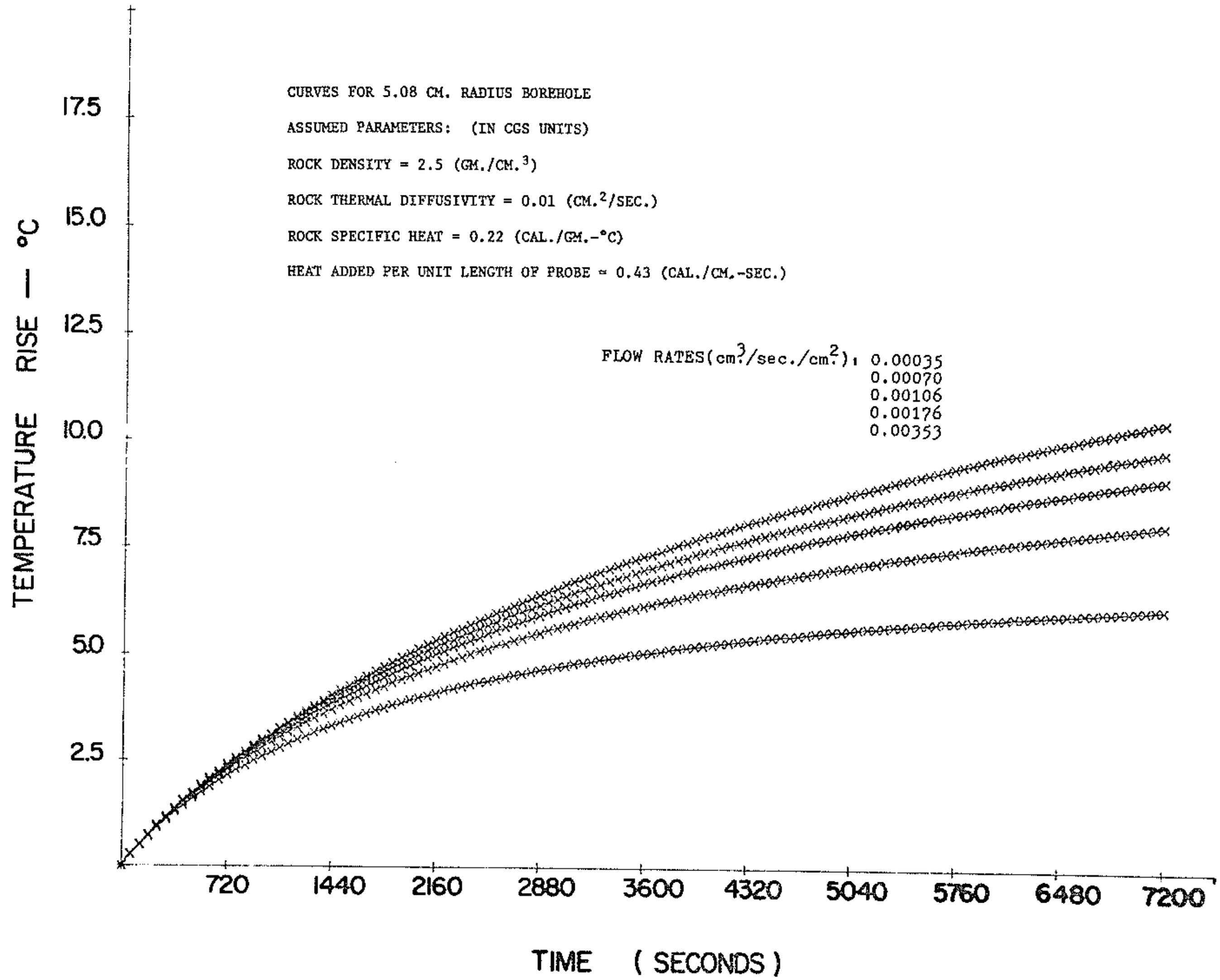

Figure 2. Theoretical curves of the temperature increase of the probe versus time for several flow rates and a 5.08 cm borehole radius.

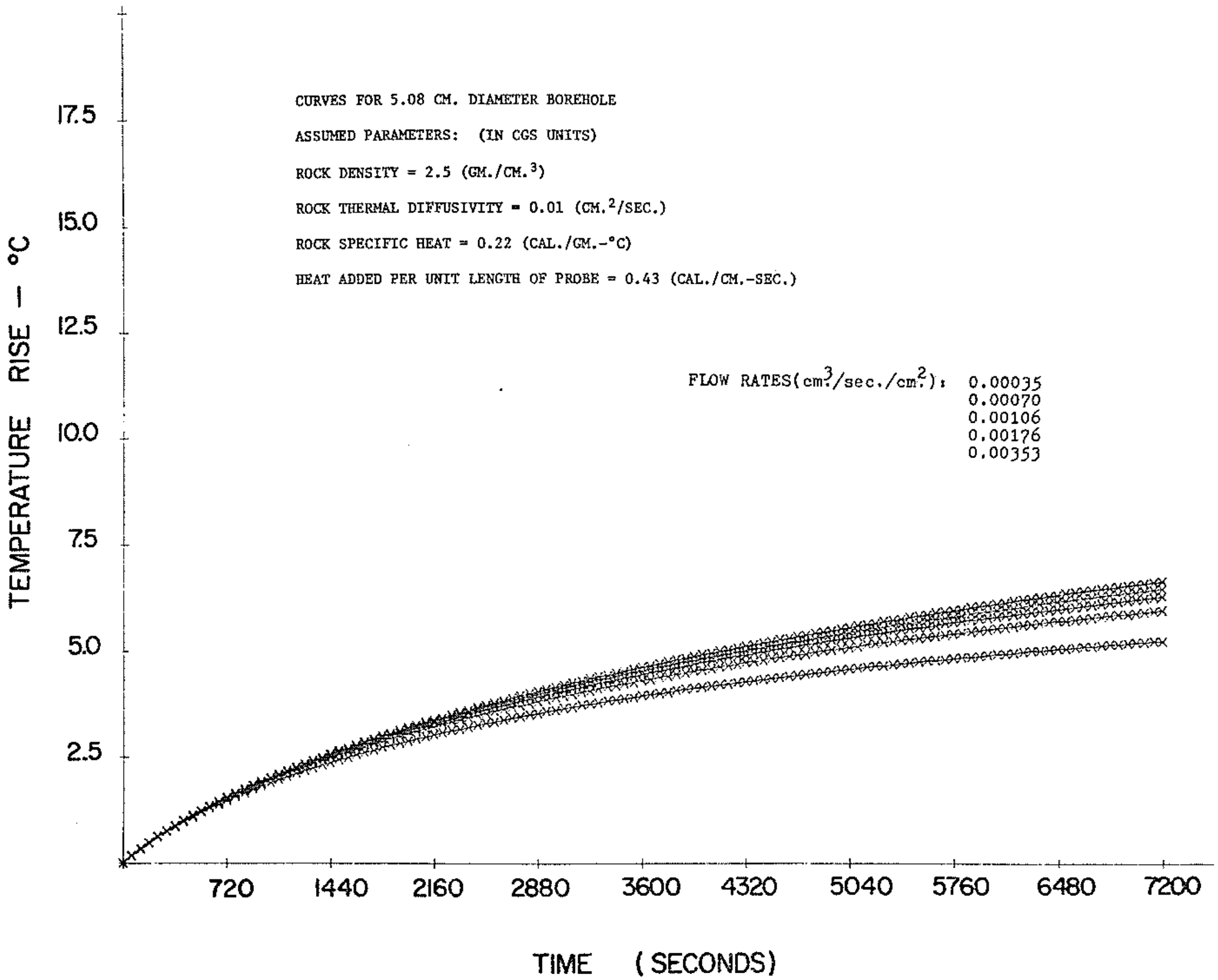

Figure 3. Theoretical curves of the temperature increase of the probe versus time for several flow rates and a 5.08 cm borehole diameter.

is not adequate to predict the response of the probe in an experimental environment. The actual experimental situation involves the interaction of the radial flow of heat with the linear flow of water, and an additional complex flow pattern close to the borehole. This complex interplay of parameters has not been considered in the theoretical problem. The theoretical problem also assumes that water entering the borehole is at the given temperature of the surrounding rock and hence the warming effect of the thermal wave from the probe is neglected. Lastly, the complexities of the water-probe system inside the borehole have been reduced in the theoretical problem by neglecting convection in the borehole and assuming the entire borehole to have the specific heat of water and the thermal conductivity of a perfect conductor.

