UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

A HEAT-PULSE FLOWMETER FOR MEASURING LOW VELOCITIES IN BOREHOLES

By Alfred E. Hess

Open-File Report 82-699

Denver, Colorado

1982

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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A HEAT-PULSE FLOWMETER FOR MEASURING LOW VELOCITIES IN BOREHOLES

By Alfred E. Hess

ABSTRACT

The U.S. Geological Survey has tested a borehole-configured heat-pulse flowmeter which has good low-velocity flow-measuring sensitivity. The flowmeter was tested in the laboratory in 51-, 102-, and 152-millimeter-diameter columns using water velocities ranging from 0.35 to 250 millimeters per second. The heat-pulse flowmeter also was tested in a 15-meter-deep granite test pit with controlled water flow, and in a 58-meter-deep borehole in sedimentary materials. The flowmeter's capability to detect and measure naturally occurring, low-velocity, thermally induced convection currents in boreholes was demonstrated. Further improvements to the heat-pulse-flowmeter system are needed to increase its reliability and improve its response through four-conductor logging cable.

INTRODUCTION

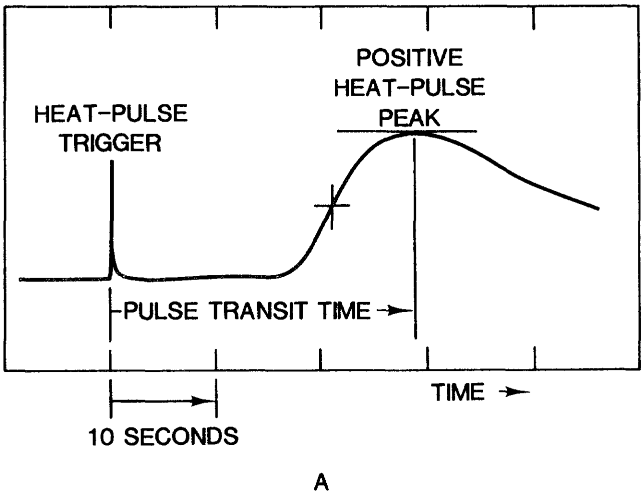
Hydrogeologists have long expressed a need for an easy-to-use, non-polluting, low-velocity borehole flowmeter to complement the conventional spinner flowmeter. Many spinner flowmeters can measure vertical water velocities of 50 mm/s (millimeters per second) and greater, and some carefully designed spinners are reported to have stall speeds as low as 10 to 15 mm/s. By trolling them at carefully regulated speeds, flow velocities of 5 or 10 mm/s may be measured.

Flow velocities less than 5 mm/s may be measured by using tracer techniques. Those most commonly used in borehole logging are the radioactive-tracer, gamma-ray detector technique as described by Bird and Dempsey (1955) and by Edwards and Holter (1962), and the salt-brine tracer, fluid-resistivity detector described by Patten and Bennett (1962) and by Keys and MacCary (1971). These tracer techniques are capable of measuring flow velocities of a few meters per day. However, the use of radioactive solutions in water wells is now subject to strict regulation, and brine injection is useful only in freshwater. High-resolution temperature logs are useful to help locate the entrance and exit of water in a borehole, but they give semiquantitative flow information at best.

THE HEAT-PULSE FLOWMETER

The U.S. Geological Survey has obtained and tested the WRC-type, heat-pulse flowmeter shown in figure 1. The heat-pulse flowmeter was manufactured by Wuidart Engineering Limited,[1/] Clifton Road, Shefford, Beds, SG17 5AB, England. To operate the flowmeter, a 1-millisecond pulse of electric current is triggered to flow through, and thus to heat, the wire-heater grid. This heats a sheet of water which is carried by the water moving through the flow tube past one of the two temperature-sensitive thermistors--one is above and the other is below the heater grid. These two thermistors normally are in a balanced thermal-electric bridge which is unbalanced when the heated water passes by one of the thermistors. This unbalanced condition is amplified and recorded on a strip-chart recorder which produces traces as shown in figure 2. Upflowing water produces a positive-pulse trace (fig. 2A) and downflowing water generally produces a negative-pulse trace (fig. 2B). The velocity of the water is a function of the time it takes for the heated sheet of water to travel the 20-mm (millimeter) distance from the heater grid to a thermistor temperature sensor. This period of time is determined from the chart recording by measuring the travel time from the trigger pulse to the thermistor pulse. The time may be measured in several ways. One is to measure the time between the peaks of

1/The use of trade names in this report is for identification only and does not constitute endorsement by the U.S. Geological Survey.



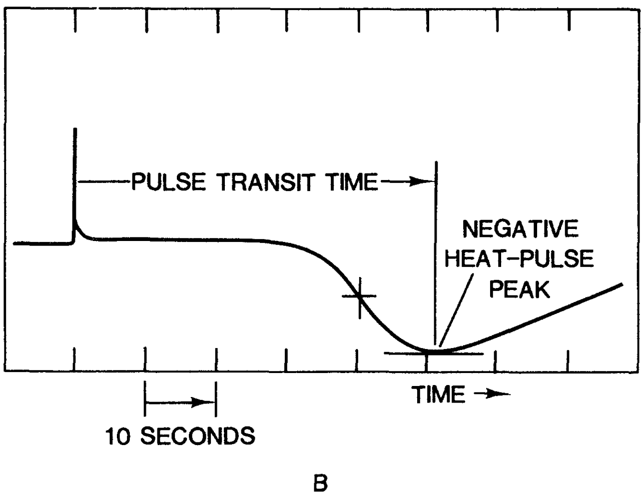


Figure 2. Diagrams showing typical heat-pulse flowmeter response: (A) upflow-pulse response: and (B) downflow-pulse response.

Thermal-flow-sensing techniques can be very sensitive to low-velocity fluid movement. Skibitzke (1955) and Chapman and Robinson (1962) have reported borehole-configured thermal flowmeters which detected flow velocities of 5 mm/s in boreholes. Experiments with heated-surface anemometers show good low-velocity flow resolution in water down to at least 0.3 mm/s. However, anemometers used to measure water velocity have limited use because they are adversely affected by precipitants and small fluctuations in water temperature.

Dudgeon and others (1975) of the Water Research Centre's (WRC) Medmenham Laboratory in England have developed a heat-pulse flowmeter which measures vertical water velocities in boreholes between 1 and 240 mm/s while avoiding some of the problems of thermal flowmeters previously reported. The heat-pulse flowmeters ability to measure low-velocity flow also makes it sensitive to slight flow-disturbing factors such as thermal convection currents and hole rugosity. These factors cause eddies in the fluid that complicate the problem of relating the flow velocity measured by the flowmeter to the average fluid-volume movement across a plane in the borehole.

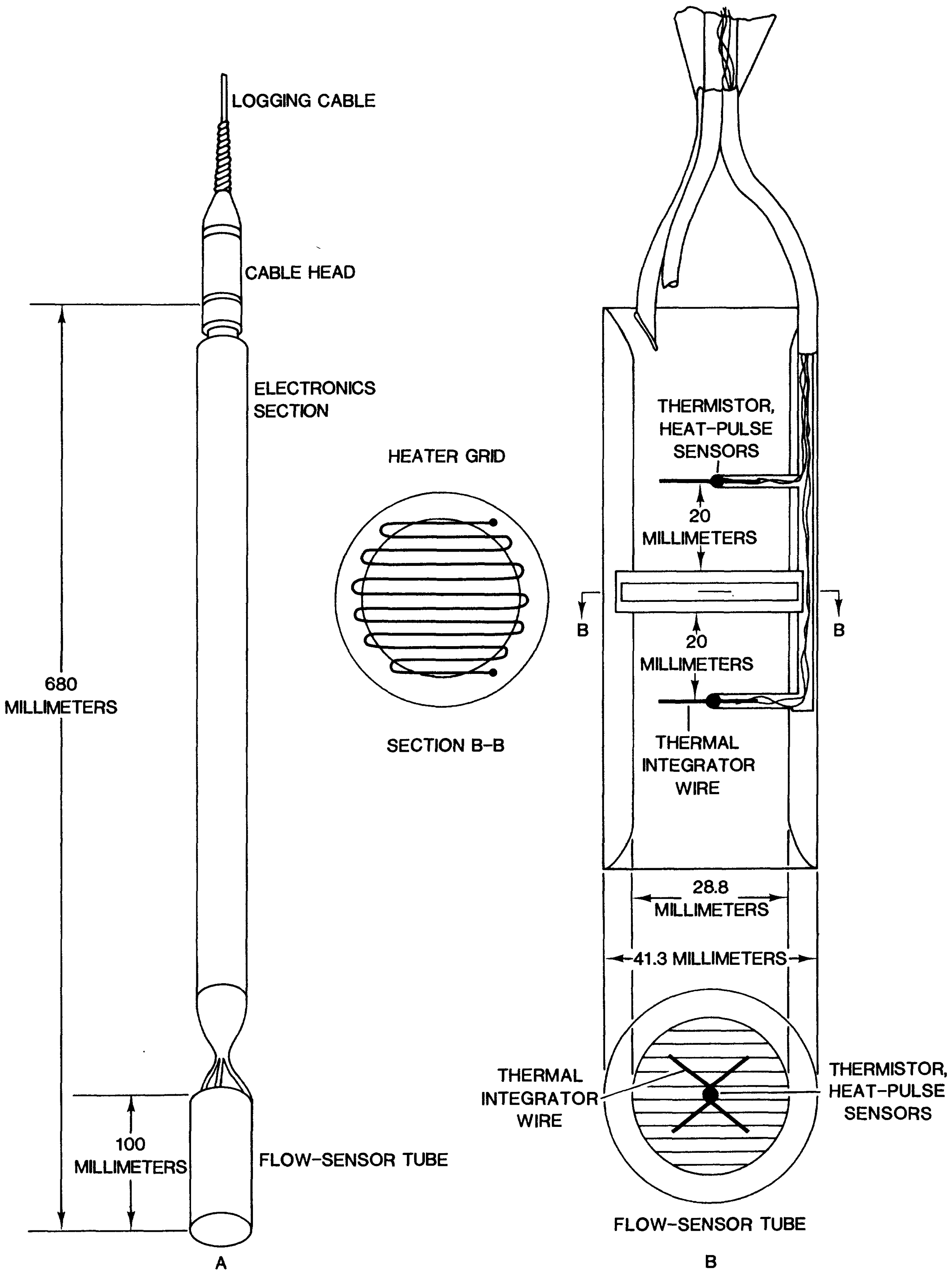


Figure 1. Sketches of heat-pulse flowmeter (A) one-quarter scale, and flow sensor (B) full scale.

the pulses. Other ways might be to measure the time between the half-maximum points of the pulse peaks or between some other fraction of the peak amplitude. Because the peak amplitude varied considerably, and because some of the response records had considerable noise and drift, it was determined that the peak-to-peak technique gave the best repeatability under the circumstances and it was used throughout the study.

