THERMAL-PULSE FLOWMETER FOR MEASURING SLOW WATER VELOCITIES IN BOREHOLES

By A.E. Hess

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.40	millimeter
inch per minute (in./min)	0.4233	millimeter per second
foot (ft)	0.3048	meter
foot per minute (ft/min)	0.3048	meter per minute
gallon per minute (gal/min)	0.06309	liter per second

Degree Fahrenheit (°F) may be converted to degree Celsius (°C) with the following equation:

$$°C = (5/9)(°F-32)$$

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) with the following equation:

$$°F = (9/5)(°C)+32$$

Other unit abbreviations used in the report are:

microsecond (μs)
second (s)
minute (min)
kilohertz (kHz)
volt (V)

THERMAL-PULSE FLOWMETER FOR MEASURING SLOW WATER VELOCITIES IN BOREHOLES

By A.E. Hess

ABSTRACT

The U.S. Geological Survey has developed an all electronic, thermal-pulse flowmeter for measuring slow axial-velocities of water in boreholes. The flowmeter has no moving parts, but senses the movement of water (or any other fluid) by a thermal-tag/trace-time technique. In the configuration shown in this report the flowmeter can measure water velocities ranging between about 0.1 to 20 feet per minute, can resolve water velocity differences as small as 0.03 foot per minute, and distinguishes between upward and downward flow. Two diameters of interchangeable flow sensors are described; the smaller sensor is 1.75 inches in diameter including the collapsed centralizer and the larger is 2.75 inches in diameter with collapsed centralizer. The flowmeter probe is 48 inches long and has been tested and used in tubes and boreholes with diameters ranging from 2 to 10 inches. The flowmeter also should be useful in measuring slow velocity flow in larger diameter boreholes, though for best accuracy it should to be calibrated for flow at the diameter of the borehole in which it is to be used. The flowmeter probe has been designed to withstand a water pressure depth of 10,000 feet.

The report includes a description of the operation of the flowmeter, functional diagrams, mechanical drawings, and electronic schematics for both the flowmeter probe and surface electronics. Lists of parts and materials, and instructions for fabrication, assembly, and calibration also are included. These diagrams and lists should be adequate to permit the construction and use of a thermal-pulse flowmeter system by those skilled in machining and fabrication, electronics fabrication, and borehole metrology.

INTRODUCTION

Hydrogeologists commonly use borehole flowmeter logs to obtain profiles of water movement in boreholes under both normal and induced-flow (pumped) conditions to help evaluate the permeability, storage capacity, and other hydrologic properties of the adjacent formations. Most flowmeters can measure flow velocities equal to or faster than 6 ft/min in boreholes with a diameter equal to or larger than 4 in., and some flowmeters have been designed with a stall velocity as slow as 2 ft/min. However, flowmeters that can measure flows much slower than 2 ft/min are needed to adequately characterize the hydrology of many formations studied.

Fluid-tracer techniques have been reported that measure velocities as slow as a few feet per day. Those techniques most commonly used in borehole logging are the radioactive-tracer/gamma-ray detector technique described by Bird and Dempsey (1955) and Edwards and Holter (1962); and the brine-tracer/fluid-resistivity detector techniques described by Patten and Bennett (1962) and Keys and MacCary (1971). However, these techniques are slow and tedious, and they can be used only under stringent conditions. Also, the density difference between the injected tracer fluid and the borehole fluid causes uncertainies in the measurement of the slower velocities that may exceed the velocity of the fluid measured.

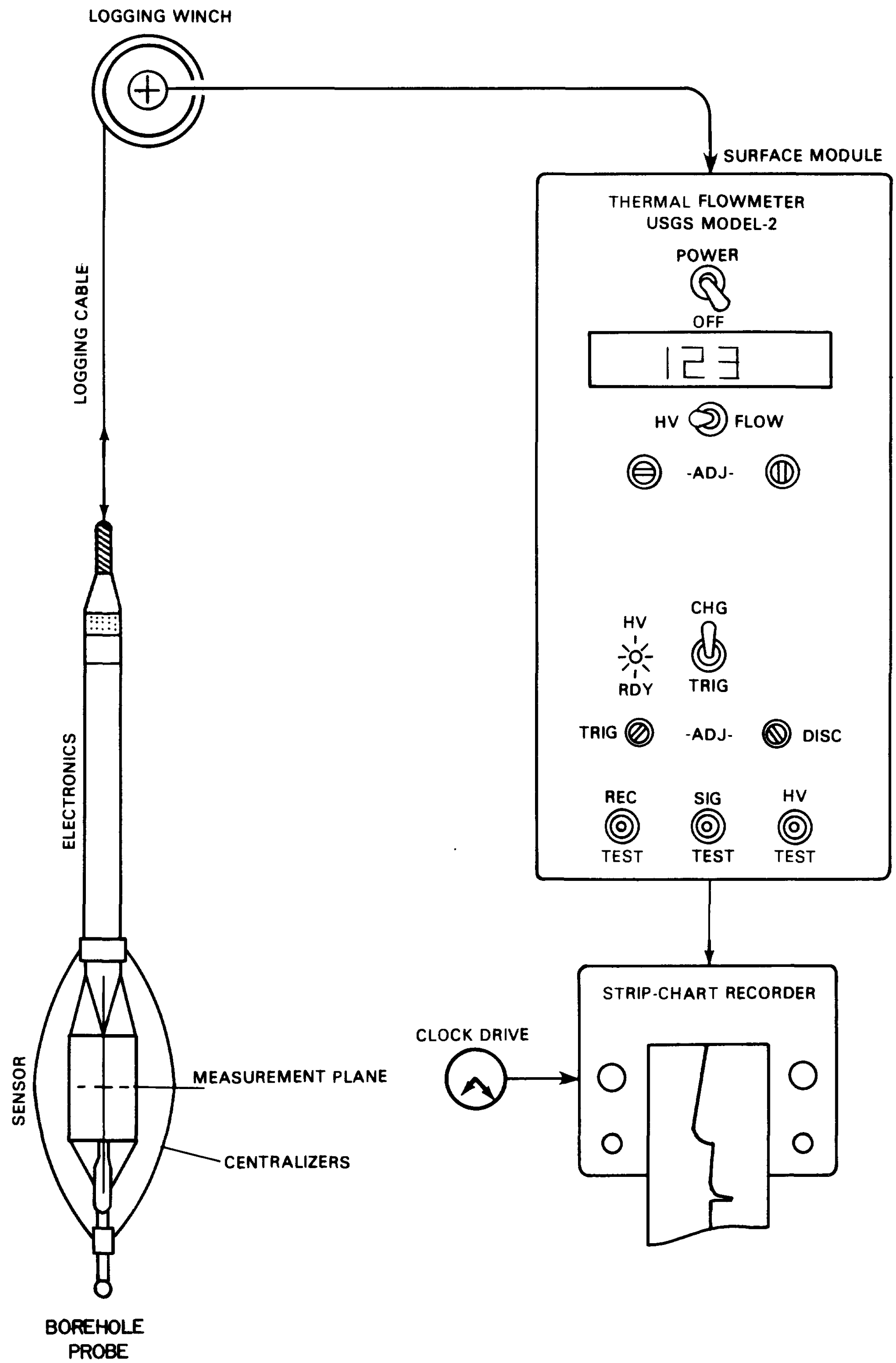


Figure 1. U.S. Geological Survey thermal-pulse flowmeter system.

Fluid-temperature and fluid-resistivity (or conductivity) logs are useful in locating the entrance and exit of contrasting fluids in a borehole, but they provide little quantitative information relating to the velocity or volume of flow. Gas anemometers and other continuous heat-transfer techniques have been tried for measuring water velocities (Skibitzke 1955, Chapman and Robinson 1962, and Morrow and Kline 1971). Some of these instruments were sensitive to slow flow, but this experimenter determined that the calibration changed so rapidly because of fouling of the sensing surfaces with substances such as mud, lint, gas bubbles, and mineral deposits so that these instruments could not be relied upon as quantitative flowmeters under normal borehole conditions.

A heat-pulse borehole flowmeter was developed by Dudgeon and others (1975) using a thermal-tag/trace-time principle that measures slow velocities while avoiding most of the problems of anemometer-type flowmeters. After evaluating the design of this heat-pulse flowmeter (Hess, 1982), the U.S. Geological Survey developed an improved thermal-pulse flowmeter probe that can operate on a standard four-conductor logging cable in deep boreholes (Hess, 1986). The probe has been designed to withstand water pressure to depths of at least 10,000 ft. Measurements made with the thermal-pulse flowmeter are unaffected by cable length and cable resistance or by electrical ground currents that usually exist in areas that are served by public utility lines. The Survey's thermal-pulse flowmeter system has been designed to be both mechanically rugged and field serviceable. The probe centralizer is an integral part of the flowmeter design, but it may be readily adjusted or reconfigured to suit particular borehole conditions. The surface electronics of the U.S. Geological Survey's flowmeter was built into a double width nuclear instrument module and received its power from a frame that physically supports and powers several modules; although with the addition of a suitable power supply the module could be operated directly from an alternating-current power source, or from a battery. The thermal-pulse flowmeter system consisting of the flowmeter probe, surface module, and clock-driven strip-chart recorder is shown in figure 1.

The thermal-pulse flowmeter described in this report has a useful velocity measuring range in water from about 0.1 to 20 ft/min, and can resolve velocity changes as small as 0.03 ft/min. The flowmeter also distinguishes between upward and downward water movement. The flowmeter probe is about 48 in. long and has two interchangeable flow sensors; the smaller flow sensor has a diameter of about 1.75 in. including the collapsed centralizers, and the larger flow sensor has a diameter of about 2.75 in. including the collapsed centralizers. Thus, the smaller sensor may be used to log the flow in boreholes with diameters of only 2 in. The flowmeter has been tested in tubes and boreholes with diameters ranging from 2 in. to 10 in. It also may be useful for measuring slow, axial flow in larger diameter boreholes, although for best accuracy it should be calibrated for flow at the diameter at which it is to be used. This is because the flowmeter senses only the water velocity in its immediate vicinity rather than the average water velocity over the entire diameter of the borehole and the water velocity in the vicinity of the flowmeter is influenced by the presence of the flowmeter.