The ultimate analytical solution to the problem will be a finite difference approach involving the digital computer. However, the basic problem is experimental and a full scale calibration is believed at this time to be the most probable method of acquiring the most reasonable set of master curves so as to evaluate the instruments capabilities.

INSTRUMENTATION FOR CALIBRATION

The instrumentation is composed of three basic parts: (1) the thermal probe, (2) the instrumentation panel, and (3) the calibration tank. Each will be described separately.

(1) The thermal probe consists of two main parts, an inner core and an outer protective sleeve (Figure 4). The inner core is a solid rod of aluminum approximately 112 cm. long and 1.1 cm. in diameter. It contains the heat source and the temperature sensor. The heat source is a glass-insulated nichrome wire embedded in a spiral groove of two turns per 2.54 cm. which has been machined in the rod. The total resistance

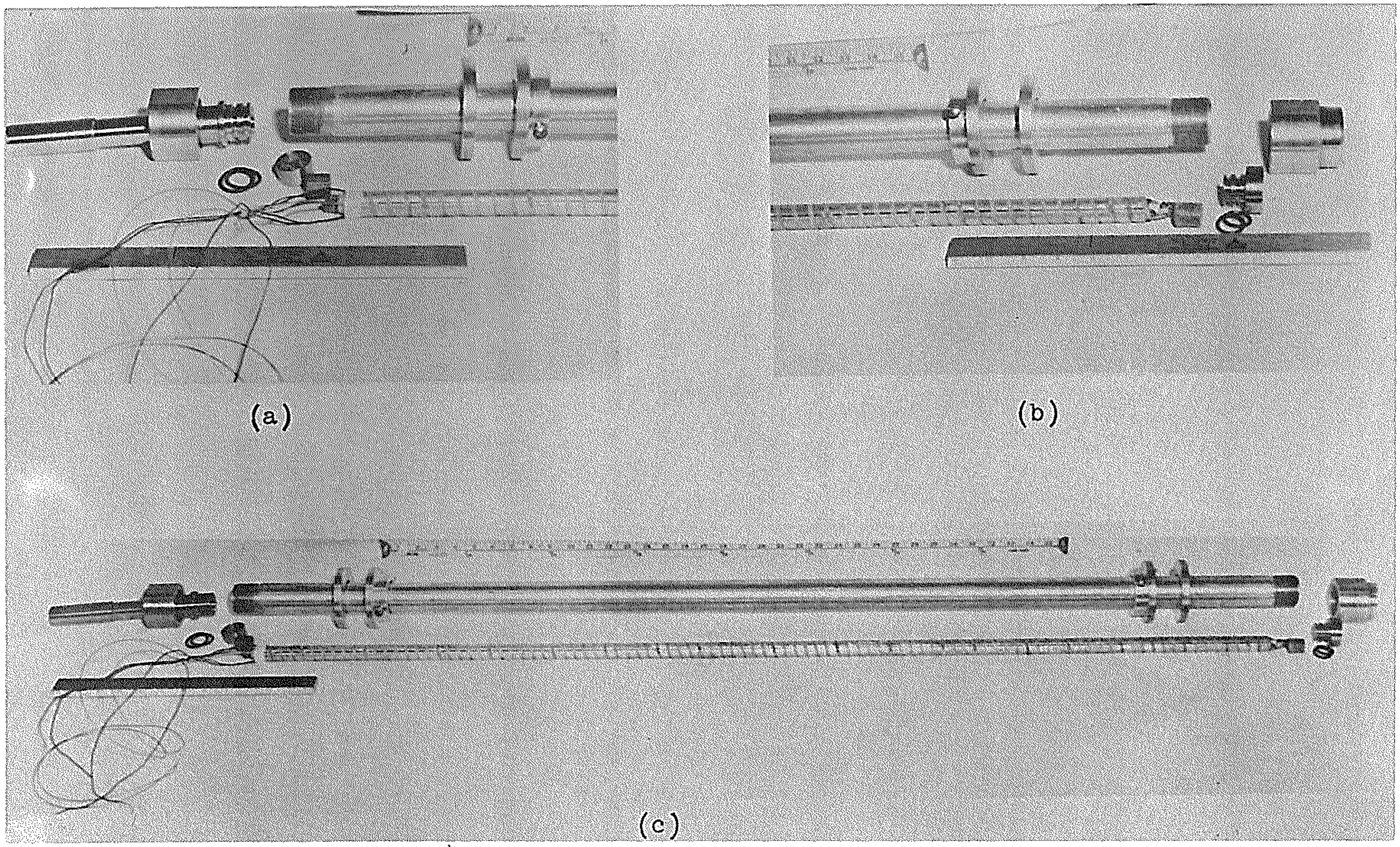

Figure 4. Thermal probe. The end of the probe that connects to the cable is shown in (a).

of the heating element is approximately 38 ohms. A known current, passed through the heating element, serves as the heat source for the instrument. Centered midway in the rod is the temperature sensor, a thermistor having a resistance of 4,000 ohms at 25°C (Fenwall - 4K - 2% isocurve device).

The outer sleeve, 3.8 cm. outside diameter, slides snugly over the inner core. The inner core is retained at both ends by use of bakelite wedges pressing firmly against stainless caps screwed over the outer sleeve. These stainless steel caps are equipped with inner O-ring seals to prevent possible water leakage into the inner core. The heating element and the thermistor are electrically connected to a six conductor cable through an outer stainless steel fitting at the top of the probe. A stress member in the cable is secured by another connector between the inner core and the outer fitting. The outer fitting is volcanized to the cable to insure against water leakage into the inner core.

Convection seals are secured to the outside of the sleeve by means of rings held in place with set screws. The seals prevent water movement parallel to the probe in the borehole and consequently insure that the flow rate measured is perpendicular to the borehole.

(2) The instrument panel consists of two main parts (Figure 5 the temperature monitoring system and the variable power supply to the heating element. The Wheatstone bridge located in the instrument panel coupled with the thermistor located in the inner core of the probe provided a resistance thermometry device. The bridge was constructed at New Mexico Tech for the present research. The bridge has a range from 0 to 100,000 ohms; however, the typical operating range with the 4K isocurve thermistor is between 5000 ohms and 2200 ohms (20°C to 40°C). The