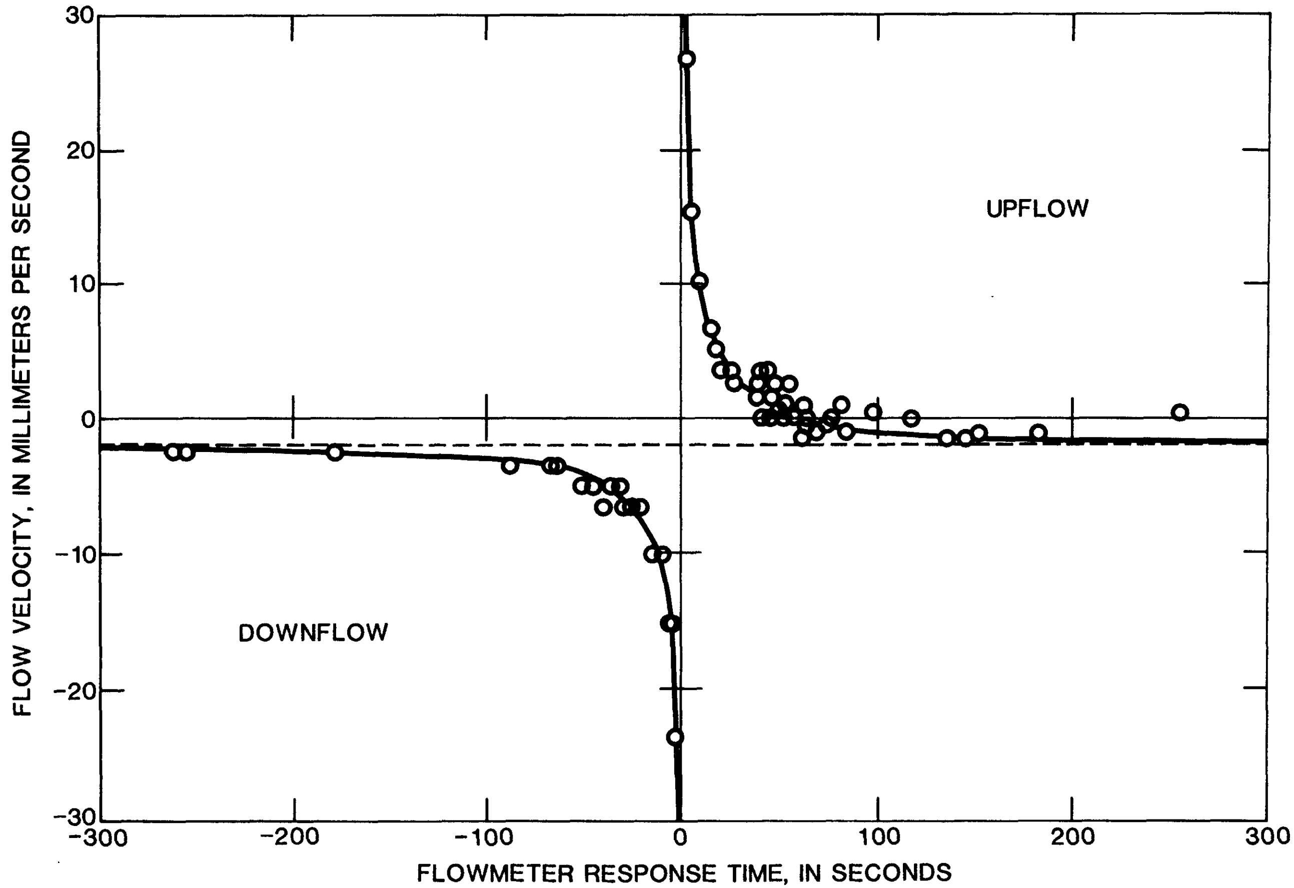


Figure 3. Graph showing calibration of heat-pulse flowmeter in a 152-millimeter-diameter column using time for the horizontal coordinate.

If the water velocity through the flow-sensor tube was the same as the average water velocity in the borehole, no further flowmeter calibration would be needed. However, the flow of the water in the tube is impeded by viscous drag on the heat grid, the thermistor and mounting posts, the tube supports, and the wall of the tube. Further, the heated sheet of water tends to rise and causes a small but measurable upflow bias. This bias, plus the nonsymmetrical construction of the probe housing and flow-sensor tube, causes the flow-calibration curves, one set of which is shown in figure 3, to be somewhat asymmetric. (The use of the negative time notation in the figures will be explained later.)

A simplified function diagram of the WRC heat-pulse-flowmeter system is shown in figure 4. The flowmeter probe consists of a flow-sensor tube below and the probe electronics above. The probe is mechanically and electrically connected to equipment at the surface by a four-conductor logging cable. The surface equipment provides power and trigger pulses to the probe and receives and conditions the converted thermal pulses from the probe. A strip-chart recorder makes a permanent record of the pulse response for velocity determinations.

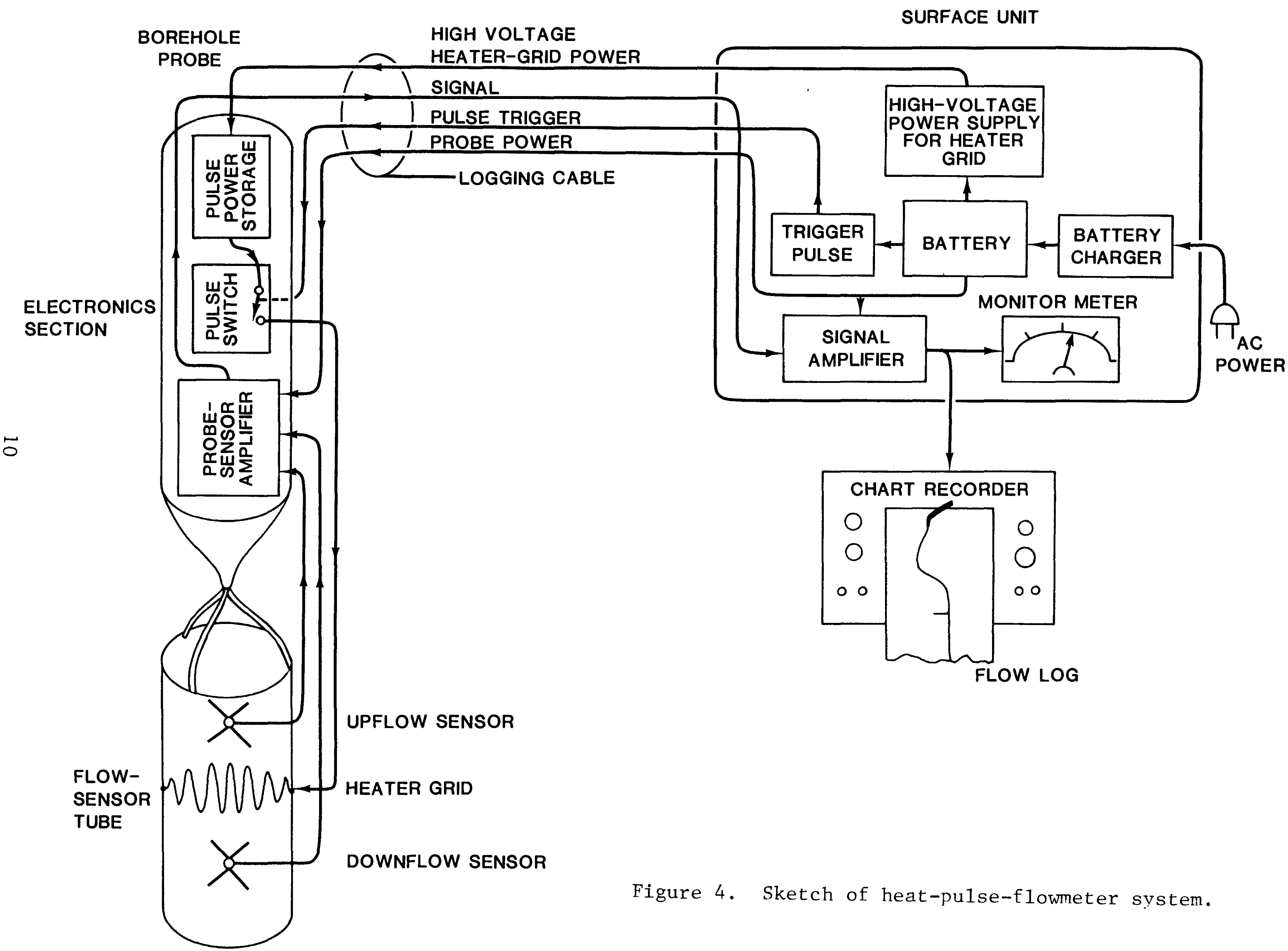


Figure 4. Sketch of heat-pulse-flowmeter system.