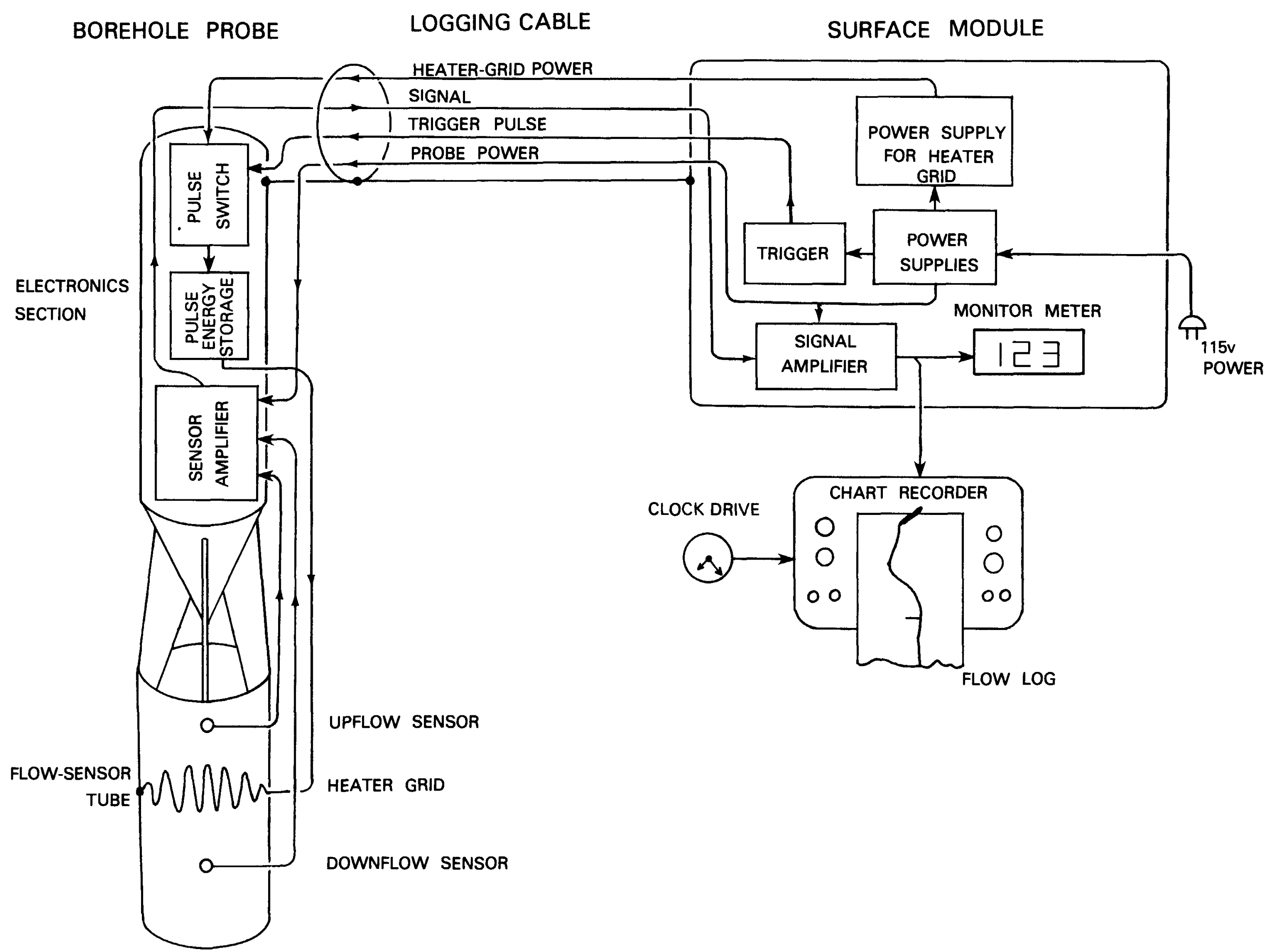


Figure 2. Functional diagram of U.S. Geological Survey's thermal-pulse flowmeter system.

Thermal-tag/trace-time instruments also have been developed by Miller and Small (1982) to measure the velocity of fluids in small diameter tubing, and by Kerfoot (1982) to measure the velocity of water through saturated soil. Tselantis (1984) made a theoretical study of a simplified configuration of the thermal-pulse flowmeter, which he compared to the results of experimental measurements.

THERMAL-PULSE FLOWMETER SYSTEM

A functional diagram of the U.S. Geological Survey's thermal-pulse flowmeter system consisting of the borehole probe, surface module, and clock-driven, strip-chart recorder is shown in figure 2. Water flowing through the hollow sensor section of the probe is thermally tagged by the heat produced by a pulse of electric current in the heater grid. (The heater is an open grid of resistance wire located at the center of the sensor tube.) This heated sheet of water is transported by the water flowing through the sensor tube past one of the two temperature sensors, one located above and the other below the heater grid. The two temperature sensors (thermistors) form two arms of a normally balanced, thermal-electric bridge that becomes unbalanced when the heated sheet of water passes it. This unbalance generates an electrical signal that is transmitted from the probe through the logging cable to the surface module where the signal is recorded on a clock-driven, strip-chart recorder.

Typical flow-response traces are shown in figure 3. The direction of thermal-electric-bridge unbalance is indicative of the direction of water movement. Thus, upward-moving water produces positive-response pulses (fig. 3A), and downward-moving water generally produces negative-response pulses (fig. 3B). The thermal-pulse response time may range from less than 1 s for fast flow to more than 1 min for slow flow.

Figure 3. Typical thermal-pulse flowmeter output responses: (A) upflow response; (B) downflow response.

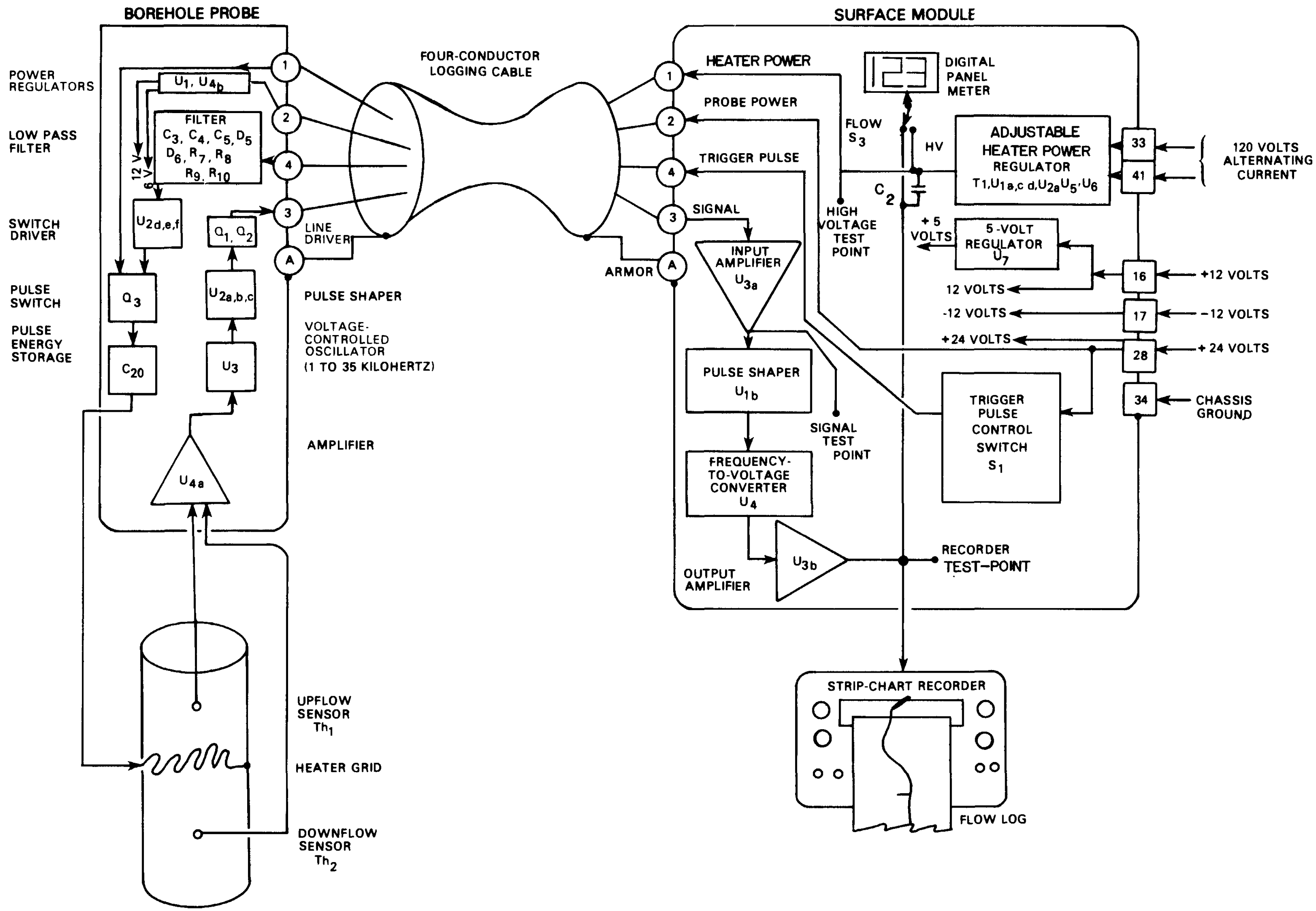


Figure 4. Operational diagram of thermal-pulse flowmeter system.

How the System Functions

The surface module provides electrical power to the probe, both low voltage for the electronics and high voltage for the heater grid. The surface module also generates the trigger pulse that starts a flow measurement, and then it receives, demodulates, and conditions the flow-response signal from the probe for display on the strip-chart recorder.

A flow-measurement cycle is started by momentarily pressing the CHG/TRIG switch, S1 on the front panel of the surface module, from CHG to TRIG (figs. 4 and 5). This sends a negative pulse down logging line 4 to the probe where it is detected and amplified by switch driver U2d,e,f, after passing through a low pass filter consisting of capacitors C3, C4, C5, resistors R7, R8, R9, R10, and diodes D5 and D6 which separates the trigger pulse from electrical noise and the response pulse-train generated in the probe. The amplified pulse from switch driver U2d,e,f, triggers switch Q3, which discharges capacitor C20 through the heater grid in the flow sensor. The resulting thermal pulse heats a sheet of water that is transported by the flowing water past one of the temperature sensors, upflow sensor Th1 or downflow sensor Th2.

A temperature difference between the temperature sensors is converted to a small differential voltage which is amplified by amplifer U4a. The voltage

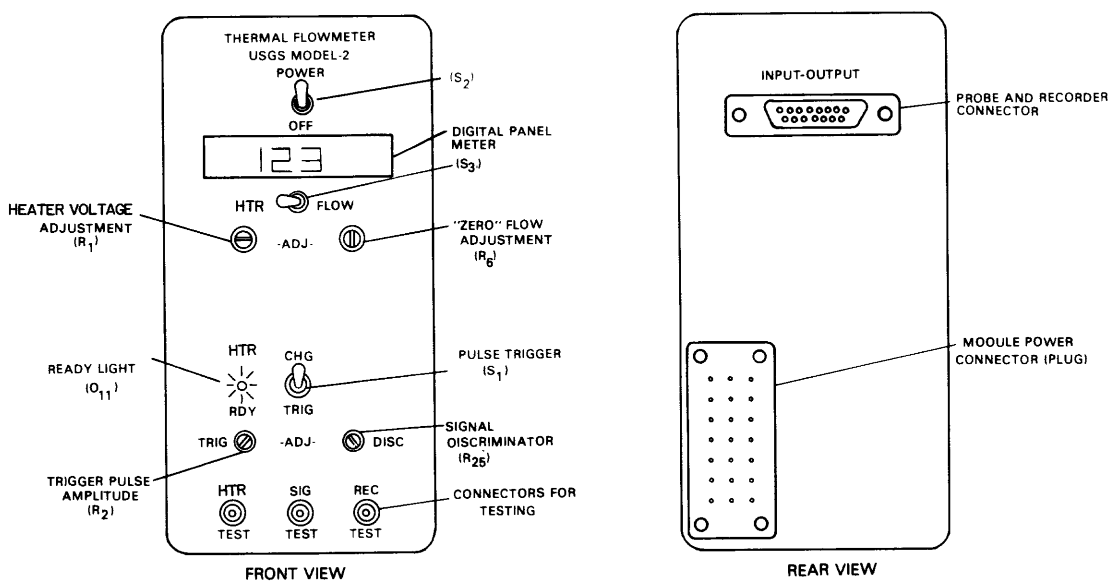
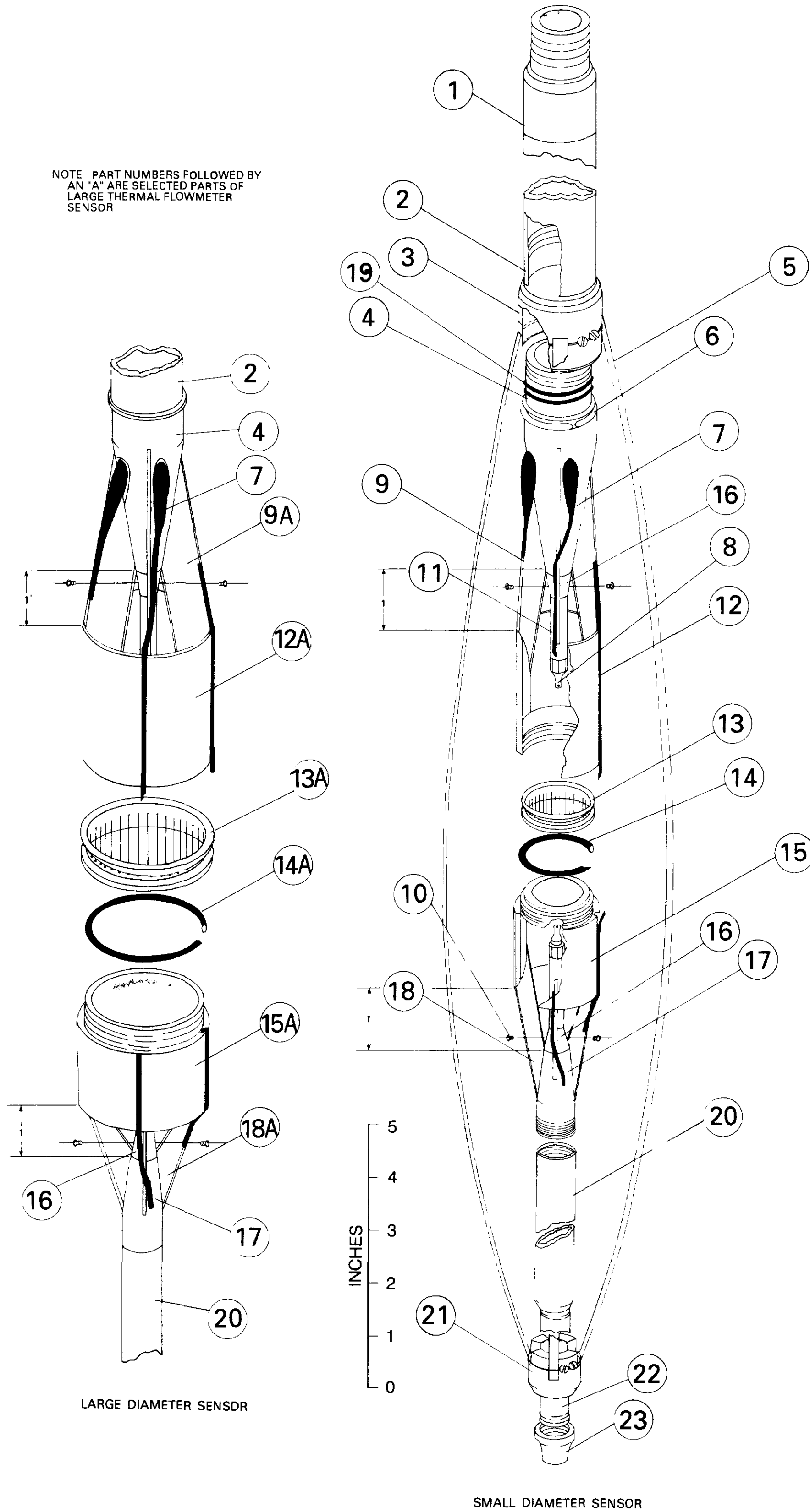