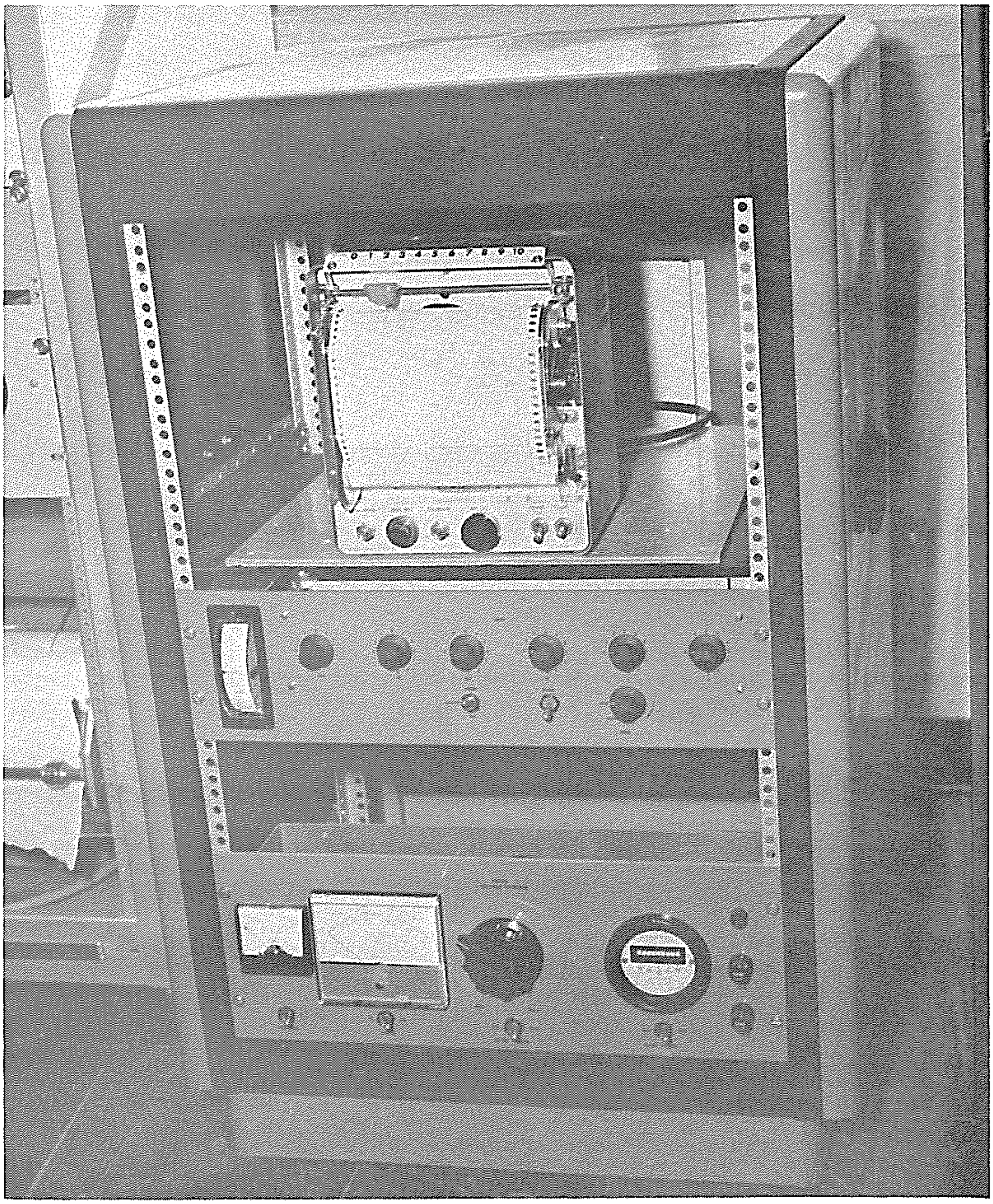

Figure 5. Instrumentation panel; temperature monitoring system above, probe power supply below.

relative accuracy of the system is probably better than ±2 ohms (about ±0.01°C).

The power supply consists of a Variac which may be adjusted to deliver from 0 to 150 volts and from 0 to 5 amperes to the heating element in the probe. Associated monitoring equipment, i.e., voltmeter and ampmeter, are employed to determine the power to the probe.

(3) The calibration tank shown in Figure 6 is built from half-inch marine plywood with aluminium bracing and beams. The central chamber of the calibration tank is filled with sand. A horizontal hole in one end of the central chamber allows for the insertion and withdrawal of the thermal probe. Well-screen with 0.0025 cm. wide slits at 0.154 cm. spacing is placed in the hole to duplicate a screened borehole. Tests conducted for a cased borehole were performed by placing an aluminum sleeve inside the well-screen. The probe is inserted in this hole and sealed to prevent water leakage (Figure 6). The central chamber is hydrologically connected to the taller side compartments by a system of holes drilled through the separating panel. Fine-mesh screen is placed over the holes to retain the sand in the central chamber.

The rate of flow through the central chamber is controlled by regulating the difference in water level between the side chambers. This is accomplished by means of a floatation switch in the taller of the chambers. When the water in that chamber subsides to a selected level, the switch activates two pumps located in a separate reservoir which transfer water into the taller chamber. The pumps are turned off when the level of water in the taller chamber has reached a height slightly above the selected level. In this way a fairly constant level may be obtained in the taller of the side compartments (±2.5 cm. with

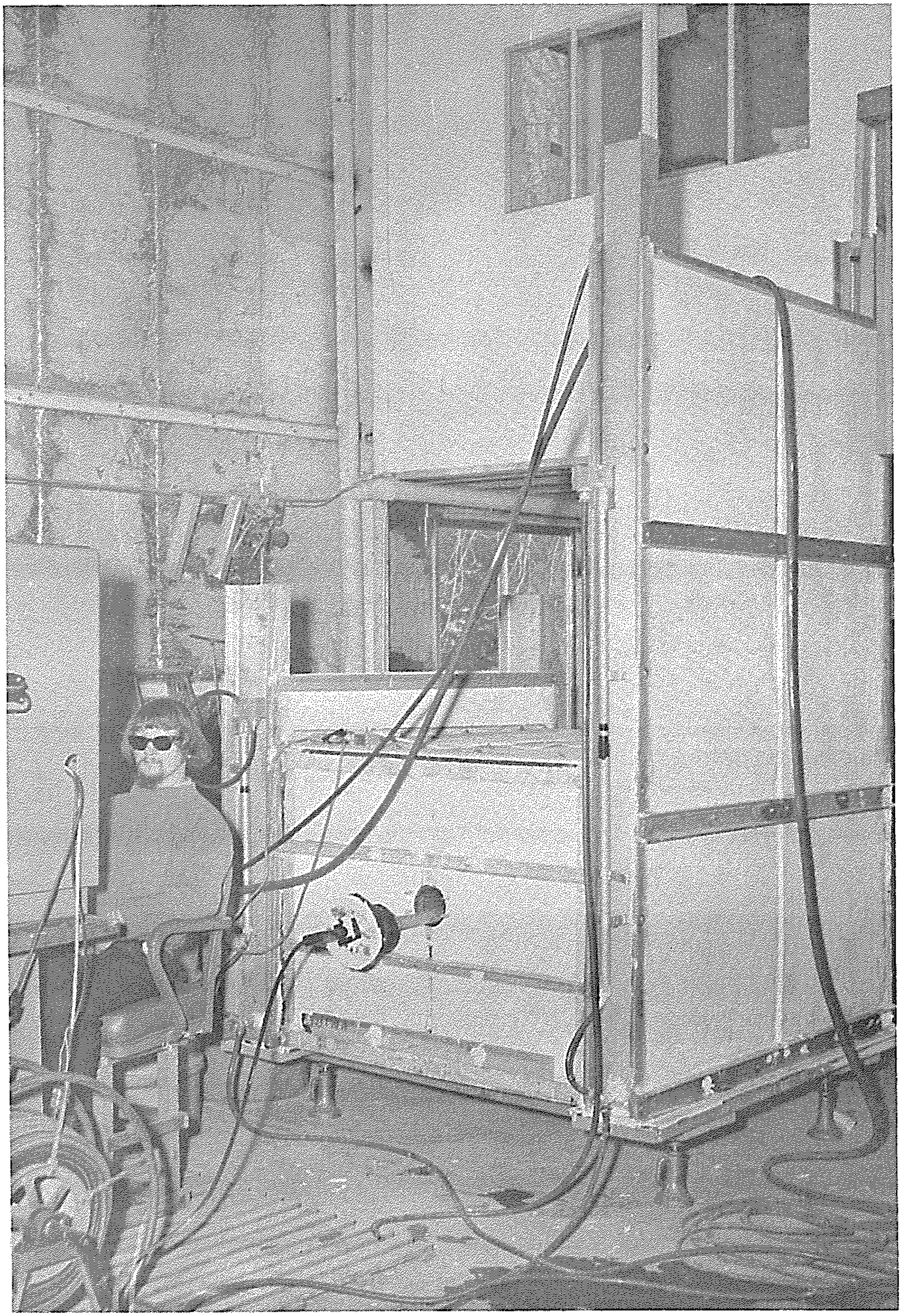

Figure 6. Calibration tank with probe partially inserted.

an oscillating period of about 30 sec.). A constant level is obtained in the shorter water compartment by fixed drain holes. The drain holes allow water to flow into a gutter placed below the holes and back into the reservoir containing the pumps. Because the system used remains closed, new water is not added.