WRC gives the following specifications for the heat-pulse flowmeter:

Velocity, upflow: 1 to 240 millimeters per second
downflow: 5 to 240 millimeters per second

Repeatability: 10 percent

Maximum pressure: 3,450 kilopascals

Maximum depth: 350 meters

Diameter, electronics housing: 35 millimeters
flow-sensor tube: 41.3 millimeters

I.D. of flow-sensor tube: 28.8 millimeters

Length, flow-sensor tube: 100 millimeters
overall: 680 millimeters

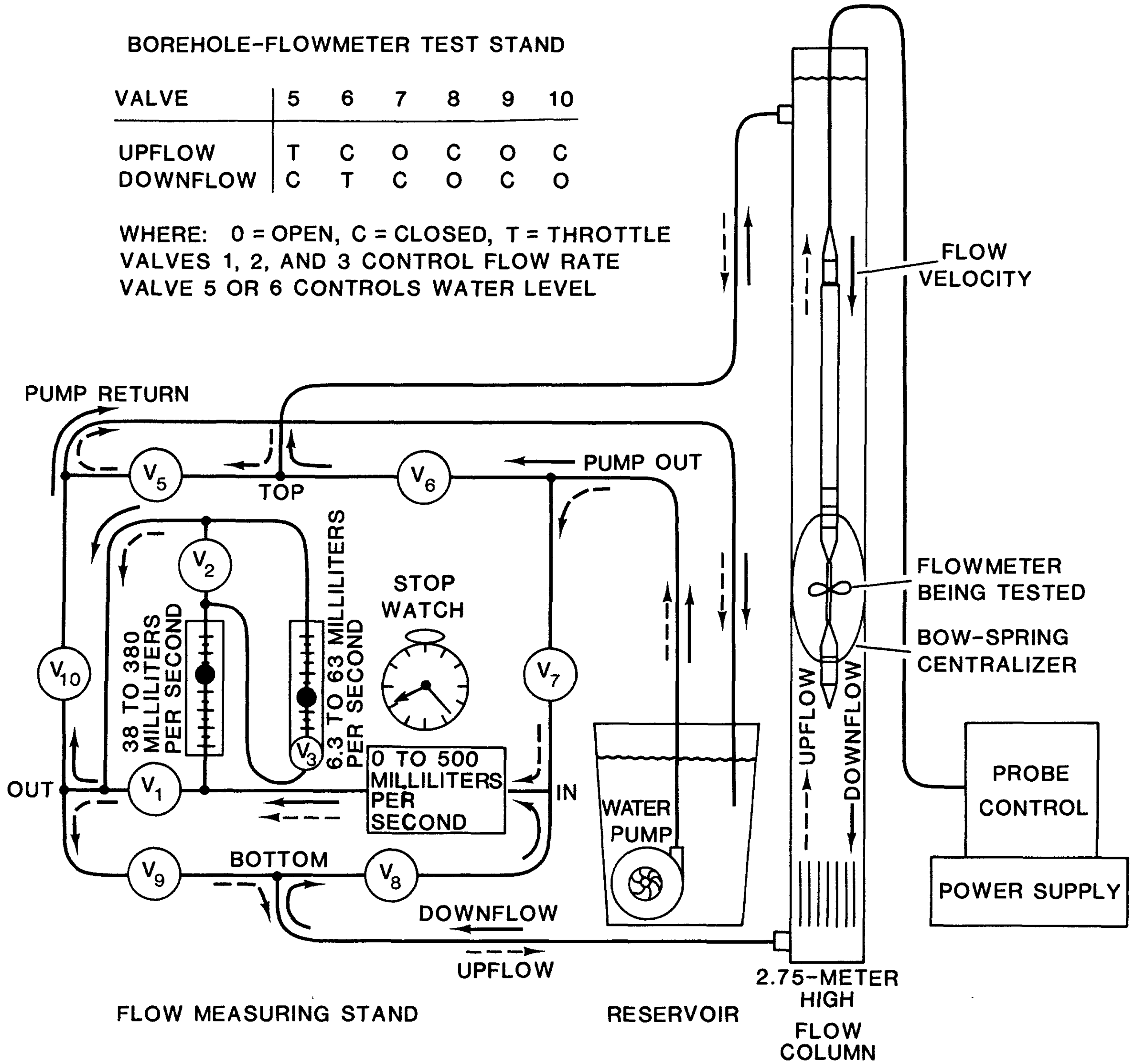
Power required: 28-volt rechargeable battery supply, (120-volt AC, charger included)

Output signal: 0 to 80 millivolts (unit tested was 0 to 500 millivolts)

External probe material: stainless steel

Centralization: user-furnished, external centralizer required

Interconnecting cable: six conductors



COLUMN FLOW VELOCITY (MILLIMETERS PER SECOND) = K x FLOW VOLUME (LITERS PER SECOND)

OR

$$\frac{\text{FLOW VELOCITY}}{\text{FLOW VOLUME}} = \text{FLOW FACTOR (K) (MILLIMETERS PER LITER)}$$

FLOW-COLUMNS			
DIAMETER (MILLIMETERS)	51	102	152
K (MILLIMETERS PER LITER)	507	123	55
VELOCITY RANGE (MILLIMETERS PER SECOND)	3-250	0.75-60	0.35-28

ESTIMATED CALIBRATION UNCERTAINTY: $\pm$(5 PERCENT + 10^{-3}K) (MILLIMETERS PER SECOND)

WATER-TEMPERATURE RANGE: 10° - 40° (CELSIUS)

Figure 5. Sketch of borehole-flowmeter test stand.

The U.S. Geological Survey has made several modifications to the WRC-type flowmeter to stabilize its flow response and to permit its use with four-conductor logging cable (five conductors including armor). A copper-wire spatial "thermal integrator" was attached to the bead thermistors as shown in figure 1B to increase the thermal-sensing area of the thermistor. This averages and smooths the output response. The planes of the thermal integrator and the heater grid are perpendicular to the axis of the flow tube. The voltage of the heater-grid power supply was stabilized so the induced heat pulses would be uniform. The pulse-trigger circuit was revised to eliminate spurious pulse triggering and to permit the trigger pulse to share the heater-grid power line. The flowmeter was centered with bow-spring centralizers during all tests and measurements.

TEST AND CALIBRATION OF THE HEAT-PULSE FLOWMETER

The heat-pulse flowmeter was tested in the U.S. Geological Survey's flowmeter test facility in Denver, Colorado. A schematic of this facility is shown in figure 5. It consists of three 2.75-m (meter)-high clear plastic columns having inside diameters of 51, 102, and 152 mm. The facility can measure and circulate volume flows of 6.3 to 500 mL/s (milliliters per second). This produces average flow velocities (up or down) ranging from 0.35 to 250 mm/s; 3 to 250 mm/s in the 51-mm-diameter column, 0.75 to 60 mm/s in the 102-mm-diameter column, and 0.35 to 28 mm/s in the 152-mm-diameter column. The limits of uncertainty of measuring the average water velocity in a column with the equipment used is estimated to be $\pm$(5 percent of flow $+10^{-3}$ K) mm/s; where K is a constant for each column and has a value of 507 for the 51-mm-diameter column, 123 for the 102-mm-diameter column, and a value of 55 for the 152-mm-diameter column.

For tests and calibration, the WRC heat-pulse flowmeter was centered in a flow column and water was pumped through the column at the desired flow rate and in the desired direction. The water flow rate, temperature, and flowmeter electronics were allowed to stabilize for at least 5 minutes before recording the flow measurements. Longer stabilizing times were required for the slower flow rates. For example, at a flow rate of 2.5 mm/s it takes about 1,100 seconds (18 minutes) to make one change of water in a 2.75-m-high column. Usually a minimum of three measurements were made at each flow rate. In order to obtain repeatable measurements, at least five flowmeter time periods or 15 minutes, whichever was the lesser, was allowed between measurements to permit the temperature and flow eddies in the flow column to stabilize. (A flowmeter time period is the time from a trigger pulse to a flow response pulse.) At flow rates of 10 mm/s or faster, the measurement recycle time primarily was limited by the 1- to 2-minute recharge time of the thermal-pulse, energy-storage capacitors. This recharge time depends on the charge condition of the battery power supply.

The tap water used in the flow facility was saturated with air, which collected on the flowmeter sensors and caused large variations in flowmeter response. This problem essentially was eliminated by adding a small quantity of wetting agent to the water and allowing it to stand overnight. To decrease the problem of thermal convection currents during calibration, it was necessary to match the temperature of the water to that of the surrounding air as closely as possible, especially for measurements of flow rates between +5 and -5 mm/s. This will be discussed in greater detail in the next section.

A series of measurements was made over the flow-velocity range that was achievable in each of the three columns including zero-velocity flow response. A flowmeter response-time calibration curve for the 152-mm diameter column is shown in figure 3. Average water-column velocity, in millimeters per second, is shown on the vertical coordinate--positive (top) for upflow and negative (bottom) for downflow. The flowmeter pulse-response time in seconds is shown on the horizontal coordinate--positive (right) for upflow response and negative (left) for downflow response.

These hyperbolic-shaped calibration curves are difficult to read accurately near their extremes, and closely related low-velocity points plot at opposite sides of the calibration graph simply because the flow direction changes from up to down at zero velocity. Both of these problems are eliminated by using an inverse time scale for the horizontal coordinate.