Figure 5. Front and rear views of surface module.



NUMBER		COMPONENT NAME	QUANTITY
PART	FIGURE		
1		PROBE SUB CONNECTOR	1
2		ELECTRONICS CASE	1
3		CENTRALIZER SLIDE	1
4		TOP SENSOR BULKHEAD	1
5		BOW SPRING	4
6		SPLIT RING SLIDE STOP	1
7*		HIGH-PRESSURE CONNECTOR and CABLE	3
8*		THERMISTOR	2
9 9A		TOP FIN	4
10		SET SCREWS	4
11		THERMISTOR POST	2
12 12A		TOP FLOW TUBE	1
13 13A		HEATER FRAME	1
14* 14A*		O RING	1
15 15A		BOTTOM FLOW TUBE	1
16		CONE BUSHING	2
17		BOTTOM SENSOR BULKHEAD	1
18 18A		BOTTOM FIN	4
19*		O-RING	4
20		BOTTOM COVER	1
21		BOTTOM CENTRALIZER SLIDE	1
22*		BOTTOM SLIDE MANDREL	1
23*		CAP	1

*COMMERCIALLY AVAILABLE PART

THERMAL FLOWMETER PROBE

Figure 6. Assembly of thermal flowmeter probe.

output from U4a modulates the frequency output of voltage-controlled oscillator U3. Water upflow causes this frequency to increase and downflow causes the frequency to decrease. The frequency range of U3 is set for 1 to 35 kHz. The normal no-flow frequency is about 18 kHz. This frequency modulation method is used to avoid ground conducted noise and interference. The circuit consisting of pulse shaper U2a,b,c, and transistors Q1 and Q2 shape the output of the voltage controlled oscillator into a train of 10-µs long bipolar pulses that are transmitted through the logging cable on line 3 to the surface module.

At the surface module the pulse train is amplified by U3a (fig. 4). The pulse train then travels through pulse shaper U1b to frequency-to-voltage converter U4, which generates a voltage that is proportional to the frequency of the pulse train and, thus, proportional to the temperature difference between the temperature sensors in the flow sensor. The voltage output from U4 is amplified by operational amplifier U3b and sent to the digital panel meter via HV/FLOW switch S3 and to the strip-chart recorder via the recorder output line. Also added to the recorder output line is an attenuated portion of the pulse heater voltage-pulse from the probe that was transmitted up logging line 1 and through C2. This produces the trigger-time (fig. 3) reference pulse on the recording. The power for the thermal pulse is generated and regulated in the surface module by the adjustable heater-grid circuit consisting of R11, T1, U1a,c,b, U2a, U5, and U6.

The Probe

Mechanical drawings of the probe, including both the 1 5/8-in. and the 2 1/2-in.-diameter sensors, are included in figures 12-38 following table 4. Table 1 contains the mechanical parts list. Assembly drawings of the flowmeter probe are shown in figures 6, and 40 through 44. Schematics for the probe electronics are in figure 45, component layout and printed circuit boards (PCB) are shown in figures 46 and 47, relative PCB and pulse capacitor positions are shown in figure 40, and table 2 contains a list of commercially available electronic parts. Table 4 lists the names and addresses of some of the manufacturers from which the Survey obtained some not-to-common parts. The use of company or product names in this report is for identification only and does not constitute an endorsement by the U.S. Geological Survey.

The Surface Module

The power and control circuits in the surface module are contained in a double-wide nuclear-instrument module. The module plugs into and obtains its power from a nuclear-instrument frame. The surface module provides power and control signals for the probe, and it conditions and amplifies the signals from the probe for a recorder. The surface module whose front and rear panels are shown in figure 5 is about 2.7 in. wide, 8.7 in. high, and 10.5 in. deep. Mechanical drawings for the nuclear instrument module are not included because blank nuclear instrument modules are available commercially. A schematic of the surface module electronics is contained in figure 48. A suggested component layout diagram is shown in figure 49, table 3 contains the electronic parts list, and the names and addresses of some of the manufacturers from which the Survey obtained some not too common parts are given in table 4.

OPERATING INSTRUCTIONS

The surface module supplies power to the thermal-pulse flowmeter probe through the logging cable via the multipin INPUT-OUTPUT connector on the rear of the module (fig. 5). The surface module conditions and amplifies the flow-response signal received from the probe and outputs an analog signal to a strip-chart recorder through either the INPUT-OUTPUT connector on the rear of the module or through the test connector labeled REC/TEST on the front of the module. The surface module power switch (S2) is at the top of the front panel. The digital panel meter (DPM), located just below the power switch, displays either the heater voltage (HTR), or the flow-signal imbalance (FLOW) as determined by the position of the HTR/FLOW switch (S3). The CHG/TRIG switch (S1) near the middle of the panel controls the charging and thermal pulsing in the flowmeter probe. The three connectors at the bottom of the front panel are for signal checking. The REC/TEST connector on the lower right is for checking the analog output signal. The flow-signal pulse train, 18 ± 17 kHz may be checked at the SIG/TEST connector at the lower center and the heater voltage for the probe heater-grid may be checked at the HTR/TEST connector on the lower left.

Start-up Procedure

1. Connect the flowmeter probe to the logging-cable head, and connect the surface end of the logging cable to the surface module through the INPUT-OUTPUT connector on the rear of the surface module.

2. Place the probe in still water.

3. Connect a strip-chart recorder to the analog output of the surface module through the INPUT-OUTPUT connector located on the rear or to the REC/TEST connector on the front panel, and adjust the recorder sensitivity to 1-V full scale.

4. Use the strip-chart recorder POSITION CONTROL to center the recorder pen (with zero input voltage).

5. Turn the surface module POWER switch on.

6. Switch the HTR/FLOW switch to FLOW.

7. Adjust the DISC control with a screwdriver to its maximum clockwise position. After several minutes warm-up time, the digital panel meter should show a reading between ± 20 and the recorder pen should stabilize near the center of the strip chart.

8. Turn the DISC control to the minimum (counter clockwise) position. The recorder pen should go to the negative edge of the strip chart.

9. Turn the DISC control slowly clockwise until the digital panel meter indicates a signal lock-on by a stable reading between ± 20; the recorder pen should return to near the center of the strip chart. Turn the DISC control clockwise another 1/4 turn, which should ensure adequate signal for lock-on while rejecting noise.

10. Flip the CHG/TRIG switch to the TRIG position.

11. Flip the HTR/FLOW switch to HTR; the digital panel meter should read 0, ± 1-V.

12. Flip the CHG/TRIG switch to CHG. The digital panel meter now reads the voltage supplied to the pulse-storage capacitors in the probe. Within a 10 s or so the red HTR/RDY light should come on, and the digital panel meter should read 200 ± 1-V. The heater voltage may be adjusted with a screwdriver to the proper value by the HTR-ADJ control located just below the HTR side of the HTR/FLOW switch.

If the digital panel meter (and recorder pen) does not respond when the HTR/FLOW switch is in the FLOW position, and there are no steady pulses of at least 5-V peak amplitude at the SIG-TEST connector or 0.1 V on logging line 3, turn the power OFF and recheck all connections. The normal signal frequency on logging line 3 should be about 18 kHz, but it can range from 1 to 35 kHz, depending on the relative imbalance of the thermal-electric bridge in the probe. This bridge will be out of balance when the system is first turned on, and it will take several minutes for it to stabilize. The probe thermistors are very sensitive to small temperature changes, so the sensor section needs to be placed in quiet water (or air) to obtain a stable output response when checking the flowmeter system. Once the flow has stabilized, greater sensitivity to small temperature changes may be realized by increasing the sensitivity of the strip-chart recorder; a switch setting of 0.5 V full scale probably will be adequate for most measurements.

Initially, set the TRIG/ADJ control with a screwdriver to mid position; it may be readjusted during operation to give a trigger reference pulse of adequate amplitude (about 1/4 of full scale) on the chart recording (fig. 3). Adjust the high voltage to 200 V (as read on the digital panel meter) or to the voltage at which the flowmeter was calibrated for the probe sensor in use. The pulse-power capacitors in the probe are fully charged when the red HTR/RDY light is lit.

Measurement Procedure

1. Position the thermal-pulse flowmeter probe sensor in the borehole to the depth desired. The effective plane of measurement is at the center of the flow-sensor tube (fig. 1).

2. Flip the CHG/TRIG switch to CHG. Wait until the red HTR/RDY light has come on and the recorder output has stabilized. This may require 10 min or longer when measuring very slow velocities.

3. Start the strip-chart recorder drive at the desired speed (about 1 in./min for flow velocities of less than 0.3 ft/min and as fast as 100 in./min for flow velocities of 10 ft/min or greater). It may take a few attempts to determine the best chart speed for a given situation.

4. Start a flow-velocity measurement cycle by flipping the CHG/TRIG switch to TRIG. Hold it for a second, until a negative start pulse is recorded on the strip chart and the red HTR/RDY light has gone off, then return the switch to the CHG position.