EXPERIMENTAL PROCEDURE

The method for the most reliable calibration of the thermal probe is as follows:

1. The thermal probe and the water in the calibration tank are allowed to come to the same temperature. Equilibrium is considered attained when the temperature of the probe, found from the resistance of the thermistor embedded in the probe, agrees within a few degrees Centigrade of the temperature of the water. Normally the probe and water are near the same temperature whenever an experiment is about to be conducted because the pumps that control the flow of water in the calibration tank are allowed to operate continuously. If the pumps are turned off, the time required for the probe and the water to equilibriate depends upon the initial difference in temperatures and upon the rate of flow of water, i.e., fast water flow brings the probe temperature to the water temperature more quickly.

A second method used to insure an equilibrium temperature of the probe with the water is to monitor the resistance of the thermistor in the probe over a period of twenty minutes just before the test begins. If the resistance of the thermistor does not change during this period of time, it is assumed that the probe temperature is very nearly the same as the water temperature.

2. After equilibrium has been established between the temperatures

of the probe and of the water in the calibration tank, a measurement to determine the rate of flow of the water in the tank is performed. The calculation of the flow rate proceeds by collecting a known volume of water over a known time interval from the discharging side of the tank. Dividing the volume by both the cross-sectional area of the tank and the collection time yields the rate of water flow. If flow rate is divided by the porosity of the media, an estimate of the water velocity is obtained. To be sure the flow rate remains constant, this procedure is repeated three times during one calibration test: at the start, halfway through the test, and at the end of the test.

3. The actual experiment is now ready to proceed. The resistance of the bridge at the equilibrium temperature is recorded for time zero. The resistance of the bridge is lowered approximately 200 ohms because the heating of the probe will decrease the resistance of the thermistor. Power to the heating elements and a stopwatch are activated synchronously. When the bridge null-detector indicates the new resistance has been reached, the associated time and thermistor resistance are recorded. After the first data point, the resistance of the bridge is again lowered by 200 ohms and the procedure is repeated. An average test consists of 25 to 35 of these readings over a period of two hours. The successive lowering of the resistance of the bridge varies from 200 ohms at the start of the experiment to as little as 10 ohms toward the end of the experiment. The actual choice of the resistance setting is more a matter of technique than of standard procedure.

Due to the difficulty in estimating the amount of time required for the null-detector to come to zero for each reading, the bridge is left on during the entire length of the experiment. The self-heating effect of the thermistor was investigated by allowing the bridge current to pass through the thermistor continuously for 30 minutes. During that time no change in the thermistor resistance could be recorded; therefore, the bridge current was below the self-heating stage of the thermistor.

During the calibration runs there were indications that the resistance of the heating element would increase during a test. A decision was made to keep a constant current in the heating element. To keep a constant current through the heating element required that the voltage be continually changed. During the calibration tests a current was selected and the voltage to the heating element was changed as necessary to keep the current constant. In the majority of the tests a current of 2.4 amps was used. The change in power to the probe from the start to the finish of a test was typically less than 1%.

4. After the completion of a calibration test, the recorded times and resistance are punched onto computer cards. A computer program changes the recorded resistances to temperatures in degrees centigrade and plots the temperature rise in the probe as a function of time. The above procedure is repeated for different flow rates allowing one to acquire a set of curves for the temperature rise in the probe versus time for various rates of flow of water in a borehole.

5. The pumps controlling the rate of water in the central chamber of the calibration tank are allowed to operate continuously. They are shut off only when necessary: e.g., when a calibration test involving zero flow rate is made, or when repairs on the equipment are necessary. By keeping water in the tank at all times, one can be more sure that the sand in the central chamber remains saturated. Between some of the first calibration tests, the water was drained after each run and filled

directly before the next run. It is now believed that the results of these first tests are questionable since it is doubtful that the sand could have been completely saturated.

PRESENTATION AND DISCUSSION OF CALIBRATION DATA

The data obtained during the calibration of the thermal probe are presented in Tables 1 and 2 and Figures 5, 6, 7, 8, 9, and 10. Table 3 explains the headings used in Tables 1 and 2. Plotted in the Figures is the temperature rise of the probe versus time for different rates of water flow. The number of the test run is given on the Figures for cross-reference with the Tables.

Cased Borehole

The first set of calibration tests of the thermal probe was made to determine if changes in rate of water flow past a cased borehole could be sensed by the probe. The results of these tests are presented in Table 1 and Figure 7.

Curves D through I on Figure 7 are for tests in which 2.4 amperes were applied to the probe. For the duration of these runs, about 2100 seconds, differences in rates of flow cannot be clearly distinguished. Increasing the applied current to 2.9 amperes does not appear to improve the situation (curves B and C). The test represented by curve A in Figure 7 was made with the tank drained. The distinctly different character of this curve as compared with the other curves indicates water was surrounding the probe during the other tests.

The results of the calibration tests for the cased borehole are considered inconclusive. The durations of the tests were probably too short to separate differences in flow rate. In addition, these tests were the first performed, and consequently the techniques followed were

Table 1. Data for calibrations runs: Cased Borehole

Test No.	Date	V/T/A	H	TD	T	KΘ	ST°C	ET°C	TD°C	RT°C	I	W	D	Comments
1-C	8-26-72	.00722	12.06	?	?	.073	24.7	36.4	11.7	?	2.4V?	D	2270	
2-C	9-13-72	.00818	13.65	?	?	.073	24.7	36.4	11.7	?	2.4V?	D	2370	
3-C	9-13-72	.00818	13.65	?	?	.073	27.5	38.8	11.3	?	2.4V?	D	2200	
4-C	9-14-72	?	19.37	?	?	?	27.5	39.2	11.7	?	2.4V?	D	2020	No flow rate determined
5-C	9-15-72	.00000	0.0	0.0	0.0	-	25.0	36.1	11.1	?	2.4V?	D	2230	
6-C	9-18-72	.00000	0.0	0.0	0.0	-	23.4	34.1	10.7	?	2.4V?	D	2040	
7-C	9-17-72	.00000	0.0	0.0	0.0	-	22.1	54.4	32.3	?	2.4V?	-	763	Test with no water in tank
8-C	9-20-72	.00000	0.0	0.0	0.0	-	22.6	38.8	16.2	?	2.9V?	D	2156	
9-C	9-21-72	.0118	20.32	?	?	.071	24.2	41.6	17.4	?	2.9V?	D	2575	

Table 2. Data for calibration runs: Uncased Borehole.