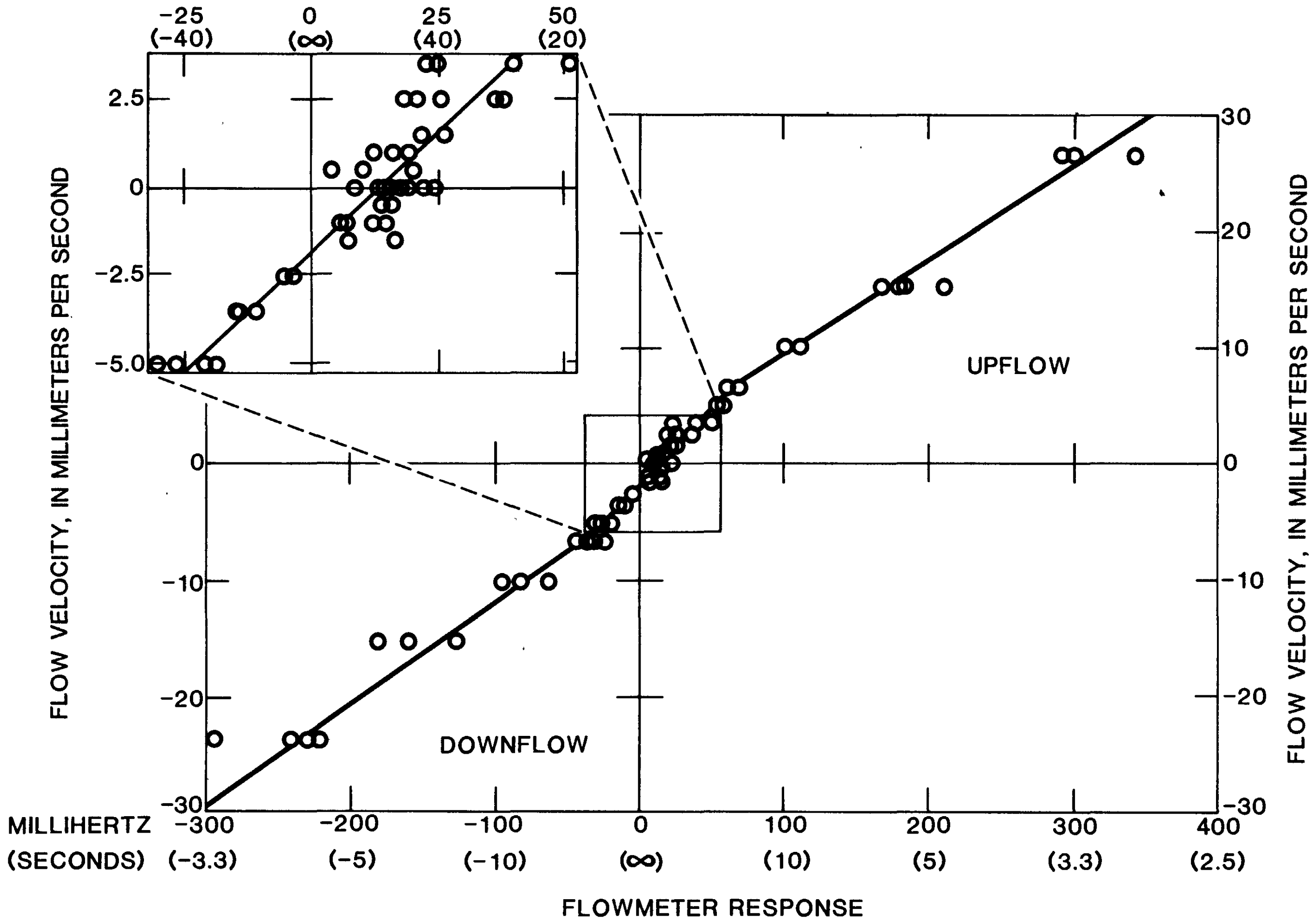


Figure 6. Graph showing calibration of heat-pulse flowmeter in a 152-millimeter-diameter column.

This is illustrated in figure 6 which shows a plot of the same flow-calibration data shown in figure 3 but uses inverse time (1/second=hertz) for the horizontal coordinate. The resultant flowmeter calibration curve is almost a straight line with a relatively smooth transition between upflow and downflow. This follows logically from the expression for velocity, distance per time (millimeters per second) where time is the common denominator. However, this does require the user to calculate the reciprocal of the flow response time, a simple operation for a computer or pocket calculator.

The term hertz (Hz) used in this report is defined as "cycles per second" (s^{-1}). For the heat-pulse flowmeter, the period of a trigger-pulse to thermistor-pulse cycle usually is between 1 and 1,000 seconds which corresponds to an inverse time of between 0.001 and 1 Hz. To simplify the expression of quantities between 0.001 and 1 Hz, the recommended prefix milli (X 0.001) is used with the unit hertz. For example, 25 mHz (millihertz) is equal to 0.025 s^{-1}, which corresponds to 40 seconds. Time (in seconds) is shown in parentheses in the calibration graphs.

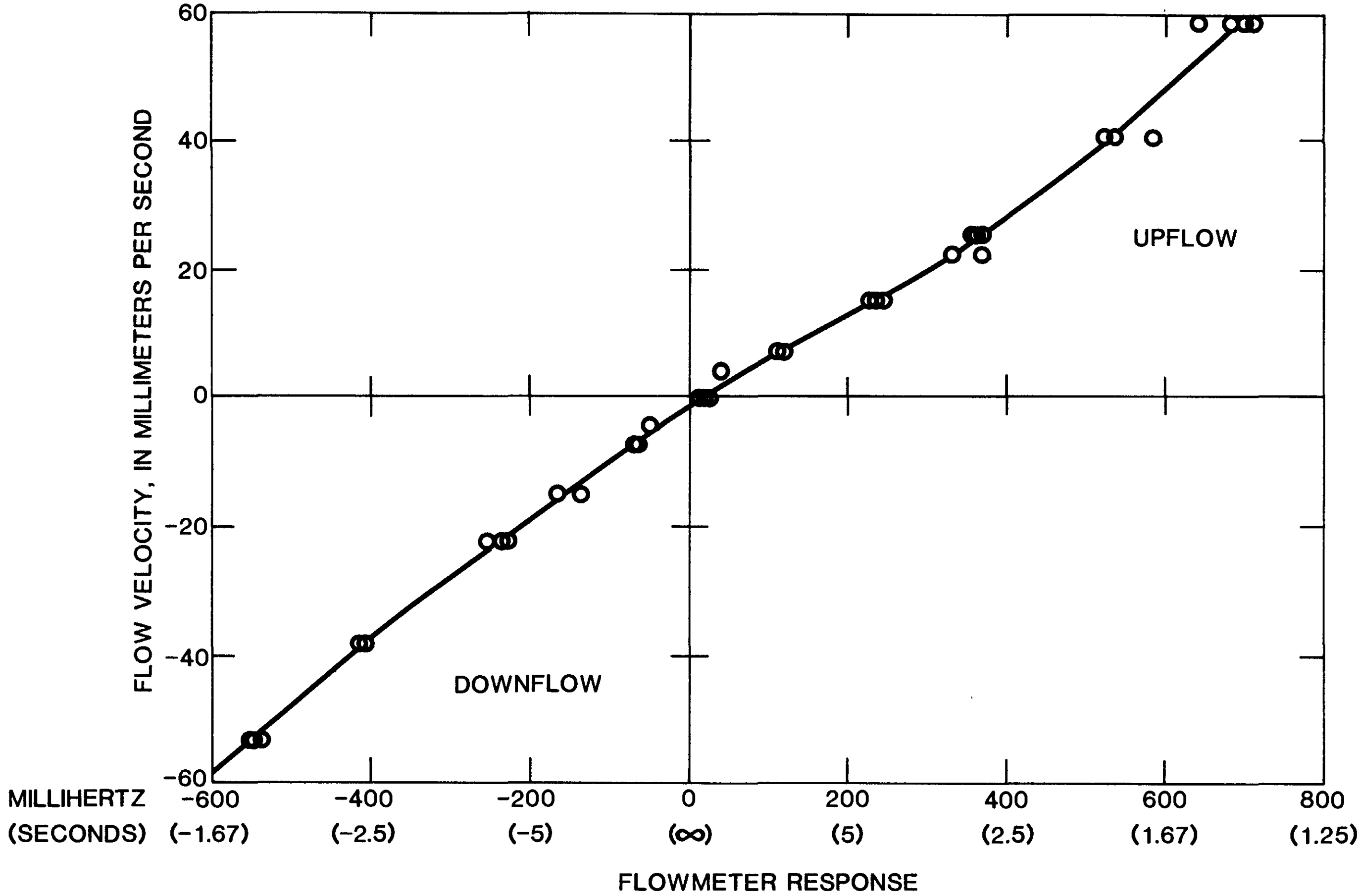


Figure 7. Graph showing calibration of heat-pulse flowmeter in 102-millimeter-diameter column.

A calibration graph of the heat-pulse flowmeter in a 102-mm-diameter column for average water velocities between +60 and -60 mm/s is shown in figure 7, and a calibration of the flowmeter in a 51-mm-diameter column for average water velocities between +230 and -150 mm/s is shown in figure 8. The large nonlinearity of the 51-mm calibration curve is thought to be caused by the combined effects of the 38-mm-diameter flowmeter largely filling the 51-mm-diameter column, and water velocities approaching the minimum pulse-resolution time (about 0.6 second) of the flowmeter. These three calibration charts are combined in a single chart in figure 9 which better shows the relationship between column diameter and flowmeter response to average-flow velocity.

As can be seen in figure 6, most of the flow-calibration points have a positive pulse response for upflow and negative pulse response for downflow. However, a few central points have a positive pulse response in spite of low-velocity downflow in the column. This is because the convective-rise force of the heated sheet of water is slightly greater than the very low downflow force. This phenomenon of positive pulse response in the presence of low average-velocity downflow was rarely observed and had significant measurement variation indicating an unstable condition. The calibration curve in figure 6 generally follows the average of the calibration points. For flow rates faster than +5 and -5 mm/s, the variation of the transit-time measurements was about 10 percent, but between +5 and -5 mm/s the variations were considerably greater.