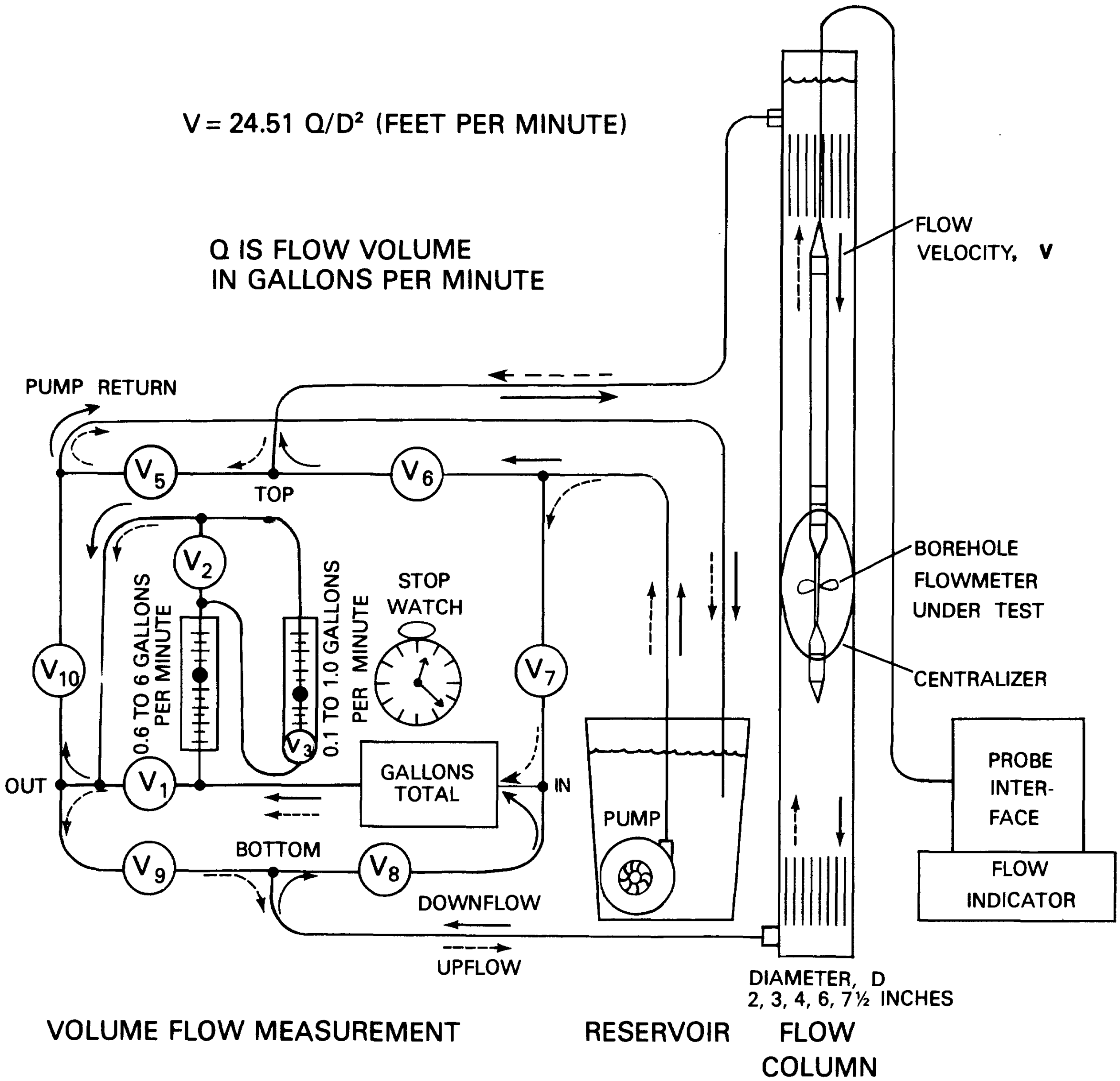


Figure 7. Calibration system for slow velocity flowmeters (modified from Hess, 1986).

The HTR/RDY light will remain off indefinitely when the switch is in the TRIG position. The HTR/RDY light should come on 5 to 10 s after the switch is returned to the CHG position, indicating that the pulse capacitors are charged and ready for another flow-measurement cycle.

Normally the sharp, negative trigger start pulse on the strip chart is followed by a slow-forming positive or negative flow-response peak as shown in figure 3. A negative flow-response peak indicates downward flow and a positive flow-response peak usually indicates upward flow. Under certain very slow, down flow conditions, a positive rather than a negative response peak may be formed because of the slight positive buoyancy of the pulse-heated sheet of water.

The flow-response time is measured from the start pulse to the peak of the flow-response pulse. Repeated measurements should be made, allowing adequate time between trigger pulses, until three successive measurements repeat to within a few percent and no longer have a monotonic drift trend. Allow five flow-response time periods or 10 min, whichever is the least, between flow-measurement cycles to permit the heat pulse to dissipate and the flow in the vicinity of the flow sensor to stabilize after each measurement. Thus, a flow-measurement cycle may take from less than 10 s for flow velocities of 10 ft/min or greater, to more than 10 min for flow velocities of 0.3 ft/min or less. The flow rate is determined from the average of the last several measurements. Determine the rate of flow from the flow calibration for the particular flow sensor and borehole diameter involved. Because the strip-chart recorder is used to measure the flow-response time, it is very important that the speed of the time drive be accurately known.

CALIBRATION AND ACCURACY

The thermal-pulse flowmeter should be calibrated, perhaps by using a borehole-flowmeter calibration facility similar to that shown in figure 7. Direct calibration of the flowmeter avoids the problem of trying to determine the exact relation between the flow in the flow-sensor tube and the total flow in the borehole. The fluid velocity in the flow sensor usually will be somewhat less than in the borehole because of the interacting effect of probe size and geometry, borehole diameter, water viscosity, and so forth. The U.S. Geological Survey's flowmeter-calibration facility consists of four vertical clear plastic columns with inside diameters of 2, 3, 4, and 6 in.; and a reservoir, circulating pump, flow controls, and measuring instruments. The system can circulate and measure water volumes ranging from 0.1 to 8.0 gal/min to produce average water velocities (either up or down) ranging from a minimum of 0.06 ft/min in the 6-in.-diameter column, to a maximum of 50 ft/min in the 2-in.-diameter column.

For calibration, the thermal-pulse flowmeter with its centralizer is positioned in the center of the column, and a metered flow of water is circulated through the column at the desired rate and direction. The water needs to be free of any gas that could collect on the heater grid and thermistors. One way to ensure this is to fill the system reservoir with hot water and let it cool overnight. Another way is to cool the reservoir water with cold water through temperature-control coils in the reservoir. The water temperature needs to be adjusted to match the room air temperature near the flow column to avoid thermal convection currents in the water. Even a

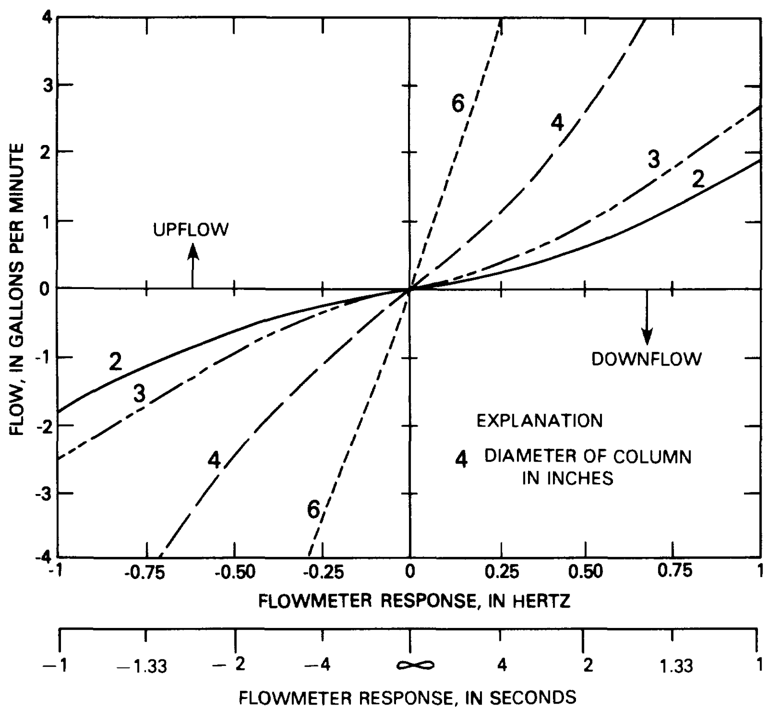


Figure 8. Calibration example of a thermal-pulse flowmeter in 2-, 3-, 4-, and 6-inch diameter columns at 25°Celsius.

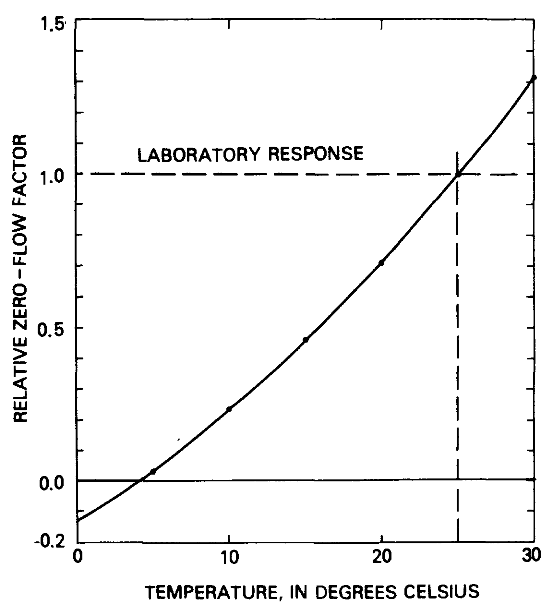


Figure 9. Relative zero-flow response in water as a function of temperature.

1°C difference in temperature may cause a calibration error that is measurable at very slow flow rates (Hess 1986). The system temperature and flow rate need to be adjusted and allowed to stabilize for at least 5 min before starting calibration measurements. Longer stabilization times may be needed for the slower velocities. To obtain repeatable measurements, allow at least five trigger to flow-response times between trigger pulses, or 10 min, whichever is the lesser, to permit the effects of the heat pulse to dissipate, and for the flow through the flow sensor to stabilize after each pulse. Thus, a flow measurement cycle may take from only a few seconds for flow velocities of 10 ft/min or greater, to 10 min or longer for velocities of 0.3 ft/min or less. The system has adequately stabilized when three or more consecutive measurements agree to within a few percent and no longer show a monotonic drift trend. The average of the last several measurements are used in determining the flow velocity.

A series of measurements should be made across the velocity range achievable by the system, including zero flow, in each diameter column. These measurements may be plotted and fitted with a best-fit curve to form a family of calibration curves such as those shown in figure 8; this family of curves was made for a thermal-pulse flowmeter in columns having diameters of 2, 3, 4, and 6 in. The vertical coordinate in figure 8 is the actual water volume flow in the column, positive for upflow and negative for downflow. The horizontal coordinate is the time (actually inverse time) for the corresponding pulse response of the flowmeter, right for positive-response pulses and left for negative-response pulses. The use of inverse time, s^{-1} or hertz, permits the calibration curve to be a continuous, nearly straight line through the zero flow range. The temperature of the sheet of water heated by the thermal pulse is only a few tenths of a degree higher than the ambient water temperature but that is enough to give it a slight positive buoyancy. This buoyancy produces a slight upflow bias that causes the calibration curves to be slightly asymmetric at very slow velocities. A slight difference in the spacing between the heater grid and the upflow and the downflow sensors will cause the calibration curves to be asymmetric at higher flow velocities.

The uncertainty of the thermal-pulse flowmeter calibration by the U.S. Geological Survey's facility is estimated to be no more than 5 percent of the indicated flow plus 0.1 ft/min at room temperature (about 23°C). Water temperatures in boreholes usually are lower than 23°C, usually ranging from 10 to 20°C, but borehole temperatures may range from freezing to boiling (or greater in geothermal wells). The thermal-pulse flowmeter calibration is slightly temperature dependent because of the change in water density and viscosity with temperature (Hess 1986), so a small temperature-dependent correction factor may need to be applied to the calibration curve, especially at slower velocities. A typical temperature-dependent zero-flow response curve is shown in Figure 9. Notice that at 4°C a thermal-pulse-heated sheet of water has neutral buoyancy, and therefore has no net zero-flow bias; whereas at temperatures below 4°C a heated sheet of water has a slight negative buoyancy and the zero-flow bias is negative. This effect is seen in the low temperature end of the zero-flow response of the curve in figure 9.