Test No.	Date	V/T/A	H	TD	T	KΘ	ST°C	ET°C	TD°C	RT°C	I	W	D	Comments
1-U	10-17-72	.0154	23.81	17.8	113	.079	25.3	35.6	10.3	?	2.4V?	D	1457	
2-U	10-18-72	.01533	18.1	17.8	112	.103	24.3	35.7	11.4	?	2.4V?	D	2567	
3-U	10-18-72	.01157	13.02	17.8	151	.109	25.8	37.7	11.9	?	2.4V?	D	3220	
4-U	10-19-72	.0016	3.33	7.6	467	.059	24.2	36.7	12.5	?	2.4V?	D	3528	Questionable run
5-U	10-20-72	.0031	3.18	7.6	242	.119	23.6	39.2	15.6	?	2.4V?	D	7117	Questionable run
6-U	10-21-72	.01725	20.0	17.8	101	.105	27.7			?	2.4V?	D	-	Terminated early
7-U	10-22-72	.00000	0.0	0.0	000	-	22.1	38.1	16.1	?	2.4V?	ND	7075	
8-U	10-23-72	.01993	25.40	17.8	87	.096	23.6	34.7	11.1	23.3	2.4V?	ND	7200	
9-U	10-24-72	.01798	19.4	17.8	93	.110	23.5	35.3	11.8	27.3	2.4V?	ND	7247	
10-U	10-25-72	.00000	0.0	0.0	000	-	24.3	39.6	15.3	20.0	2.4V?	ND	7087	
11-U	10-26-72	.01111	11.43	17.8	156	.119	22.5	35.3	12.8	25.0	2.4V?	ND	6932	
12-U	10-27-72	.01118	11.43	17.8	154	.120	24.3	37.6	13.3	25.0	2.4V?	ND	7102	Questionable test
13-U	10-29-72	.0119	11.75	17.8	146	.123	20.8	34.0	13.2	22.5	2.4V?	ND	7188	Questionable test
14-U	10-30-72	.0076	7.62	17.8	212	.122	21.4	35.4	14.0	26.7	2.4V?	D	7153	
15-U	11-03-72	.0059	7.62	15.2	366	.095	25.5	39.0	13.5	28.1	2.4V?	?	7150	Questionable test
16-U	11-05-72	.00539	8.26	15.2	345	.083	22.9	36.7	13.8	23.9	2.4V?	ND	6952	Questionable test
17-U	11-06-72	.00000	0.0	0.0	000	-	21.7	36.9	15.2	22.5	2.4V?	ND	7075	
18-U	11-07-72	.00549	7.94	15.2	336	.084	21.2	34.9	13.7	24.4	2.4V?	ND	7200	
19-U	11-08-72	.01603	20.0	15.2	115	.098	22.1	33.9	11.8	26.5	2.4V?	ND	7200	
20-U	11-09-72	.01646	20.0	15.2	112	.101	21.6	33.4	11.8	23.3	2.4V?	ND	7140	
21-U	11-10-72	.01007	12.7	15.2	183	.097	22.0	34.9	12.9	20.5	2.4C	ND	7200	
22-U	11-11-72	.01007	12.7	15.2	183	.097	20.2	33.3	13.1	16.1	2.4C	CF	7200	
23-U	11-13-72	.00696	7.94	15.2	266	.104	21.2	35.7	14.5	21.7	2.4C	CF	7200	
24-U	11-14-72	.00678	7.94	15.2	272	.105	21.1	35.3	14.2	25.5	2.4V	CF	7200	
25-U	11-15-72	.00665	7.62	15.2	277	.107	22.2	37.1	14.9	21.9	2.4C	CF	7200	
26-U	11-17-72	.00670	7.62	15.2	275	.108	22.3	36.9	14.6	22.2	2.4C	CF	7200	
27-U	11-20-72	.00000	0.0	0.0	000	-	22.0	37.4	15.4	21.7	2.4C	CF	7150	
28-U	11-21-72	.00000	0.0	0.0	000	-	21.2	37.0	15.8	23.9	2.4C	ND	7200	
29-U	12-06-72	.01144	15.24	17.8	188	.092	19.7	32.6	12.9	25.5	2.4V	CF	7200	
30-U	12-07-72	.00238	3.05	7.6	387	.095	22.2	37.6	15.4	28.3	2.4C	CF	7200	Questionable test
31-U	12-10-72	.00000	0.0	0.0	000	-	22.3	37.2	14.9	23.9	2.4C	CF	7200	
32-U	12-11-72	.00469	5.08	15.2	381	.113	24.0	38.5	14.5	23.9	2.4C	CF	7240	Questionable test
33-U	12-12-72	.01779	20.32	12.7	90	.107	23.8	36.1	12.3	?	2.4C	CF	7280	
34-U	12-13-72	.0120	15.24	12.7	133	.096	23.9	36.3	12.4	?	2.4C	CF	6320	Questionable test
35-U	12-14-72	.00699	8.26	15.2	275	.103	23.0	37.1	14.1	?	2.4C	CF	7200	

Table 3. Description of headings listed on tables 1 and 2.

Heading	Description
Test No.	Sequential number of test, where C refers to a cased borehole and U refers to an uncased borehole.
Date	Date that the test was performed.
V/T/A	Flow rate in $cm.^3/sec./cm.^2$.
H	Difference in the levels of the water in the side chambers of the calibration tank in cm.
TD	The depth of water (in cm.) in the reservoir tank at the time the flow rate was computed.
T	Time required to collect the discharge volume used in the calculation of flow rate.
KΘ	The product of permeability and porosity.
ST°C	The temperature of the probe at the start of the test in degrees Centigrade.
ET°C	The temperature of the probe at the end of the test in degrees Centigrade.
TD°C	The difference between the temperatures in the probe at the start and end of the test.
RT°C	The temperature in the laboratory at the time the test was performed in degrees Centigrade.
I	Starting electric current to probe in amperes. When followed by V?, the current may have changed slightly during the run, and when followed by a C, the current was held constant during the run.
W	D indicates tank was filled just before test, ND indicates water was in tank a prolonged period before the test, and CF indicates water was circulated through the tank for a prolonged period before the test.
D	Duration of test in seconds.

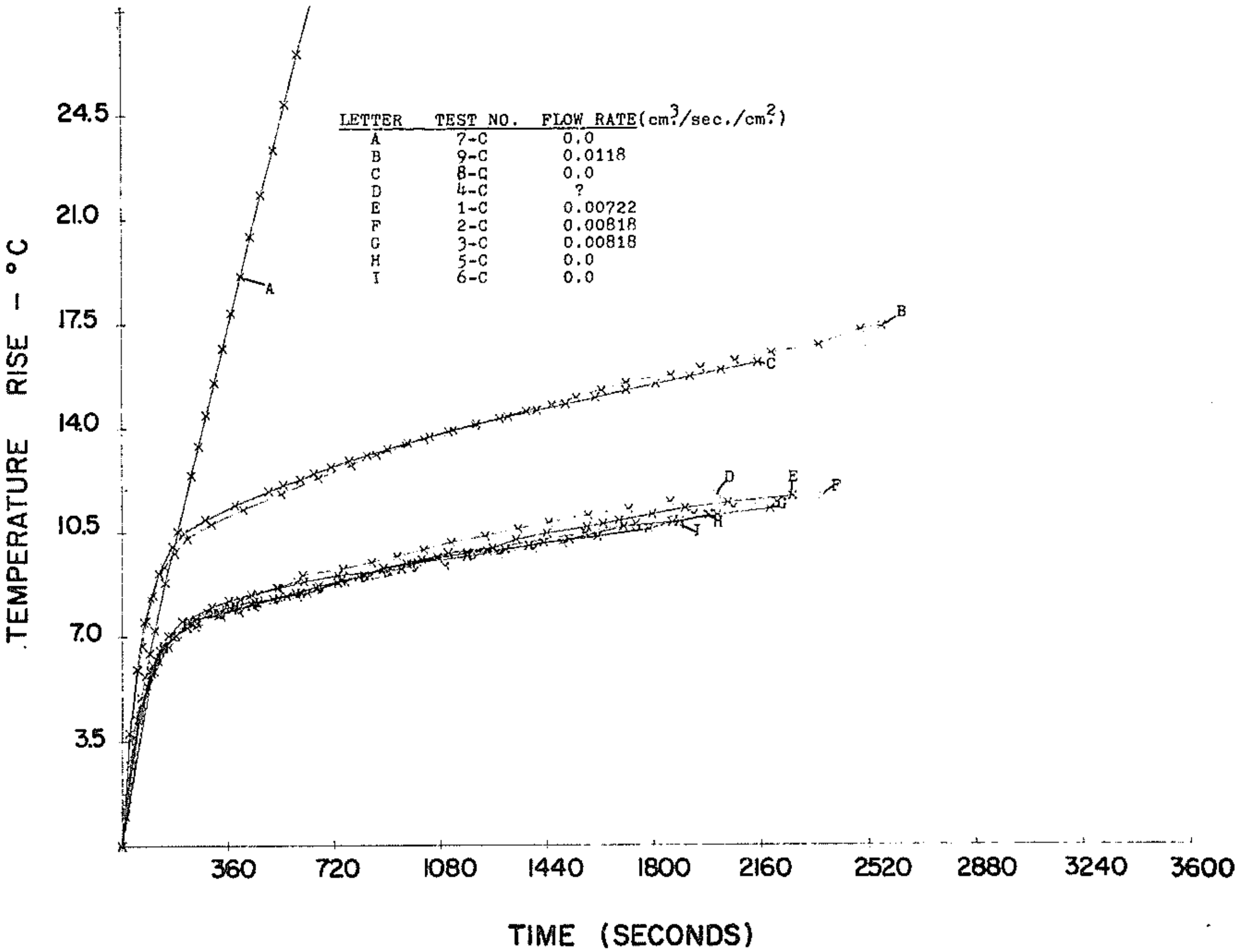

Figure 7. Experimental curves of the rise in temperature of the thermal probe versus time for a 10.16 cm. diameter cased borehole