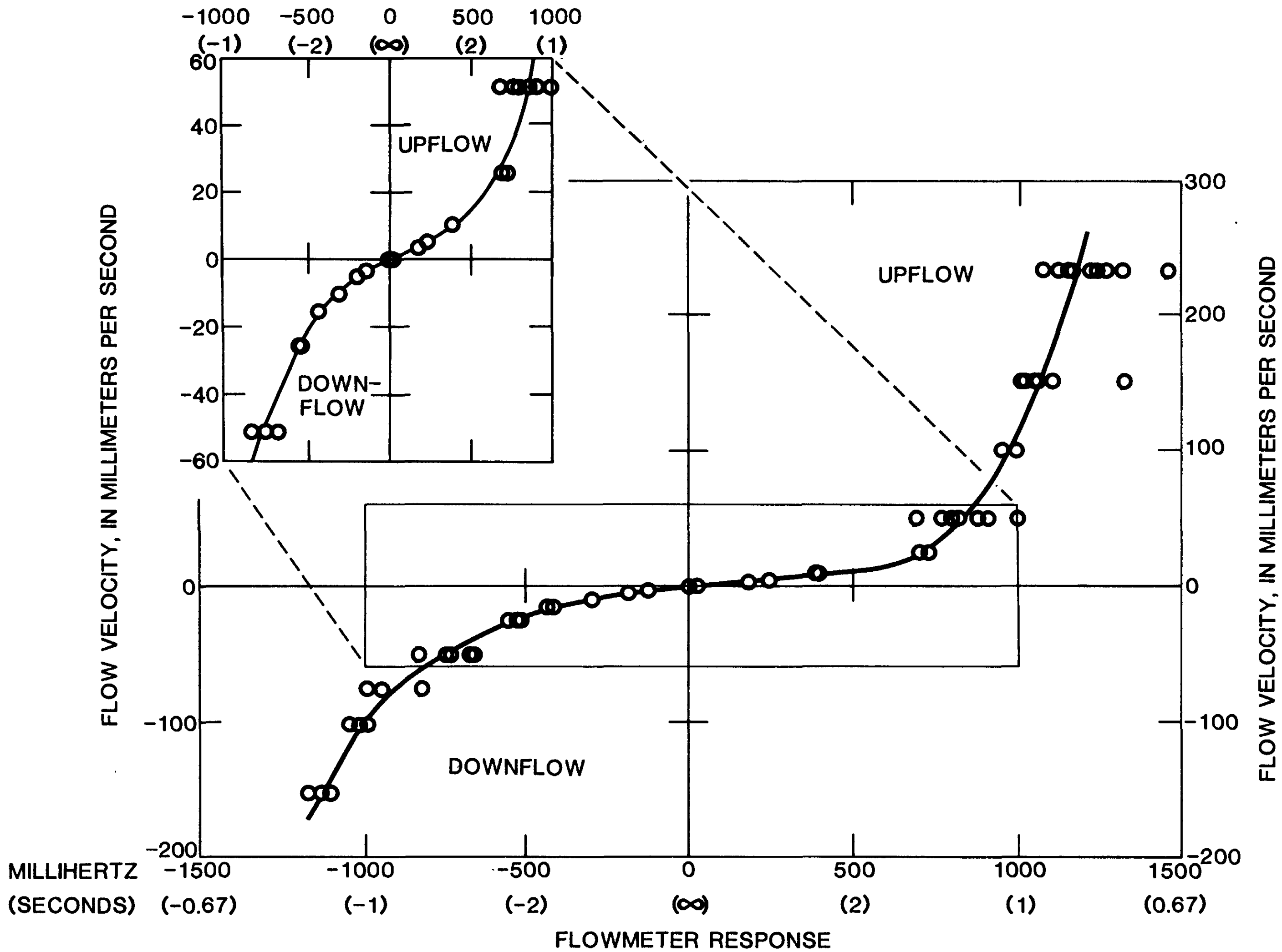


Figure 8. Graph showing calibration of heat-pulse flowmeter in 51-millimeter-diameter column.

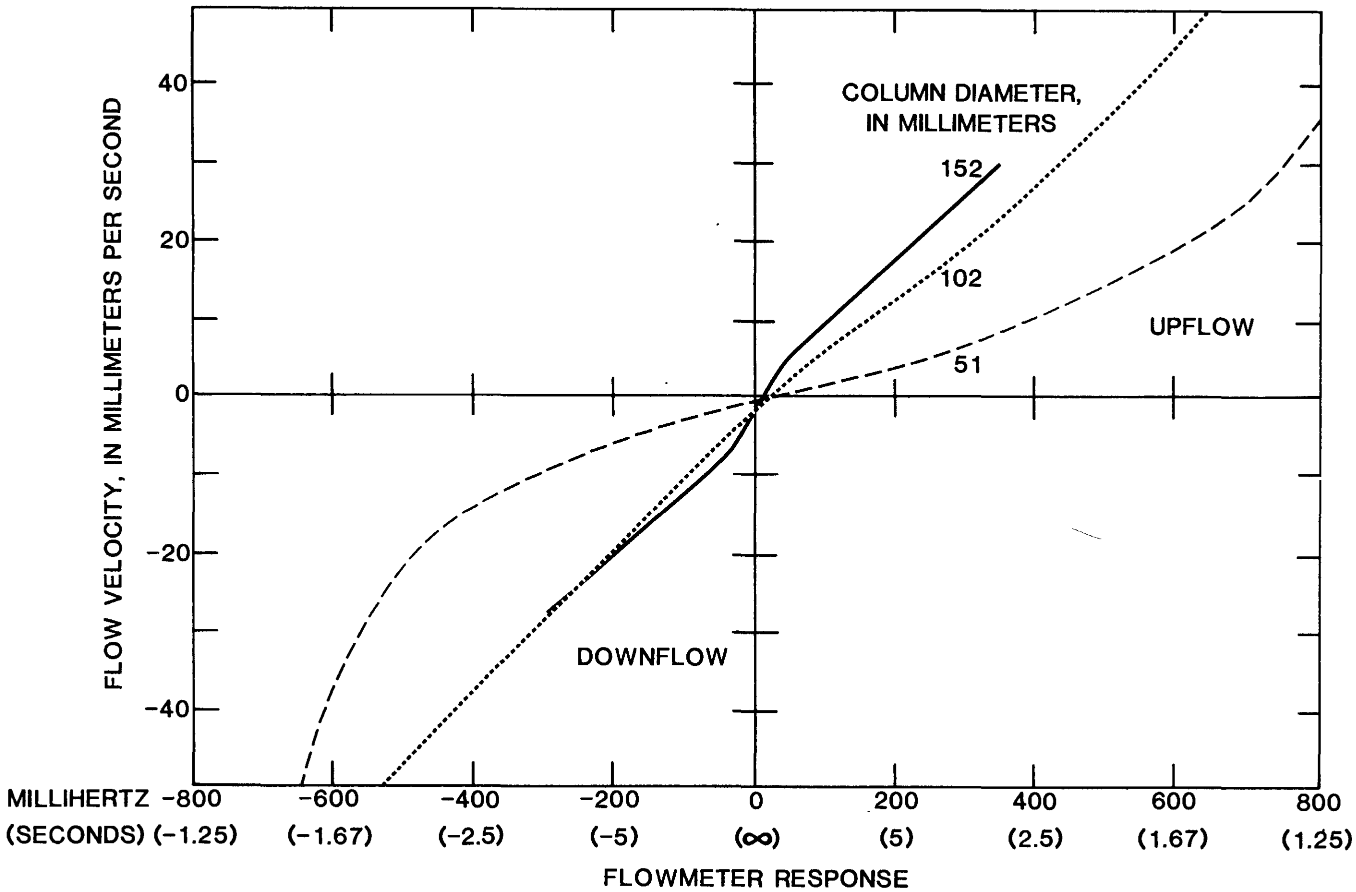


Figure 9. Graph showing combined calibration curves of heat-pulse flowmeter in 51-, 102-, and 152-millimeter-diameter flow columns.

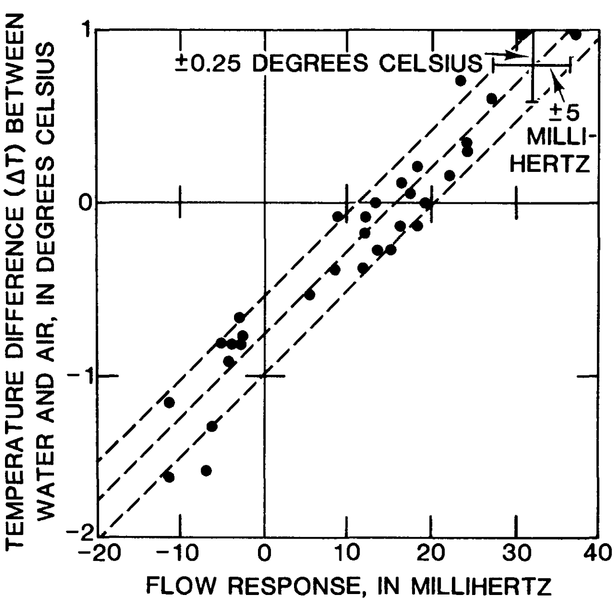


Figure 10. Graph of zero net-flow test of WRC-type, heat-pulse flowmeter in 152-millimeter-diameter column for ΔT between -2° and +1° Celsius.

These large variations may be caused partly by thermally induced convection currents in the column. To test for this possibility, a series of measurements was made with zero net flow through the column while adjusting and noting the temperature difference between the water in the column and the surrounding room air temperature. A plot of the differential water-air temperature versus reciprocal flow-response time in millihertz for the 152-mm-diameter column is shown in figure 10. Notice that a +1°C water-air temperature difference causes about +35 mHz flow response, which corresponds to a midcolumn upflow velocity of about 3 mm/s in the 152-mm-diameter column (fig. 6 insert). A -1°C water-air temperature difference causes about -5 mHz flow response, which corresponds to a midcolumn downflow velocity of about 3 mm/s. Similar, although less pronounced, results were observed in the 102- and 51-mm-diameter columns. Because there is zero net flow through the column, a volume of water observed by the heat-pulse flowmeter to be flowing in the center of the column must be matched by a counterflow along the column wall. A probable cross section of the flow velocity profile caused by thermal convection is shown in figure 11.