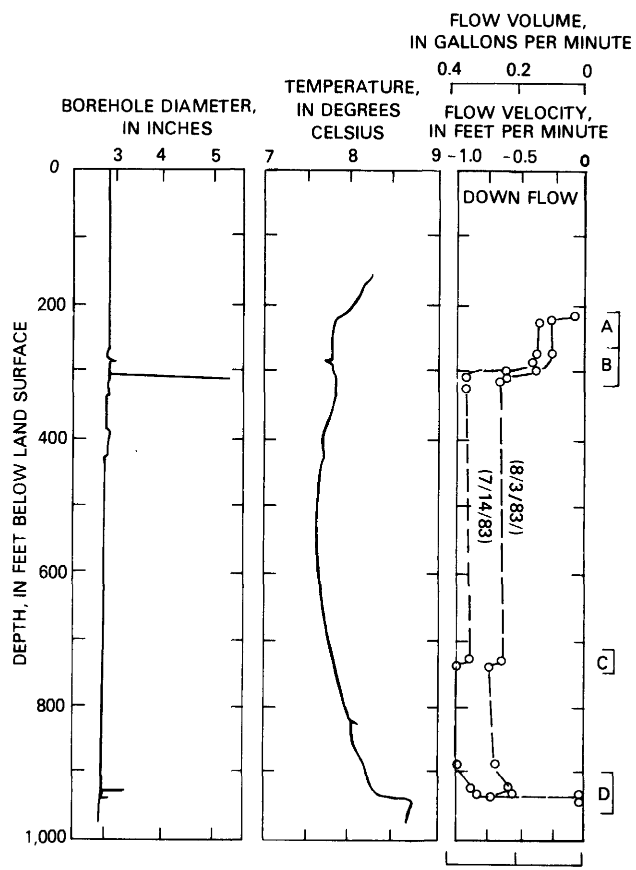


Figure 10. Caliper, temperature, and flow velocity logs of URL-10, modified from Keys (1984).

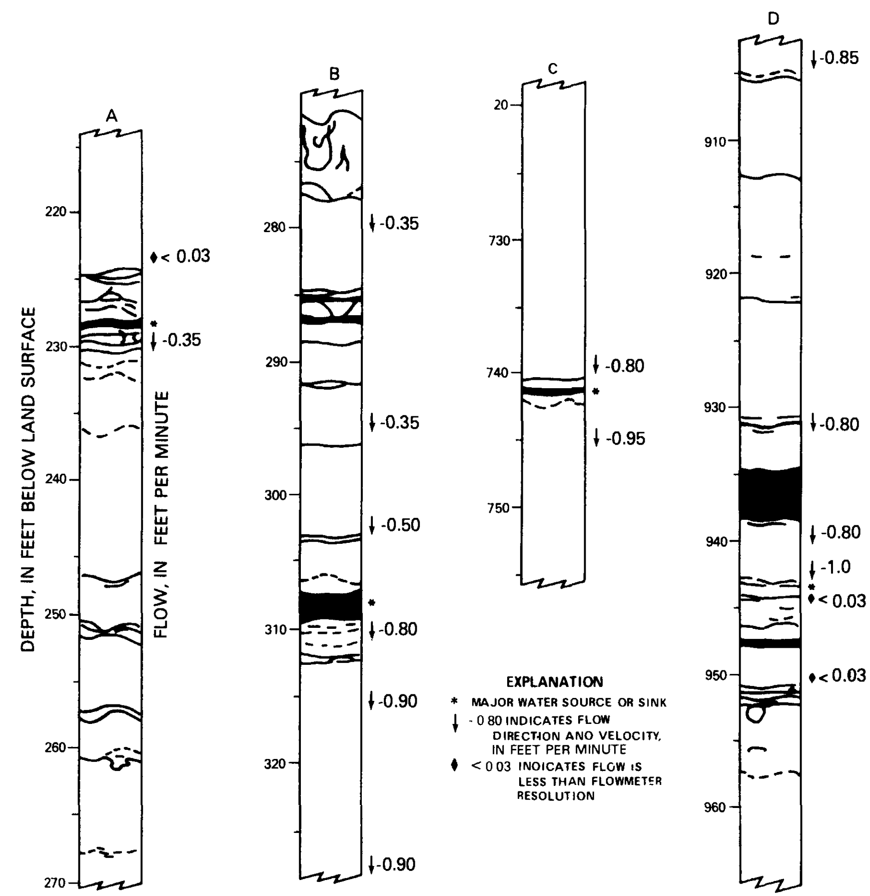


Figure 11. Acoustic televiewer logs of selected depths of URL-10, modified from Keys (1984).

The zero-flow response of the thermal-pulse flowmeter may be checked in a borehole by positioning the flowmeter at a depth where it is known that there is no flow; such as in the casing just below the water level that is known to be static, and where the temperature gradient is zero or the temperature decreases with depth.

EXAMPLE OF THE USE OF THE THERMAL-PULSE FLOWMETER

A logging trip to assist in the study of fracture hydrology in a granite pluton near Lac du Bonnet in Manitoba, Canada, afforded an opportunity to demonstrate the slow flow measuring capability of the U.S. Geological Survey's thermal-pulse flowmeter. The Canadian site is being developed by Atomic Energy of Canada, Limited, as the Underground Research Laboratory to conduct geotechnical research and to validate predictive models as part of Canada's Nuclear-Fuel, Water-Management program. An overview of the geology of the area is given in a 1983 report by Green and Mair. Flowmeter logs were used along with caliper, temperature, and acoustic-televiewer logs to determine which fractures actually were transmitting water during the then-existing conditions. The borehole described in this report was unpumped during the measurements, but pumping tests later were determined to have been conducted in nearby boreholes during part of the flow test, and the flow in the borehole apparently was affected by these pumping tests.

The thermal-pulse flowmeter was operated from the U.S. Geological Survey's borehole logging van through about 6,000 ft of conventional four-conductor logging cable (five-conductors when the cable armor is included). The same precautions were taken when making flow measurements at the borehole site as were taken during flowmeter calibration in the laboratory. Adequate time, usually about 5 min, was allowed after the flowmeter was positioned at the desired depth to permit any water turbulence caused by moving the flowmeter through the water to cease and for the natural flow to re-establish itself. Then five instrument-response-time periods or 10 min, whichever was the lesser, was allowed between measurements to permit the thermal pulse to move out of the sensor, or to dissipate. A minimum of three measurements were made at each depth, which required from just a few minutes for velocities of 2 ft/min or greater, to as much as 40 min for velocities of 0.2 ft/min or less. The flow was considered to have adequately stabilized when repeated measurements agreed to within a few percent.

The measurements of this example were made in a borehole that is 3 in. in diameter and 1,000-ft deep (URL-10), and which deviated more than 20° from the vertical. Thermal-pulse flowmeter calibration in a laboratory column oriented 20° from the vertical virtually was almost identical to those calibrations made in the vertical column. Furthermore, because a thermal pulse has almost neutrally buoyant at a water temperature of about 8°C in the borehole, it was concluded that the borehole deviation had practically no effect on the flowmeter response. See the discussion in the previous section regarding temperature related corrections to the calibration of the flowmeter. Caliper, temperature, and flow-velocity logs of this hole are shown in figure 10; acoustic televiewer logs of the fractures at several depth intervals of interest are shown in figure 11.

The caliper log in figure 10 is quite smooth except for a large-aperture fracture at a depth of 308 ft, and smaller-aperture irregularities at a depth of 285 ft and between 935 to 948 ft. The shape of the temperature-log suggests a downward movement of water between 226 and 942 ft with a slight change in flow at a depth of 308 ft.

The flowmeter log dated 7/14/83 indicates little flow (less than 0.03 ft/min) above a depth of 223 ft. A downward flow of about -0.36 ft/min was evident below a depth of 231 ft, downward flow increased from -0.36 to -0.9 ft/min between depths of 295 and 315 ft, and increased further to -0.95 ft/min at a depth of 741 ft. This downward-flow velocity remained nearly constant to a depth of 896 ft. At a depth of 938 ft, the flow had decreased slightly from -0.95 to about -0.8 ft/min, and at depth of 945 ft, the flow was less than 0.01 ft/min.

The flowmeter log dated 8/3/83 (fig. 10), made about 2 weeks later, indicated the same flow pattern but the flow velocity was only about two-thirds of the flow velocity of the earlier log. Later it was learned that pumping tests were being conducted in a borehole about 1,000 ft away during the earlier flow measurements but not during the later measurements. The termination of the pumping tests apparently caused the change in flow rate. These later measurements indicated that water was entering the borehole in the depth interval between 223 and 312 ft, and that the depth interval between 307 and 311 ft was the major contributor (about 60 percent of the flow). Fractures in the depth interval between 738 and 745 ft contributed another 10 to 15 percent to the total flow. Most of this flow exited the borehole near the bottom, in the depth interval between 942 and 944 ft.

The flow volume, Q, in gallons per minute, may be determined from the relation:

$$Q = 0.0408 \times V \times D^2, \qquad (1)$$

where V equals flow velocity, in feet per minute, and D equals borehole diameter, in inches. The 0.0408 value is derived from the determination of the volume of 1 ft of borehole.

The acoustic televiewer logs in figure 11 are plotted on an expanded depth scale and show a group of fractures in the depth interval between 223 and 232 ft, section A; the widest fracture is at a depth of 228 ft. Because these fractures were not detected by the caliper log, they apparently have rather small apertures. However, the flowmeter and temperature logs show that some downward flow was originating in this depth interval. Log section B shows another group of fractures in the depth between 302 and 314 ft; the widest fracture is at a depth of 308 ft. The fracture at a depth of 308 ft has the widest aperture seen on the caliper log, and this fracture is a major water contributor. Log section C shows a small group of fractures at a depth of about 741 ft, where downward flow again increased slightly. Near the bottom of the borehole, log section D shows a large group of fractures in the depth interval between 932 and 955 ft, with a wide, dark fracture area in the depth interval between 935 and 938 ft. However, as already noted, the majority of the flow was exiting in the depth interval between 942 and 944 ft, probably through the small fracture indicated on log section D at a depth of 942.6 ft. The acoustic televiewer logs show many fractures scattered throughout the borehole, but only a few discrete fractures appear to have been transmitting water during the hydraulic-head conditions that existed at the time of measurements.

The flowmeter logs in figure 10 have a resolution of about 0.03 ft/min. However, the actual uncertainty of the flow velocities may be as much as 0.1 ft/min as was discussed in a previous section. A more complete discussion of the fracture hydrology and the integration of flowmeter results with other geophysical data for this borehole is given in a report by Keys (1984), and a hydrogeological characterization of the Underground Research Laboratory site is given by Davison (1984).

SUMMARY

This report has described the theory of operation, construction, calibration, and use of a sensitive thermal-pulse flowmeter developed by the U.S. Geological Survey for measuring the movement of slow-velocity water in boreholes. The flowmeter, which uses the thermal-tag/trace-time principle, has a useful flow measuring range of from about 0.1 to more than 20 ft/min, and has a resolution of about 0.03 ft/min. It has no moving parts and distinguishes between upflow and downflow. The slight buoyancy effect in the thermal-pulse flowmeter caused by a change in density of thermal-pulse heated water usually is less than 0.2 ft/min and is accounted for during calibration.

The thermal-pulse flowmeter is more than an order of magnitude more sensitive than the traditional spinner-type flowmeter, and it is faster and more accurate than radioactive- or brine-solution tracer flow measuring techniques. The later techniques are characterized by relatively large errors caused by the differences in the densities between the borehole and the tracer fluids, or the existence and effect of convection currents in the borehole that usually are ignored or are inadequately accounted for.

Two sizes of flow sensors are described; the 1 5/8 in. diameter flow sensor is useful in boreholes with diameters of 2 to 4 in. The 2 1/2 in. diameter flow sensor is useful in boreholes with diameters equal to or larger than 3 in. The borehole configured thermal-pulse flowmeter does not replace the traditional spinner-style flowmeter, but rather complements it, greatly extending the lower range of accurate water velocity (and volume) measurements available to hydrogeologists and others studying ground-water movement.