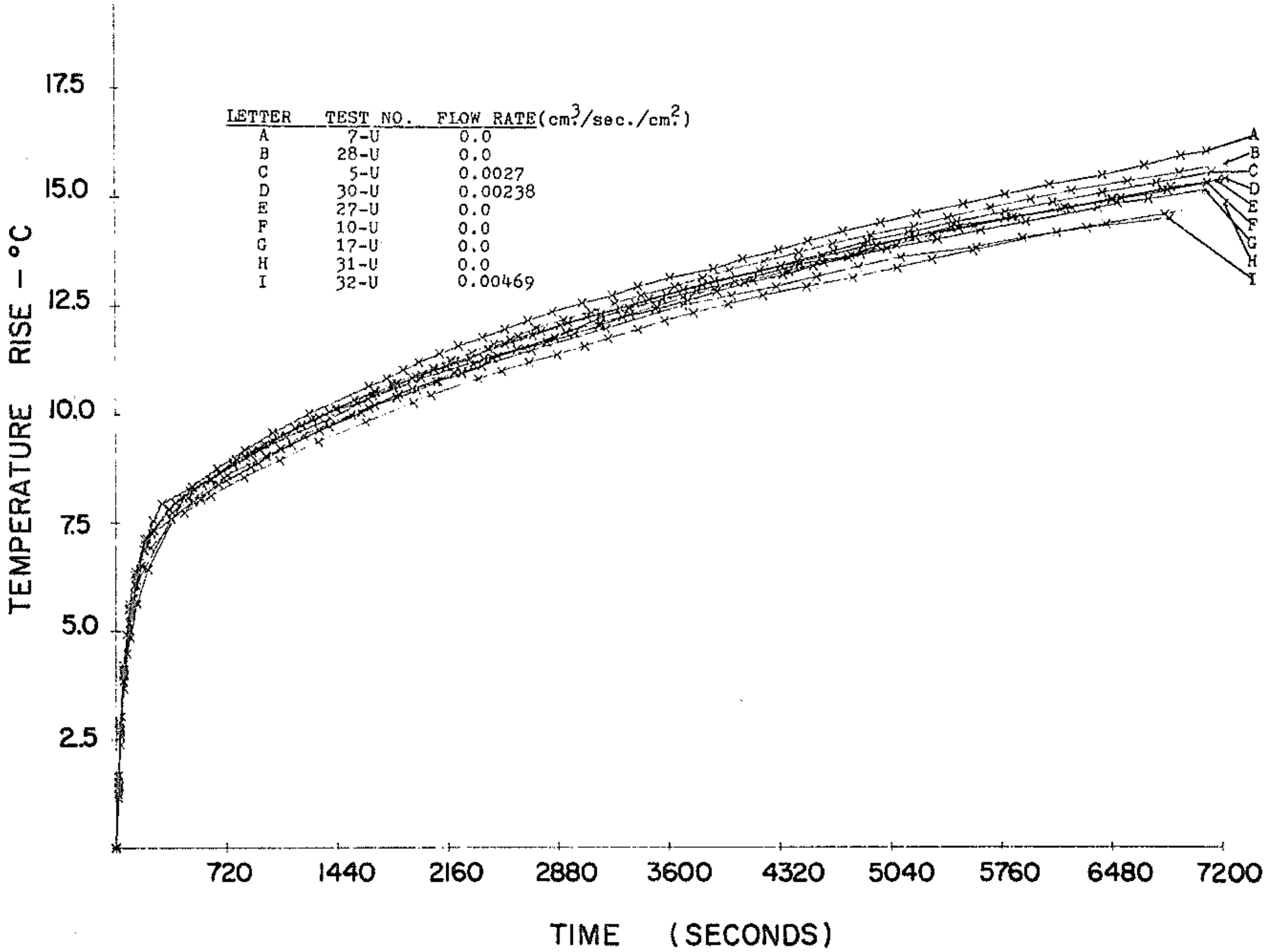

Figure 8. Experimental curves of rise in temperature versus time for flow rates of 0.0 to 0.005 $cm^3/sec/cm^2$ in a 10.16 cm. diameter uncased borehole

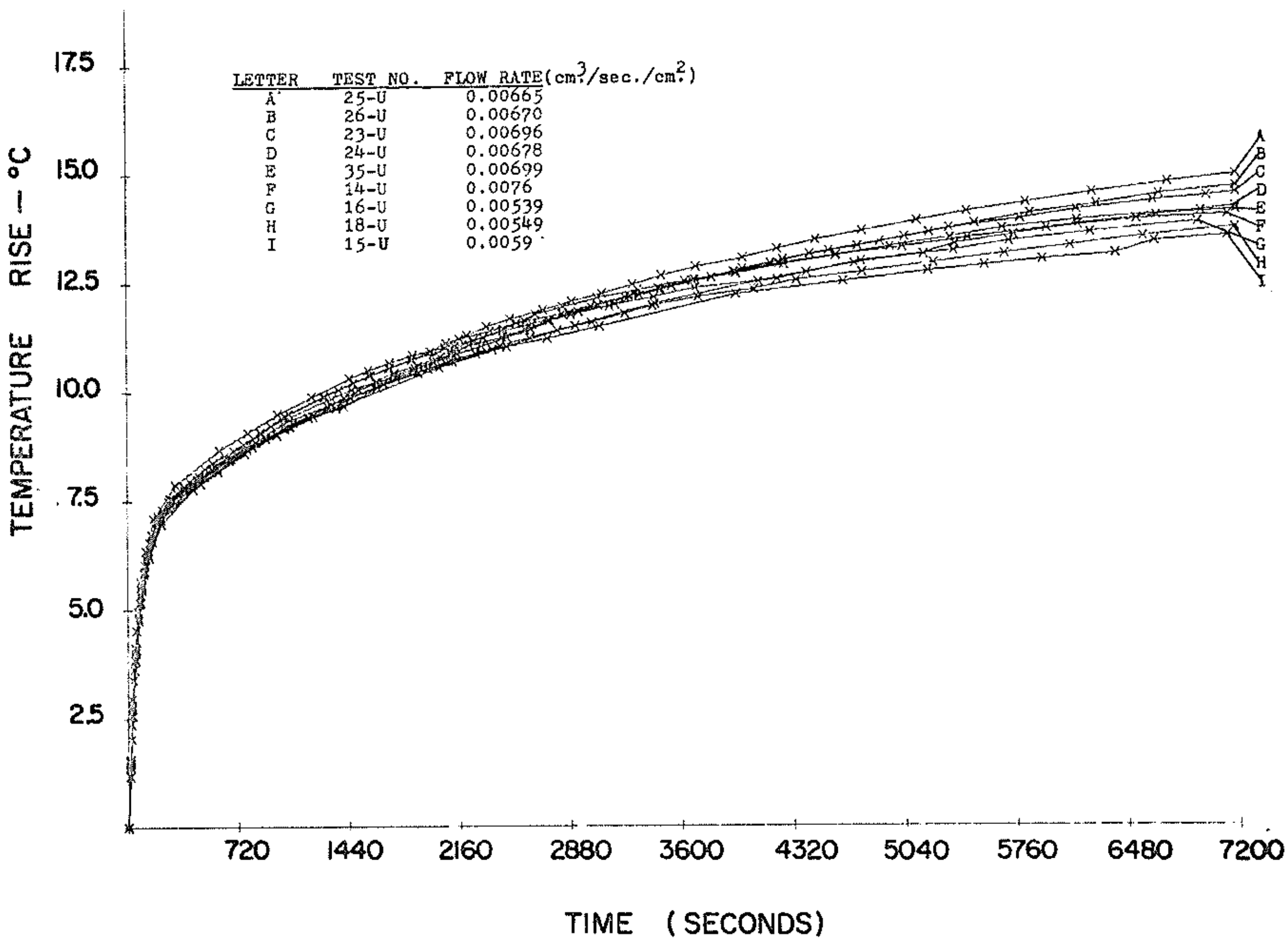

Figure 9. Experimental curves of rise in temperature versus time for flow rates of 0.005 to 0.01 $cm^3/sec/cm^2$ in a 10.16 cm. diameter uncased borehole