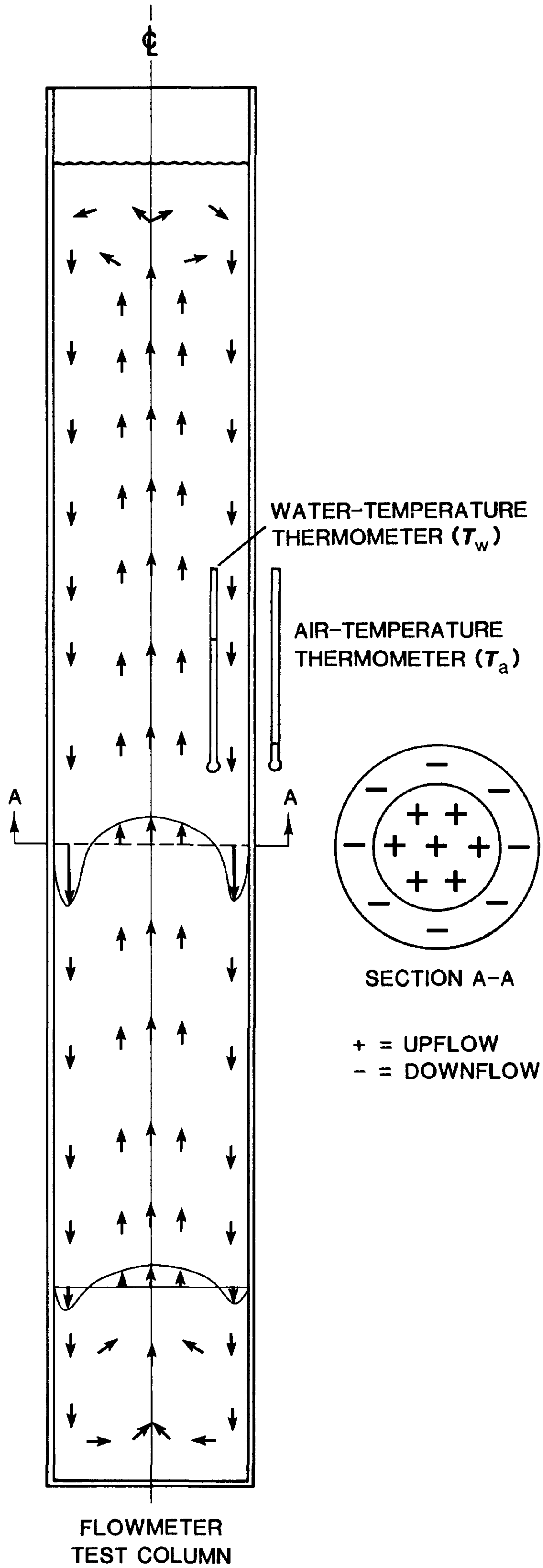


Figure 11. Sketch showing probable cross-section profile of differential temperature-induced convection flow when $T_w > Ta$.

Because of the relatively low thermal conductivity of the 6-mm-thick plastic column pipe and the poor thermal coupling between the air and the plastic pipe, the actual temperature difference between the inner wall of the pipe and the water is only a fraction of the measured water-air difference. This emphasizes what relatively large convection velocities may result from seemingly insignificant water to well-wall temperature differences. Dudgeon and others (1975), developers of the heat-pulse flowmeter, were aware of the thermal-convection flow, but they circumvented the problem during laboratory calibration. Other authors who have observed and studied this phenomenon include Krige (1939), Gretner (1967), Diment (1967), and Sammel (1968).

Thus, the scatter in the data between +5 and -5 mm/s in figure 6 is thought to be largely due to thermal convection currents caused by relatively small, varying, temperature differences between the water and the column wall.

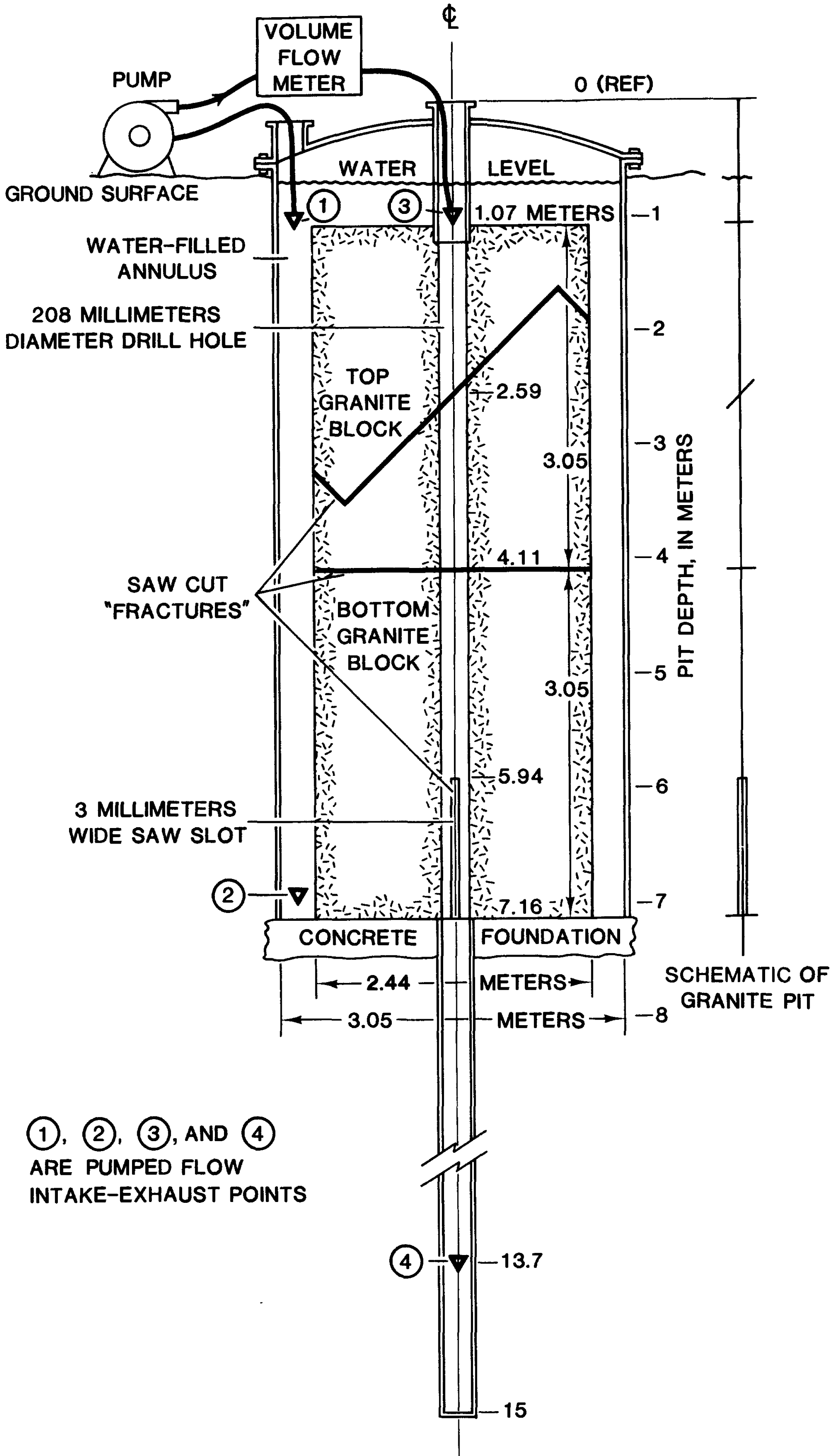


Figure 12. Sketch of granite test pit: two 2.44-meter-diameter by 3.05-meter-high blocks with 208-millimeter-diameter drill hole.

FLOW MEASUREMENTS IN A GRANITE TEST PIT

The heat-pulse flowmeter was tested in a 15-m-deep, 3.05-m-diameter granite test pit (fig. 12). The test pit consists of two 3.05-m-high by 2.44-m-diameter granite blocks stacked one upon the other within a 3.05-m-diameter sealed water-filled pit. A 208-mm-diameter vertical drillhole through the center of the granite blocks is in line with a 9-m-deep plastic pipe sealed "tail hole". The top granite block has a diagonal saw cut to simulate a diagonal fracture plane, and the bottom granite block has a 1.22-m-long by 3-mm-wide vertical saw cut centered on the drillhole to simulate a vertical fracture.