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GLOSSARY

The following terms, abbreviations, and definitions are used in this report:

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ac = alternating current
ADJ = adjust
AMP = amplifier
ATV = acoustic televiewer
BNC = the International Electronics Commission designation for a specific type of electronic coaxial connector

C = capacitor, an electronic component
(C) = a commercially available part
CHG = charge
CHG/TRIG = a 2-position switch so labeled
CYL = cylinder, or cylindrical

D. = diameter, when used with or as a dimension
D = diode, when used as an electronic component
dc = direct current
DIA = diameter
DISC = discriminator control

DPM = digital panel meter
DWG = drawing
ea = each
FLOW ADJ = a screwdriver-adjustable flow-zero control
F = farad, unit of capacitance, an electrical quantity

ft = foot
ft/min = foot per minute
heat-pulse = thermal-pulse
H = henry, unit of inductance, an electrical quantity
Hz = hertz (cycles per second)

HTR = heater
HV = heater voltage
HV ADJ = a screwdriver-adjustable heater-voltage control
HV/FLOW = a 2-position switch so labeled
HV-RDY = heater-voltage ready light

HV-TEST = heater-voltage test connector
IC = integrated circuit, an electronic component
ID = inside diameter
in = inch
in/min = inch per minute

L = length, when used as a dimension
L = inductor, when used as an electronic component
LCD = liquid crystal display
LED = light emitting diode display
MAT'L = material

GLOSSARY continued

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min = minute(time)
NEF = national extra fine (thread)
NF = national fine (thread)
NIM = Nuclear Instrumentation Module, an instrument module which physically slides into, and electrically receives it's power from a NIMs-BIN.

NIMs-BIN = a metal case which physically supports one or more Nuclear Instrument Modules and provides them with electrical power.
NPT = national pipe thread
O-ring = a "rubber" seal shaped like the letter "O"
OFF = off position of switch

ON = on position of switch
ON/OFF = a 2-positon switch so labeled
OUT = output
PCB = printed circuit board
PN = part number
PS = power supply

psi = pounds per square inch
Q = flow volume, gallon per minute, when used in a flow formula.
Q = transistor, when used as an electronic component
R = resistor, an electronic component
REC/TEST = recorder-test connector

REF = reference, a dimension given for convenience, but not to be used for determining parts tolerance.
REG = regulator
s = second(time)
SCR = silicon controlled rectifier, an electronic component

spinner = a spinning type flowmeter
SIG/TEST = signal-test connector
SS = stainless steel
STD = standard
Survey = United States Geological Survey

Sw = switch
T = transformer, an electronic component
TC = temperature coefficient
Th = thermistor, a resistor that has a large negative temperature coefficient
thermal-pulse = heat-pulse

THD = thread
THD/IN = thread per inch
TPFM = thermal-pulse flowmeter
TRIAC = a dual silicon controlled rectifier for ac circuits
TRIG = trigger

GLOSSARY continued

TRIG ADJ = a screwdriver-adjustable trigger-pulse amplitude control
U = integrated circuit, an electronic component
UN = unified national (thread)
UNF = unified national fine (thread)
USGS = United States Geological Survey

V = voltage, when used as an electrical quantity
V = velocity, when used as a mechanical quantity
w = watt of power, when used as an electrical quantity
x = times (multiply)
W = wide, when used in mechanical drawings

Z = zener diode, an electronic component

===

Other abbreviations used

Ω = ohm, a unit of resistance, an electrical quantity
/ = per (divided by)
∠ = angle
° = degree, angle, when used in mechanical drawings
" = inch(es), when used with dimensions

===

Dimensional prefixes used

M- = mega = $x10^{6}$
k- = kilo = $x10^{3}$ (i.e. 18 kHz = 18 kilohertz = 18 x 10^{3} hertz)
m- = milli= $x10^{-3}$
u- = micro= $x10^{-6}$
n- = nano = $x10^{-9}$
p- = pico = $x10^{-12}$

===

Table 1.-- Mechanical parts list for the thermal-pulse flowmeter probe.

Part number	Figure number	Description	Material	Number per set
1	F-12	Probe connector sub	stainless steel	1
2	F-13	Electronics case (tube)	*stainless steel	1
3	F-14	Top centralizer slide (1 5/8"D.)	brass	2
4	F-15	Top sensor bulkhead	stainless steel	1
5	F-16	Bow spring	stainless steel	4
6	F-17	Split ring slide stop (spring)	stainless steel	1
7	F-38	Hi-pres. connector and cable (C)		3
8	F-37	Thermistor (C)		2
9	F-18	Top fin (1 5/8"D)	stainless steel	4
9A	F-20	Top fin (2 1/2"D)	stainless steel	4
10	no dwg	Set screws, (C)	stainless steel	2
11	F-21	Thermistor post	stainless steel	2
12	F-22	Top flow tube (1 5/8"D)	stainless steel	1
12A	F-23	Top flow tube (2 1/2"D)	stainless steel	1
13	F-24	Heater frame (1 5/8"D)	Nylon or Delron	1
13A	F-25	Heater frame (2 1/2"D)	Nylon or Delron	1
14	no dwg	O-ring, 2-025 (for 1 5/8"D) (C)	Viton	
14A	no dwg	O-ring, 2-033 (for 2 1/5"D) (C)	Viton	
15	F-26	Bottom flow tube (1 5/8"D)	stainless steel	1
15A	F-27	Bottom flow tube (2 1/2"D)	stainless steel	1
16	no dwg	Cone Bushing	Nylon or Delron	1
17	F-28	Bottom sensor bulkhead	stainless steel	1
18	F-19	Bottom fin (1 5/8"D)	stainless steel	4
18A	F-20	Bottom fin (2 1/2"D)	stainless steel	4
19	no dwg	O-ring, 2-024 (C)	Viton	4
20	F-29	Bottom connector cover	stainless steel	1
21	F-30	Bottom centralizer slide	stainless steel	1
22	F-31	Bottom slide mandrel(1/4" nipple)(C)	stainless steel	1
23	F-31	Cap, 1/4" (C), modified	ss or brass	1
24,25	no dwg	(no part)		
26	F-32	Probe connector carrier	brass	1
27	F-17	Connector clamp screw	brass	
28	F-33	Heater assembly jig (1 5/8")	brass or steel	1
28A	F-34	Heater assembly jig (2 1/2")	brass or steel	1
29	no dwg	(no part)		
30	F-35	Bulkhead, electronic chassis	brass	3
31	F-35	Bulkhead, bottom connector	brass	1
32	F-36	Printed circuit board support block	brass	1
33	F-39,40	Rail for electronic chassis	steel	2
34	no dwg	Insulator, standoff (C)		3
35-39	no dwg	(no part)		

Table 1.--Mechanical parts list for the thermal-pulse flowmeter probe, continued

Part number	Figure number	Description	Number per set
40	F-37	Connector, 4-pin, female (C)	1
41	no dwg	Connector, 6-pin, male (C)	1
42	F-41	Connector, 6-pin, female (C), modified	1
43	no dwg	(no part)	
44	F-38	Hi-pressure feedthru (C)	4
45	F-38	Hi-pressure connector with cable (C)	3
46	F-38	Hi-pressure connector (C)	1
47	F-37	Insulating boot, 4-pin (C)	1

NOTES: (1) Material: *stainless steel to be high strength non-corroding.
(2) (C) indicates that the part is commercially available, for special items see table 3.
(3) Break (round) all edges unless otherwise stated.
(4) All dimensions are in inches and all tolerances are +/- 0.005 inch unless otherwise stated.

COMMERCIAL AVAILABLE HARDWARE FOR PROBE:

Screws & nuts	used with (part #)	Material, (steel except as noted)	Number per set
4-40 X 1/4" flathead	Rail (30)		20
4-40 X 1/4" panhead	Bow spring slide (3),(21)	Stainless steel	4
4-40 X 3/8" panhead	Probe PCB mounting blocks (32)		12
4-40 X 5/8" panhead	Probe PCB mounting blocks (32)		12
3-48 X 7/8" panhead (or fillister head, turned to 0.165"D.)	6-pin connector (42)		2
4-40 nuts	Probe PCB mounting blocks		12

O-RINGS: (Part numbers are for Parker Seals, or equivalent; material, Viton)

Part number	Parker size	Inside diameter X width	Part used with	Part No.	Number per set
--	2-006	1/8 X 1/16	Hi-pres. feed-thrus	(44)	3
--	2-011	5/16 X 1/16	Thermistor post	(11)	2
--	2-013	7/16 X 1/16	GOI 4-pin connector	(40)	2
19	2-024	1 1/8 X 1/16	Electronics case	(2)	4
14	2-025	1 3/16 X 1/16	Heater (1 5/8"D)	(13)	1
14A	2-033	2 X 1/16	Heater (2 1/2"D)	(13A)	1
--	2-115	11/16 X 3/32	GOI connector carrier	(26)	1

Table 2.-- Electronic-parts list for thermal-pulse flowmeter probe.

Part number	Description
	CAPACITORS (All are non-polarized except as noted):
C1	78uF/50v electrolytic
C2	1.5F/15v electrolytic
C3	6uF/15v electrolytic
C4,5	1.5F/15v electrolytic
C6	1nF
C7	100pF
C8	1nF
C9	33uF/15v electrolytic
C10	5nF*
C11-14	1.5uF/15v electrolytic
C15	10nF
C16	33uF/15v electrolytic
C17,18	1.5F/15v electrolytic
C19	100nF
C20	2x100uF/450v electrolytic
	DIODES (as shown or equivalent):
D1	1N2989B, 30V/10w, zener
D2	1N4001
D3-10	1N914
D11	1N4005
	TRANSISTORS (as shown or equivalent):
Q1	CA40361
Q2	2N3096
Q3	2N4443
Q4	2N3904

Table 2.-- Electronic-parts list for thermal-pulse flowmeter probe, continued

Part number	Description
	RESISTORS (all are 1/4W except as noted):
R1	100 OHM, 1/2w
R2	100k
R3	10 OHM
R4	2k2
R5	8k
R6	10k
R7	2M
R8	680k
R9,10	100k
R11,12	10k
R13,14	2k2
R15-17	10k
R18	*1M
R19	*10k
R20,21	5k1
R22	10k
R23	470k
R24	4k7
R25	470k
R26	none
R27	2k2
R28	10 OHM, 1/2w
R29	10k, 1/2w
Heater	5 to 50 OHM, hand made using insulated resistance wire, 0.020-inch diameter or smaller.
Th1&Th2	50k, thermistor, temperature sensors, (commercial part listed in table 3).

NOTES:
* Stable, low temperature coefficient components.

Part number	Description
	INTEGRATED CIRCUITS:
U1	7812, 12V regulator
U2	74C14, hex inverter
U3	CA4046, voltage controlled oscillator
U4	LF343, dual operational amplifier

Table 3.-- Electronic-parts list for the thermal-pulse flowmeter surface module.

Part number	Description
	CAPACITORS: (all are non-polarized except as noted, i.e. 60uF/400v, electrolytic)
C1	60uF/400v, electrolytic
C2	0.1uF/400v
C3-5	78uF/35v, electrolytic
C6	47uF/35v, electrolytic
C8	2nF
C9	*1nF
C10-12	1.5uF/15v, electrolytic
C13	0.1uF
C14	3uF/+15v, electrolytic
	DIODES (all are 1N914 or equivalent except as noted)
D1-4	1N4004 or 400v diode bridge
D5	1N5230, 4.5v zener
D11	LED, red
D14	1N5232, 5.5v zener
D20	1N279 (Germanium)
	RESISTORS (all are +/-5%, 1/4w except as noted)
R1	1k
R2	1k trimpot
R3	100k
R4	1k, 1w
R5	390 ohm
R6	1k, 1w
R7,8	22M
R9	300k
R10	240k
R12	3k3
R13-15	1k
R16	100k
R17	510 ohm, 1/2w
R18	18k
R19	100k

Table 3.-- Parts list for the thermal-pulse flowmeter surface panel, continued

Part number	Description
	RESISTORS (all are +/-5%, 1/4w except as noted)
R20	*200k, 1%
R21	*5k trimpot
R22	*20k, 1%
R23	1k
R24	9k1
R25	5k trimpot
R26	none
R27	22k
R28	220 ohm
R29	2k2
R30,31	51k
R32	2k7
R33	*51k
R34	20k
R35	10k
R36	2k2
R37	10k trimpot
R38	10k
R39	10k trimpot
R40	9k1
R41	1k0
R42	5k1
R43	15k
R44	2k
R45	220 ohm

NOTES: * = stable, low temperature components

Part number	Description
S1	Switch, double-pole, double-throw, spring return
S2	Switch, 4-pole, single-throw
S3	Switch, single-pole, double-throw