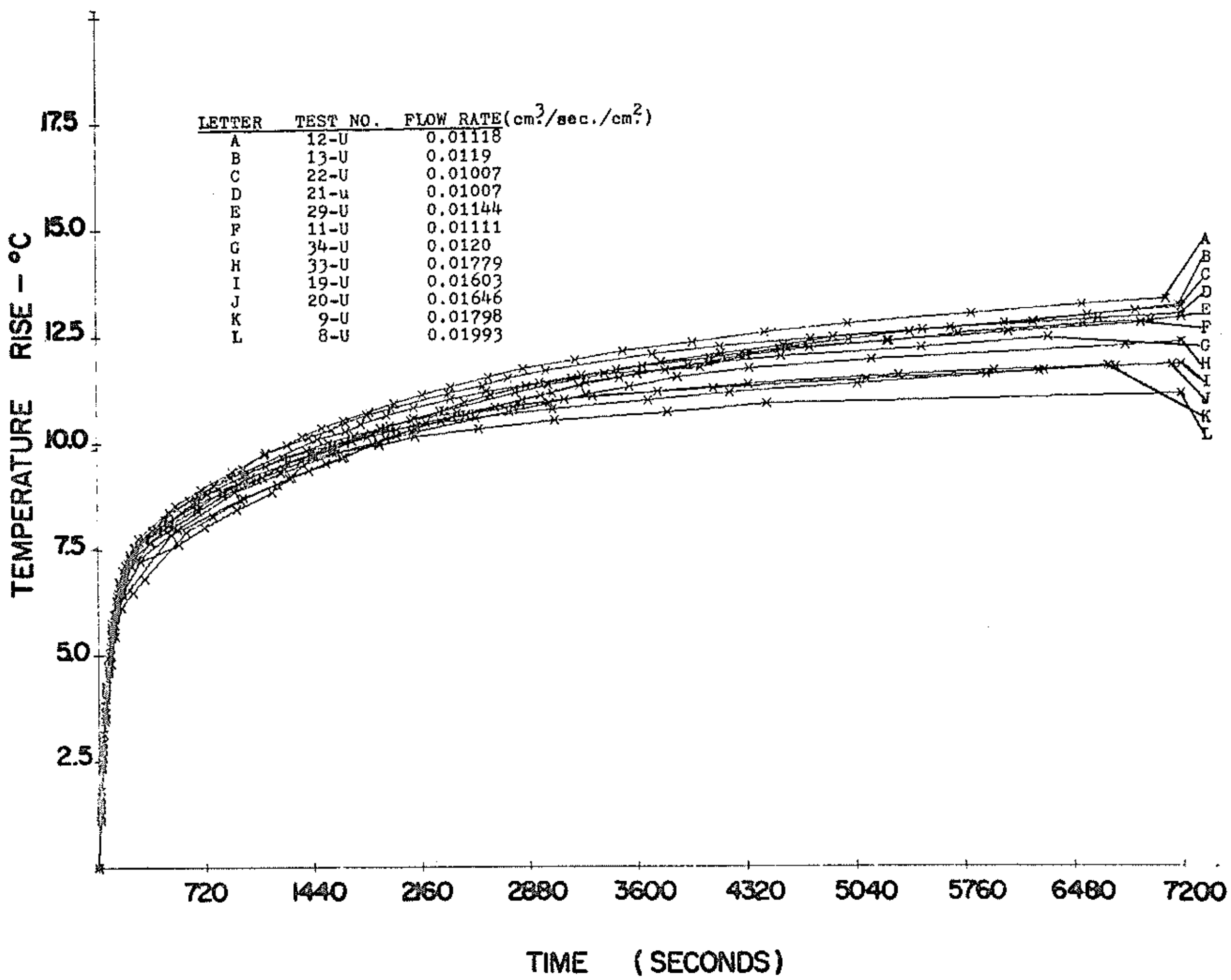

Figure 10. Experimental Curves of rise in temperature versus time for flow rates over 0.01 $cm^3/sec/cm^2$ in a 10.16 cm. diameter uncased borehole

not as well developed as procedures later in the program.

Uncased Borehole

The results of calibration tests for an uncased borehole are given in Table 2 and Figures 6, 8, 9, and 10. Curves appearing in 8, 9, and 10, respectively, are for flow rates of 0.0 to 0.005, 0.005 to 0.01, and greater than 0.01 $cm^3/sec/cm^2$. For these tests, the experimental borehole was lined with a 10.16 cm. diameter well-screen having 0.0025 cm. wide slots at 0.154 cm. spacing.

General Characteristics of Curves

The temperature versus time curves in Figures 5, 6, 7, 8, 9, and 10 begin with a rapid, nearly linear, rise in temperature. After about 200 seconds, the rate of temperature increase is sharply reduced and there is a gradual decrease in the rate of temperature increase up to the end of each experiment.

The sharp change in the character of the curves at about 200 seconds is caused by the onset of convection in the water surrounding the probe. Prior to this time, the temperature gradient between the probe and the well-casing is too small to sustain convection. During this phase, while the probe is warming, heat can escape from the probe only by conduction. Because the thermal conductivity of the water is quite low, the temperature of the probe rises rapidly. Once convection commences, heat is transferred more rapidly from the probe, and consequently the rate of increase of the probe temperature is sharply reduced.

Sources of Experimental Error

Early in the research, it was found that curves of temperature rise versus time could not be accurately reproduced for the same flow rates. This led to a gradual improvement in the experimental procedures so that, by experimental run 21 in Table 2, curves having a high degree of reproducibility were obtained. The conditions required for these tests were:

1. Water continuously circulated in the tank before and between calibration tests.
2. Water and probe temperature near equilibrium (within 4° C) at the beginning of a test.
3. Current to the heating elements of the thermal probe maintained at a constant 2.4 amperes.
4. Constant rate of water flow during a test determined by making at least three measurements of the rate of flow during a test.

MASTER CURVES

Although more than 40 calibration tests were made, only 8 were used to establish master curves for the thermal probe in an uncased borehole. The 8 experimental runs were tests 22, 23, 25, 26, 27, 28, 29, and 33 in Table 2. These runs of two hours duration were conducted under the experimental procedures outlined at the end of the previous section.

As a first step in establishing the master curves, we obtained the best second degree polynomial fits, in the least squares sense, to the 8 experimental curves. Coefficients for these polynomials are listed in Table 4. Curve fitting was only applied to that portion of the experimental data from time equal 1200 seconds to 7200 seconds. Consequently, the temperature rise was with respect to the observed temperature at 1200 seconds; i.e., 1200 seconds was taken as the new origin.

The first 1200 seconds of the test includes the relatively complex

Table 4. Coeffieients for second degree polynomial fits of experimental data.