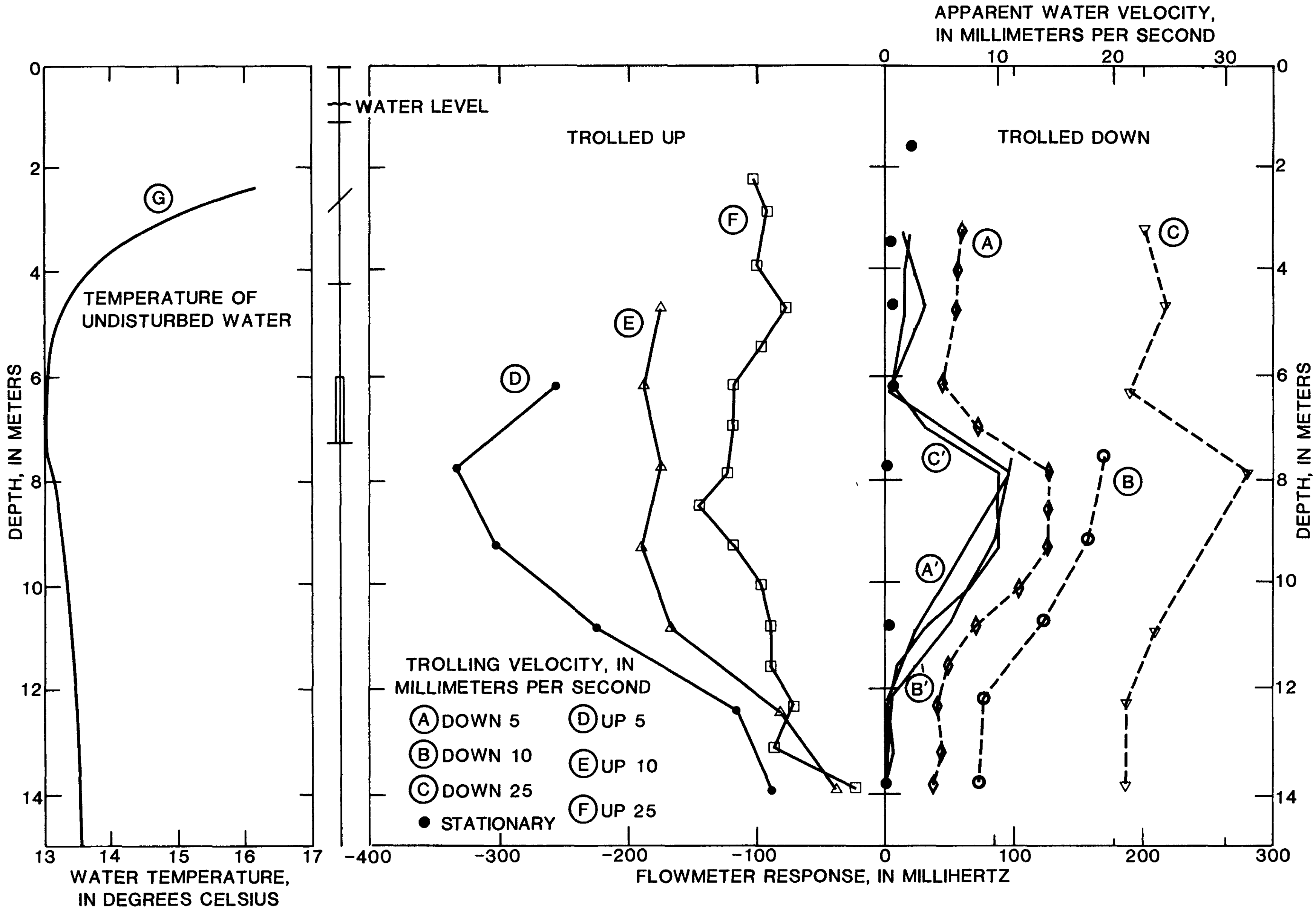


Figure 13. Profiles showing movement of undisturbed water in granite test pit measured with heat-pulse flowmeter.

Water flow was induced through the system by pumping water between two of the four points numbered (1), (2), (3), and (4) in figure 12. The rate of flow was controlled by valves and measured by volume-rate flowmeters. Water-temperature logs were made in the test pit before and during water circulation.

A simplified schematic of the test pit showing fracture positions for reference purposes is shown in figure 13 between the temperature and flowmeter response graphs. A water-temperature log made in the undisturbed water in the test hole is shown as curve (G), and a series of heat-pulse flowmeter response curves are labeled (A) through (F).

The temperature log shows a water-temperature gradient of about -1.6°C/m (degrees Celsius per meter) from 2 to 4 m, nearly zero from 5.8 to 7.3 m, and about +0.13°C/m from 8 to 11 m. Sammel (1968, p. 1005) shows that positive temperature gradients greater than 0.001°C/m in 15°C water in wells that are over 150-mm diameter will cause convection currents. Because the measured temperature gradient is two orders of magnitude larger than this, convection currents are to be expected between 8 and 11 m and possibly lower.

Curves (A), (B), and (C) on the right side of figure 13 are plots of the heat-pulse flowmeter response while trolling down at 5, 10, and 25 mm/s through unpumped water. The flowmeter was centralized within the hole with bow-spring centralizers. All three flowmeter logs show an upflow deflection between the depths of 6.5 and 11.5 m. The actual water velocity, the difference between the velocity measured by the flowmeter and the trolling velocity as shown by curves (A'), (B'), and (C'), is about 10 mm/s between 7.5- and 10-m depth for all three trolling speeds. This depth interval has the greatest positive temperature gradient, which confirms that the water movement in the hole is caused by the large positive temperature gradient. Because the borehole below 7.2 m is a sealed pipe, the observed upflow in the center of the hole must be balanced by an equal volume of downflow along the walls as was shown in figure 11.

Curves (D), (E), and (F) in the center of figure 13 are plots of the flowmeter response while trolling up at 5, 10, and 25 mm/s. The points on these curves have considerable scatter and less clearly show the convective flow in the well. This may be caused by the assymetric construction of the heat-pulse flowmeter probe, as can be seen in figure 1, and to the presence of the logging cable which extends above the flowmeter probe.

To simulate natural flow in a borehole, water was circulated through the borehole between two of the four points shown as (1), (2), (3), and (4) in figure 12 by a surface pump and appropriate pipes. For one series of measurements, water was pumped at 280 mL/s (8 mm/s average flow in the 208-mm-diameter hole) from point (4) at the bottom of the borehole, to point (2) at the bottom of the annulus outside the granite blocks. After circulating at this rate for several hours, a borehole temperature log was made (curve (H), fig. 14). Temperature log (J) was made the following day after further pumped circulation. A positive temperature gradient of about 0.15°C/m remained between 4.5 and 7.5 m depth. Temperature log (G) was made in the undisturbed water a week earlier.

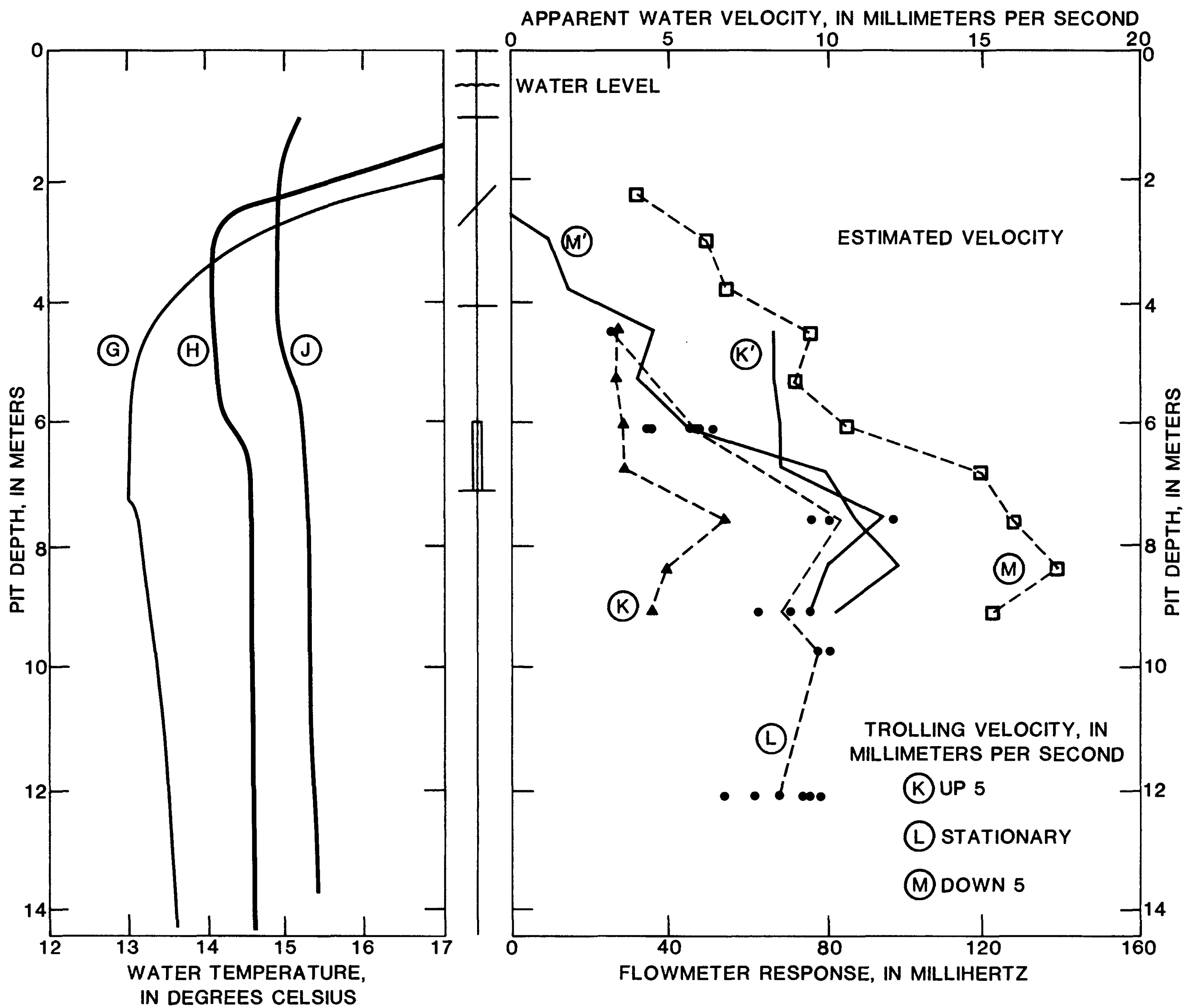


Figure 14. Temperature and velocity profiles of water in granite test pit with an average pumped upflow velocity of 8 millimeters per second below 10 meters.

The heat-pulse flowmeter response to the induced flow is shown by the three logs on the right side of figure 14. Log (K) is trolling up at 5 mm/s, log (L) is with the probe stationary, and log (M) is trolling down at 5 mm/s. When the probe velocity is substracted from the flowmeter response, the three curves generally coincide as shown by curves (K'),(L) and (M'). The upward water velocity is almost constant at 8 mm/s below a depth of 9 m. Above 9 m, the measured water velocity increases to a maximum of about 12 mm/s at about 8 m and then decreases to about 2.5 mm/s above 3 m. The faster center-stream flow at the 8-m depth probably is due to the combined effect of pumped flow and thermal convection caused by the positive temperature gradient of the water. The curves indicate that most of the water flows out through the vertical "fracture" between 5.9 and 7.2 m.