Table 3.-- Parts list for the thermal-pulse flowmeter surface panel, continued

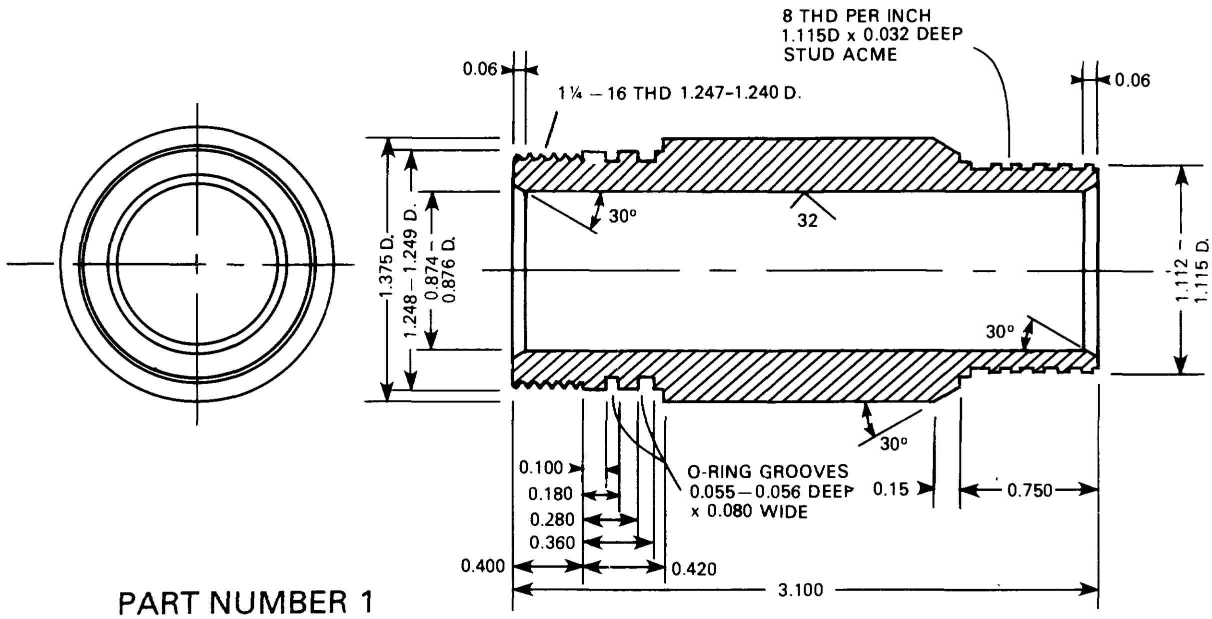
Part number	Description
	Integrated circuits, (as indicated or equivalent).
U1	CA4093, Quad S.T. NAND, CMOS
U2,U3	LF353, Dual operational amplifier, CMOS
U4	CA4528 (or CA40989) dual 1-shot, CMOS
U5	Vactec VACTROL, 76 32 VTL 5C3, photo relay
U6	MOC-3010, optically coupled triac
U7	7805, 5v regulator

Miscellaneous:		(Quantity: 1 each or as specified)
BNC-F	Front panel coaxial connectors, BNC-F	3 ea
D15-F	Rear connector, D15-F (15-PIN)	
NIM	NIMs panel, 2-wide	
DPM	Panel meter, 3-digit, +/-1v, Electronics, Inc., model MDPM (or equiv.)	
T1	Power transformer, 120v input, 250v ouput, 10w	

Table 4.--Sources of commercial parts used in thermal-pulse flowmeter.

Most hardward is available from hardware supply houses, and most electrical/electronic parts are available from electrical/electronic supply houses. Some special parts are listed below.

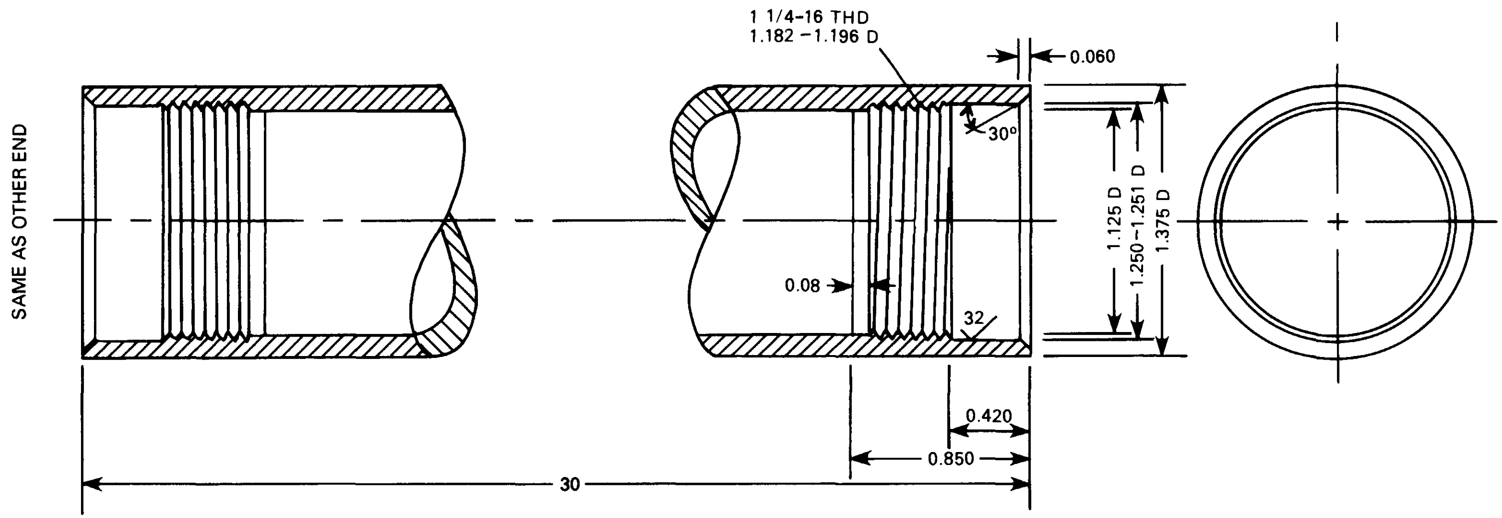
Part number	Figure number	Mfgs P/N	Manufacturer and address
7	F-38	16-B-1042	Kemlon Products, P.O.Box 14666,
44	F-38	16-A-131	Houston, TX 77021
46	F-38	16-B-430	Phone (717)747-5020
8	F-37	GA45P2S(special)	Fenwall Electronics, 450 Fortune Blvd., Millford, MA 01757 Phone (617)478-6000
40	F-37	04-9715-30	Gearhart Industries, Fort Worth, TX, or
47	F-37	06-9705-26	Brantner & Assn. Inc., 3501 Hancock St., San Diego, CA 92110
41	no dwg	BURNDY-BT06E10-6PN or MS3116F10-6P,	Arrow Electronics
42	F-41	BURNDY-BT00EC10-6SN or MS3110F10-6S	" "
DPM	F-5	MDPM-111	Electronics Incorporated, 1520 N. Main St., Mishawaka, IN 46545, Phone (219)256-5001
NIM	F-5	2-wide NIMs module	Tennelec, 601 Oak Ridge Turnpike, P.O. Box 2560, Oak Ridge, TN 37831-2560 Phone 615)483-8405



PART NUMBER 1

PROBE CONNECTOR SUB
MATERIAL: NON-CORROSIVE STAINLESS STEEL
SCALE: 1 INCH = 1 INCH

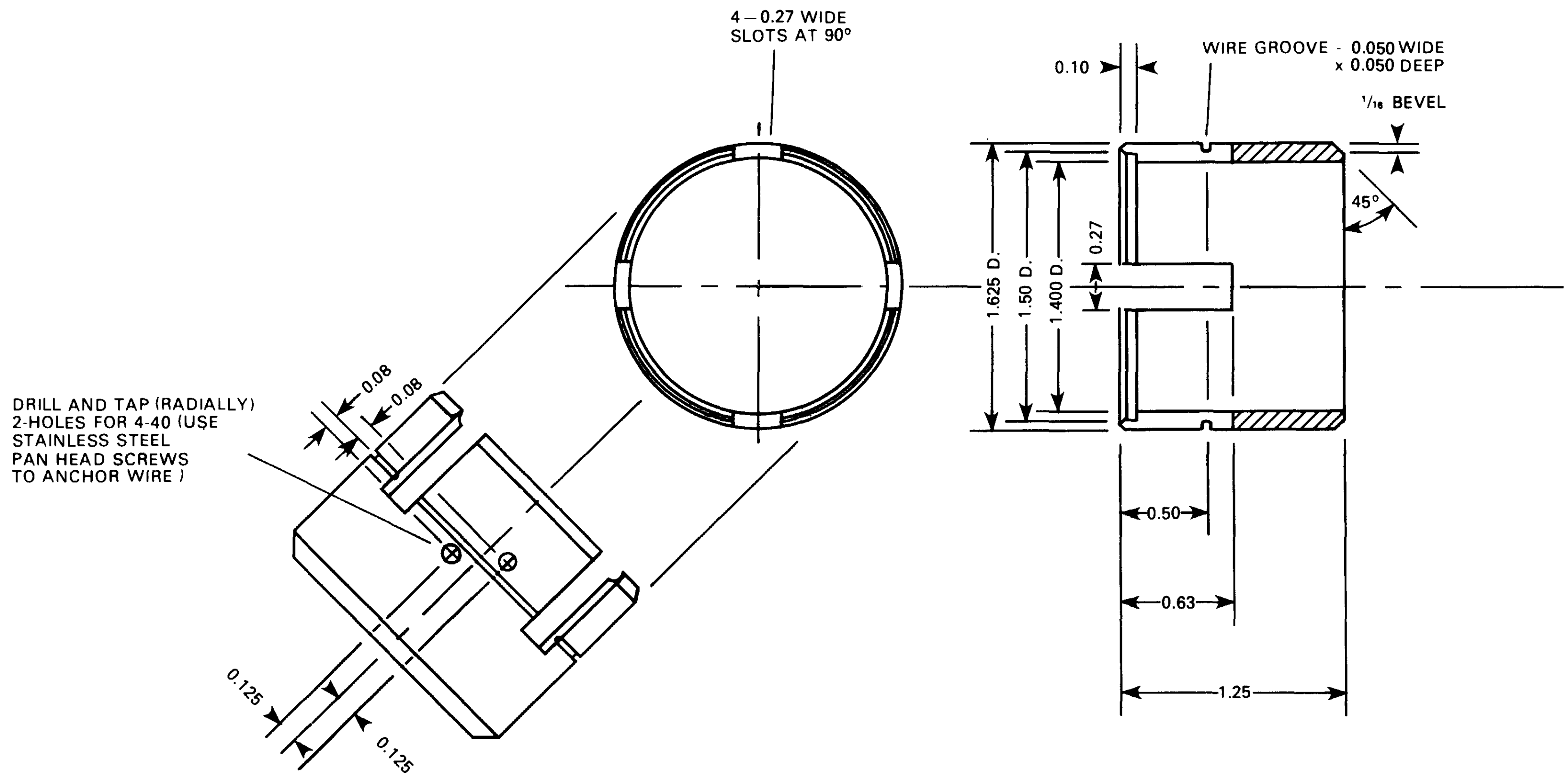
Figure 12. PN-1, probe connector sub



PART NUMBER 2

ELECTRONICS CASE
MATERIAL: NON-CORROSIVE STAINLESS STEEL
SCALE: 1 INCH = 1 INCH

Figure 13. PN-2, electronics case.



PART NUMBER 3
TOP CENTRALIZER SLIDE
MATERIAL: BRONZE
SCALE 1 INCH - 1 INCH

Figure 14. PN-3, top centralizer, slide.