Run No.	Water flow $cm^3/sec/cm^2$	A_0	A_1	A_2
27	0	-1.720	$1.650 \cdot 10^{-3}$	$-8.17 \cdot 10^{-8}$
28	0	-1.759	$1.676 \cdot 10^{-3}$	$-8.40 \cdot 10^{-8}$
25	$66.5 \cdot 10^{-4}$	-1.760	$1.685 \cdot 10^{-3}$	$-10.30 \cdot 10^{-8}$
26	$67.0 \cdot 10^{-4}$	-1.767	$1.697 \cdot 10^{-3}$	$-10.29 \cdot 10^{-8}$
23	$69.6 \cdot 10^{-4}$	-1.759	$1.699 \cdot 10^{-3}$	$-10.71 \quad 10^{-8}$
22	$100.8 \cdot 10^{-4}$	-1.587	$1.530 \cdot 10^{-3}$	$-10.55 \cdot 10^{-8}$
29	$114.3 \cdot 10^{-4}$	-1.292	$1.312 \cdot 10^{-3}$	$-9.22 \cdot 10^{-8}$
33	$178.0 \cdot 10^{-4}$	-1.369	$1.299 \cdot 10^{-3}$	$-9.63 \cdot 10^{-8}$

transition from purely conductive heat transfer to primarily convective heat transfer between the probe and the well-screen. The temperature at which this transition occurs is dependent on the initial temperature contrast between the probe and the water flowing around it. If the probe temperature is higher than the water temperature, convection begins earlier than it would if the temperatures were equal. Conversely, if the probe has a lower temperature than the water, convection will start late.

The A_o coefficient of the polynomial fit, or intercept value, depends on the temperature at which convection begins. Because the initial temperature contrast between the probe and the water ranged up to 4°C in the 8 calibration tests, no correlation between A_o values and flow rates is to be expected in the data listed in Table 4. For this reason, the A_o coefficient was arbitrarily set to zero for the development of master curves.

The A_1 coefficient, the slope of the temperature rise curve, remains fairly constant for flow rates from 0 to $70 \cdot 10^{-4} cm^3/sec/cm^2$ and then decreases in a rather consistent fashion for progressively higher flow rates. The A_2 coefficient does not appear to follow any definite trend with change in flow rate.

In order to get a preliminary set of master curves, coefficients A_1 and A_2 were assumed to vary linearly with respect to flow rate. Physical rationale does not require such a linear relation. On the other hand, the data do not exclude it, and because it is the simplest possible assumption there is some virtue in its adoption. The master curves, obtained from the best straight-line least-squared fits to the coefficients, are shown in Figure 11.

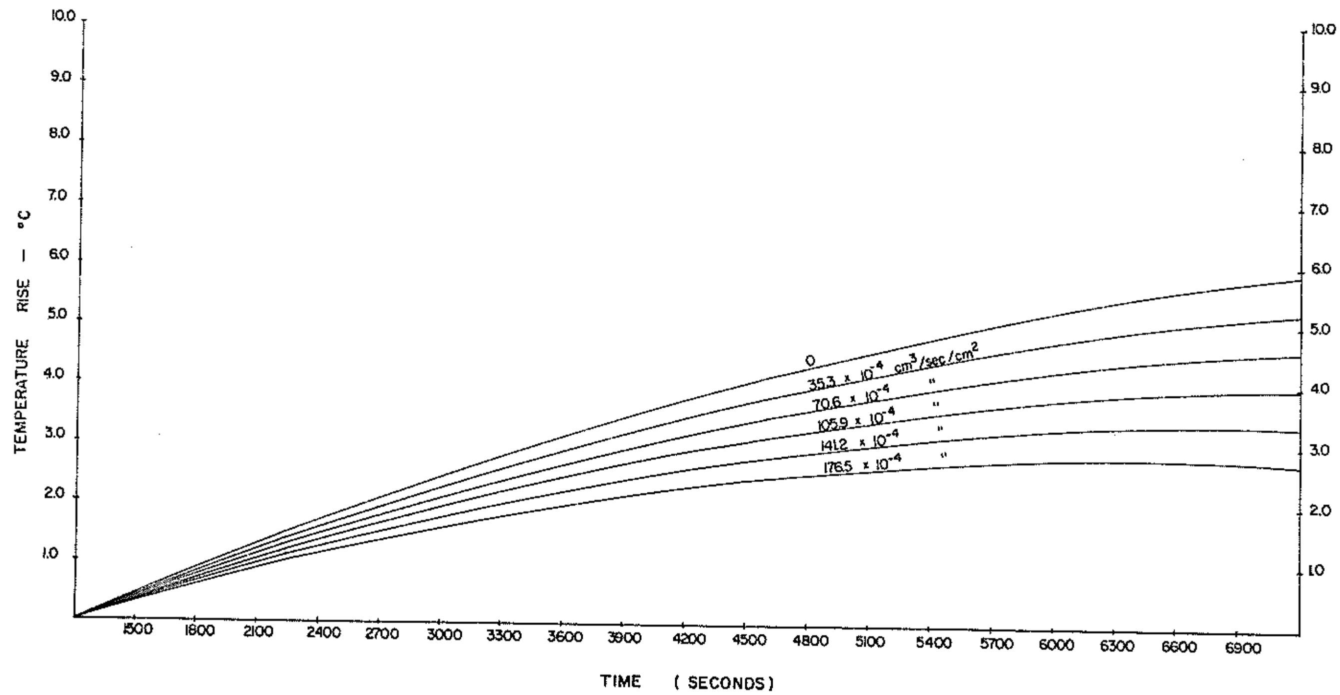

Figure 11. Master curves for uncased borehole

Despite obvious uncertainties, the master curves shown in Figure 11 seem to allow a rather reliable estimate of the expected temperature change of the probe associated with a prescribed change in flow rate. The master curves indicate that the terminal temperature of the probe will decrease about 0.2°C for each $10^{-3}cm^{3}/sec/cm^{2}$ increase in flow rate. If temperature differences of 0.1°C could be detected at the end of a two hour test, the probe would be capable of resolving differences of $5 \cdot 10^{-4}cm^{3}/sec/cm^{2}$ in flow rates. For a sandstone with a porosity of 25%, differences of $2 \cdot 10^{-3}$cm/sec(172.8 cm/day) in the velocity of water flow through the pores of the rock could then be detected.

SUMMARY AND CONCLUSIONS

For the past two years we have been investigating a thermal instrument which we believe may have the potential of estimating the horizontal component of the rate of flow of groundwater. Considerable time has been invested in the construction of the thermal probe and the calibration tank, both previously described. We believe that the laboratory calibration of the instrument, in order to experimentally estimate its actual capabilities, has been an original endeavor. The theoretical solutions to our problem have left many unanswered questions. Hopefully, the data obtained in the laboratory calibration of the instrument will provide a more accurate and logical basis for data obtained in the field: i.e., we will attempt to estimate flow rates at different field sites by comparing curves obtained in the field with curves obtained in the laboratory for known flow rates.

Because of the considerable experimental problems involved in the calibration of the instrument, much of the data overlap and are of questionable value. However, we have obtained eight experimental curves which follow quite well the sequence expected for the corresponding changes in flow rates. With increased experimental knowledge and technique, we believe that most of the calibration curves will follow the proper sequence.

By fitting a second order polynomial to the eight best experimental curves, we have attempted to acquire a set of master curves. The polynomial fitting has probably smoothed out much of the experimental data and has allowed each predicted master curve to be based upon all of the best available data. Ultimately, the polynomial fitting may be the best approach in acquiring master curves; however, the value of the curves derived by fitting is directly related to the quality of the original experimental data. If temperature differences of 0.1°C can be experimentally measured after 2 hours, then it would appear that the probe will be able to distinguish differences in flow rates of $5x10^{-4} cm^3/sec/cm^2$.

STUDENTS ON THE PROJECT

1. Thomas Croxell - M.S. in Geophysics, Dec. 1972

   Mr. Croxell was a one-half time research assistant on this project from July 1, 1971 to December 30, 1972. His Independent Study, a requirement for the M.S. degree, was written on the thermal probe.

2. Mark Dee - M.S. in Geophysics, May 1973

   Mr. Dee was a one-quarter time research assistant on this project from September 1, 1972 to May 20, 1973.

3. Rodger Smith - M.S. in Geophysics scheduled for completion Dec. 1973

   Mr. Smith was a one-quarter time research assistant on this project from January 1, 1973 through June 30, 1973.

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