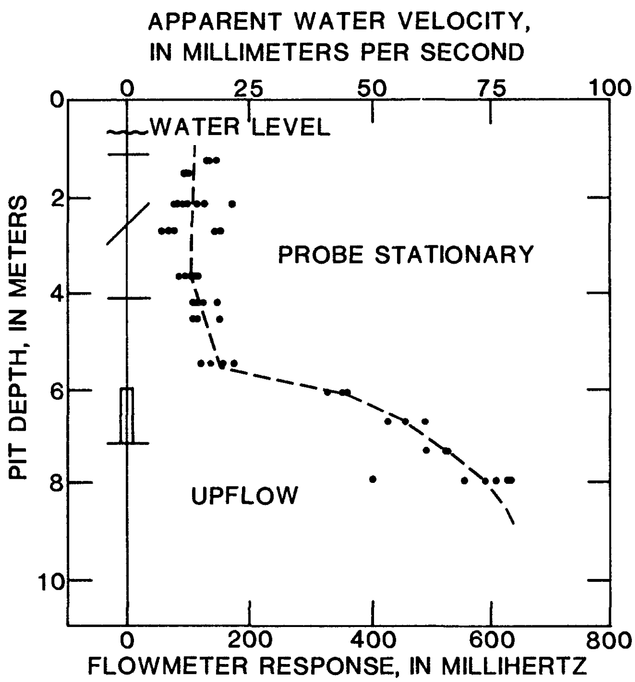


Figure 15. Graph showing flow response in granite test pit with pumped upflow of 83 millimeters per second.

The flowmeter response to upflow of 2.8 L/s (liters per second) between points (4) and (1) of figure 12 is shown in figure 15. This flow rate gives an average water velocity in the drillhole of 83 mm/s, and this is the approximate value measured by the flowmeter below 8 m. As in the previous test, most of the water is lost in the vertical "fracture" at about 6.7 m. Only about 12 mm/s flow is measured above the vertical fracture, and most of this apparently flows over the top of the granite block. Comparatively little flow is through the mid-block horizontal or diagonal fractures.

FLOW MEASUREMENTS IN A 58-METER BOREHOLE

The heat-pulse flowmeter also was tested in a 58-m-deep borehole in sedimentary sand and clay materials. This 152-mm-diameter borehole has about 9 m of surface casing, and the water level was at a depth of 11.6 m (fig. 16). The water temperature increased from 12.8°C at 12 m to 14.7°C at 55 m, giving an average temperature gradient of 0.004°C/m. There was a 0.2°C-temperature increase at 26.5 m.

Both stationary and trolled flow measurements were made in the borehole. The stationary probe readings indicate possible slight upflow. During down-trolling at about 12.5 mm/s, the flowmeter response varied from about 7 to 10 mm/s with an average response of about 8.5 mm/s. Substracting the 12.5 mm/s down-trolling speed from the 8.5 mm/s flowmeter upflow reponse gives a 4 mm/s net apparent downflow. The estimated uncertainty of these measurements is about 2 mm/s. Equipment problems precluded further measurements in this borehole.

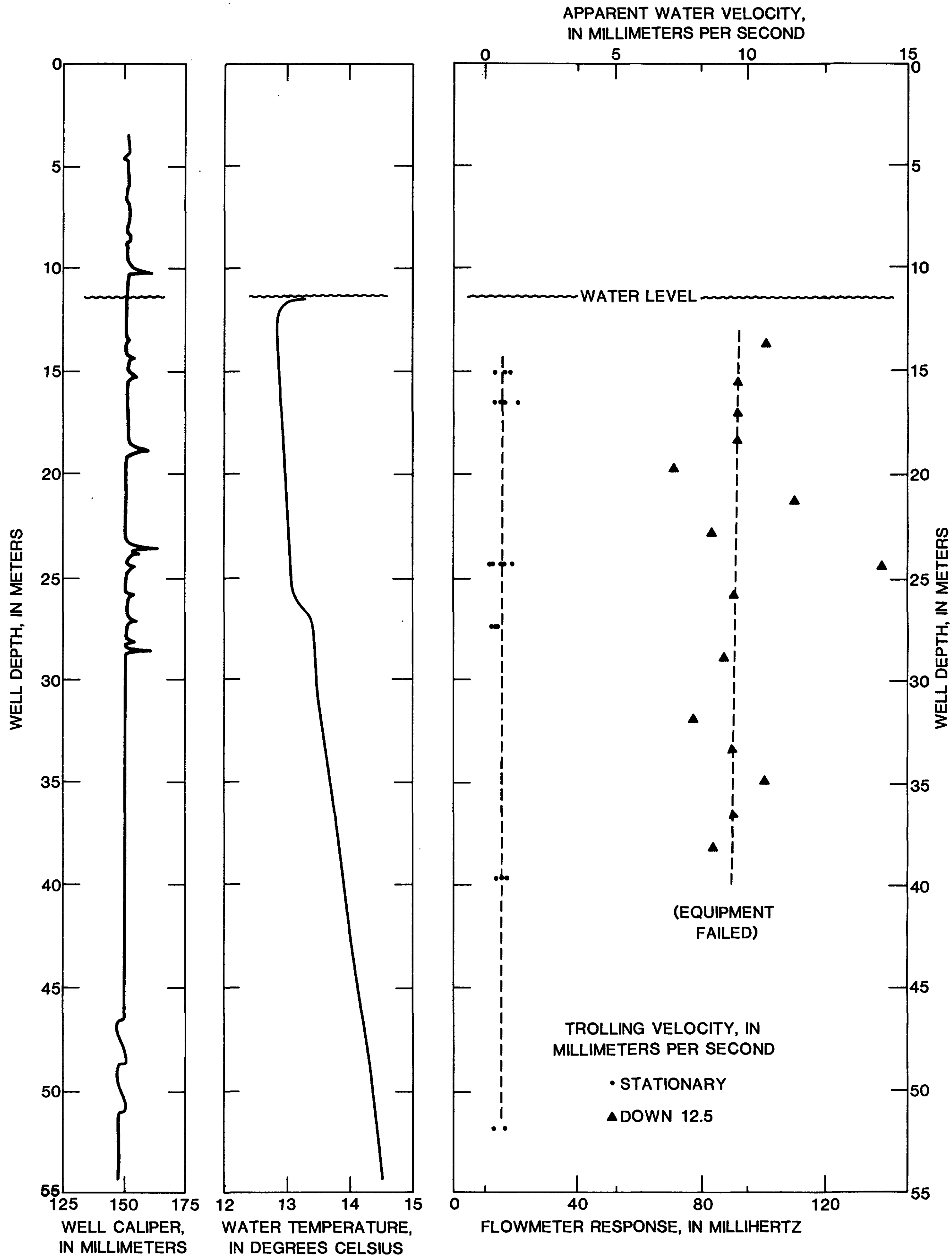


Figure 16. Caliper, temperature and heat-pulse-flowmeter logs in a 58-meter-deep borehole.

CONCLUSIONS

The WRC-type heat-pulse flowmeter is a useful low-velocity complement to the commonly used spinner flowmeter. It can sense water velocities of 0.5 mm/s or less and is usable to measure water velocities as much as 200 mm/s or greater. To aid in the interpretation of low-velocity, borehole-fluid movement, flowmeter logs need to be used in conjunction with a high-resolution temperature log, a fluid-conductivity log, and a borehole-caliper log. When interpreting low-velocity flow measurements, the possible presence and effect of thermally induced convection currents need to be considered.

The relatively large variations in the heat-pulse-flowmeter response at low-flow velocity, noticeable between +5 and -5 mm/s, probably is due to a combination of several factors, some related to the flowmeter and others related to the nature and environment of the fluid stream being measured. The presence of the flowmeter in the flow stream certainly perturbs the fluid movement to some extent. There probably are slight variations in the magnitude of the thermal-energy pulses produced by the heat-pulse flowmeter that can be decreased by further improvements in the flowmeter design. There also may be inherent variations in the movement of the fluid stream caused by irregularites in the borehole wall and by slight variations in the thermal-energy gradients in the rock adjacent to the borehole. The sensing of these small fluid-stream fluctuations may be a consequence of the very low velocity sensitivity of the heat-pulse flowmeter and may best be smoothed out by averaging many measurements.

Further improvements to the U.S. Geological Survey's heat-pulse-flowmeter system are needed to increase its reliability and to improve its response through a four-conductor logging cable for logging deeper boreholes. A probe that can measure very small differences in temperature between the center-hole water and the borehole-wall surface would be useful in evaluating the presence of thermal driving forces and, thus, of possible convection currents and flow eddies.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of R. E. Hodges, D. J. Yarrington, R. Osterburg, and D. Wickland in making the measurements.

REFERENCES CITED

Bird, J. R., and Dempsey, J. C., 1955, The use of radioactive tracer surveys in water-injection wells: Kentucky Geological Survey Special Publication 8, p. 44-54.

Chapman, H.T., and Robinson, A. E., 1962, A thermal flowmeter for measuring velocity of flow in a well: U.S. Geological Survey Water-Supply Paper 1544-E, 12 p.

Diment, W. H., 1967, Thermal regime of a large diameter borehole; instability of the water column and comparison of air- and water-filled conditions: Geophysics, v. 32, no. 4, p. 720-726.

Dudgeon, M. E., Green, M. J., and Smedmore, W. J., 1975, Heat-pulse flowmeter for boreholes: Water Research Centre, Medmenham, Marlow, Bucks, England, Technical Report TR-4, March, 69 p.

Edwards, J. M., and Holter, E. L., 1962, Applications of a subsurface solid-state isotope injector to nuclear-tracer survey methods: Journal of Petroleum Technology, v. 14, p. 121-124.

Gretner, P. E., 1967, On the thermal instability of large diameter wells--An observational report: Geophysics, v. 32, no. 4, p. 727-738.

Keys, W. S., and MacCary, L. M., 1971, Application of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, chapter E1, p. 109-114.

Krige, L. J., 1939, Borehole temperatures in the Transvaal and Orange Free State: Royal Society, London, England, Proceedings, ser. A, v. 173, p. 450-474.

Patten, E. R., and Bennett, G. D., 1962, Methods of flow measurement in well bores: U.S. Geological Survey Water-Supply Paper 1544-C, 28 p.

Sammel, E. A., 1968, Convective flow and its effect on temperature logging in small diameter wells: Geophysics, v. 33, no. 6, p. 1004-1012.

Skibitzke, H. E., 1955, Electronic flowmeter: U.S. Patent no. 2,728,225.

GPO 837-436