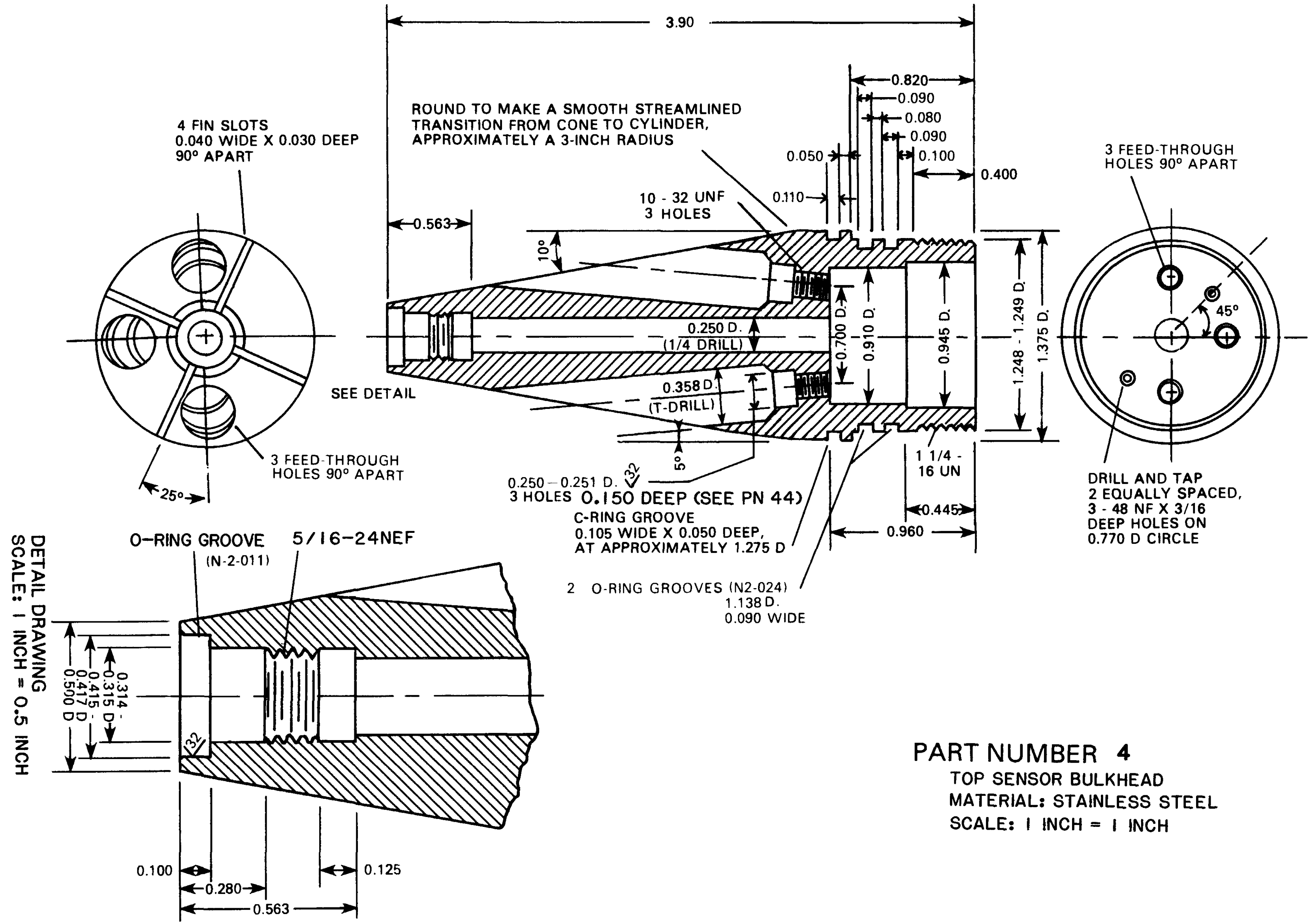


Figure 15. PN-4, top sensor bulkhead.

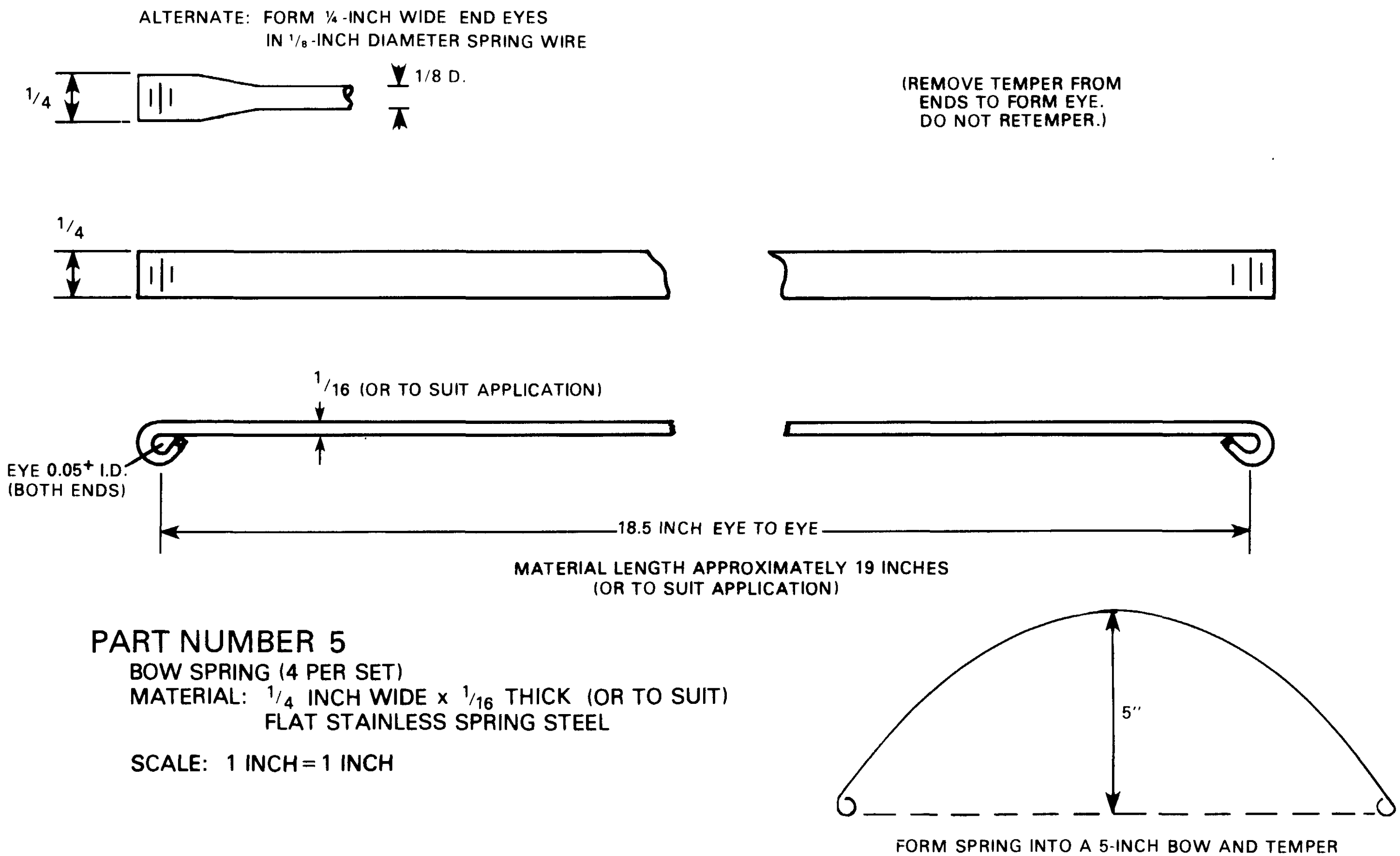


Figure 16. PN-5, bow spring.

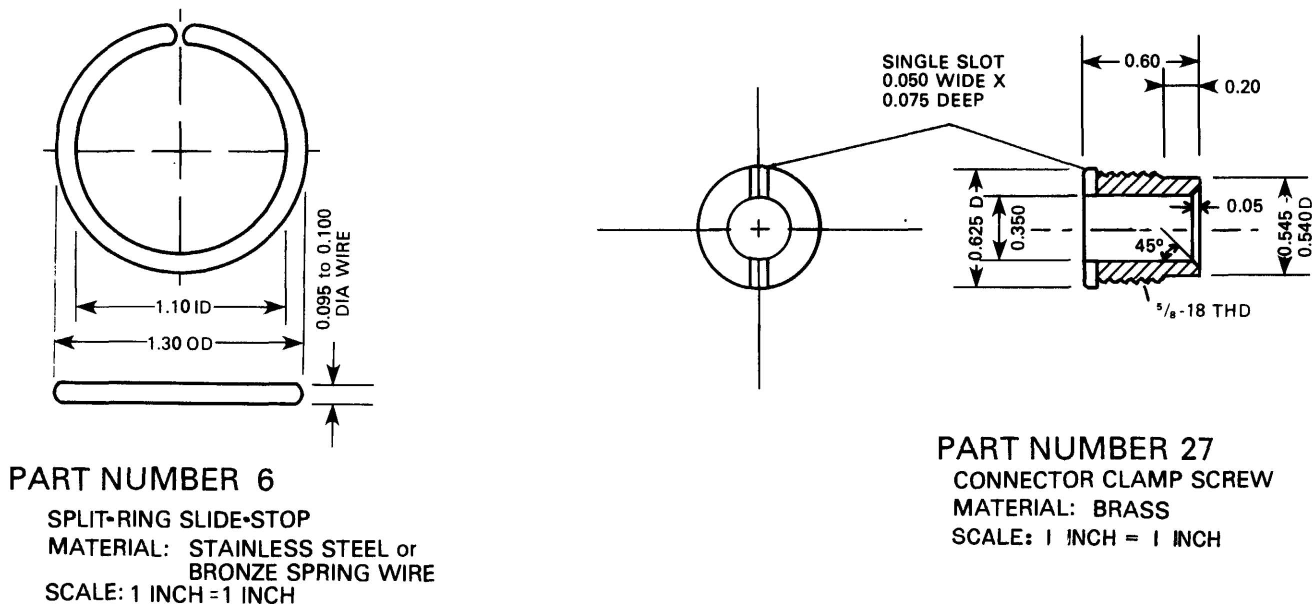
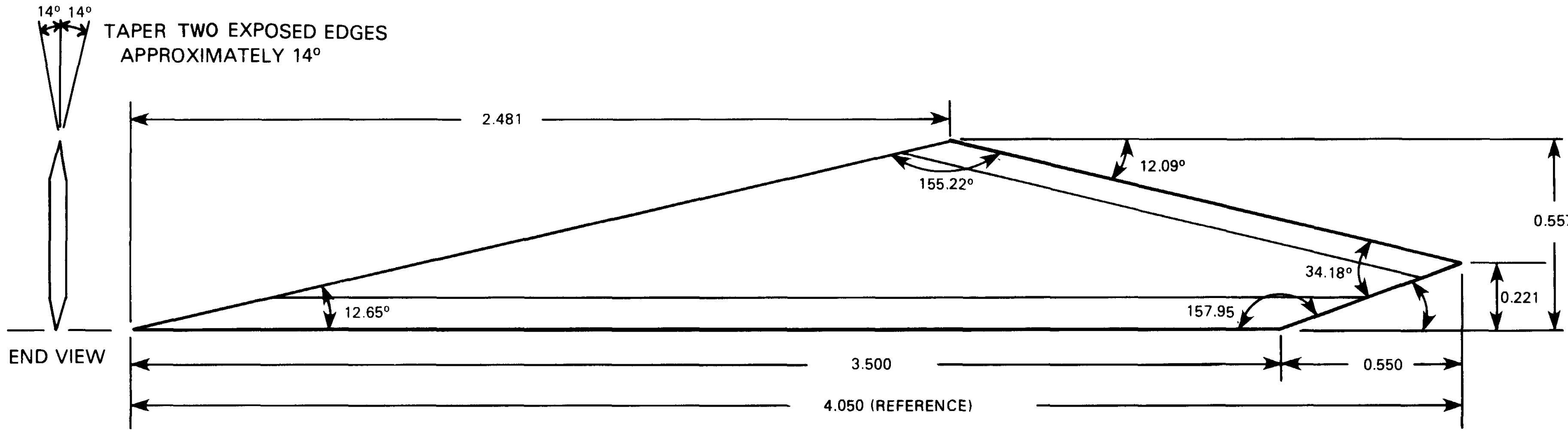


Figure 17. PN-6, split ring slide stop; PN-27, connector clamp screw.



PART NUMBER 9

TOP FIN 1 5/8

MATERIAL: 0.05-INCH THICK STAINLESS STEEL

SCALE: 1 INCH = 1/2 INCH

Figure 18. PN-9, top fin, 1 5/8.

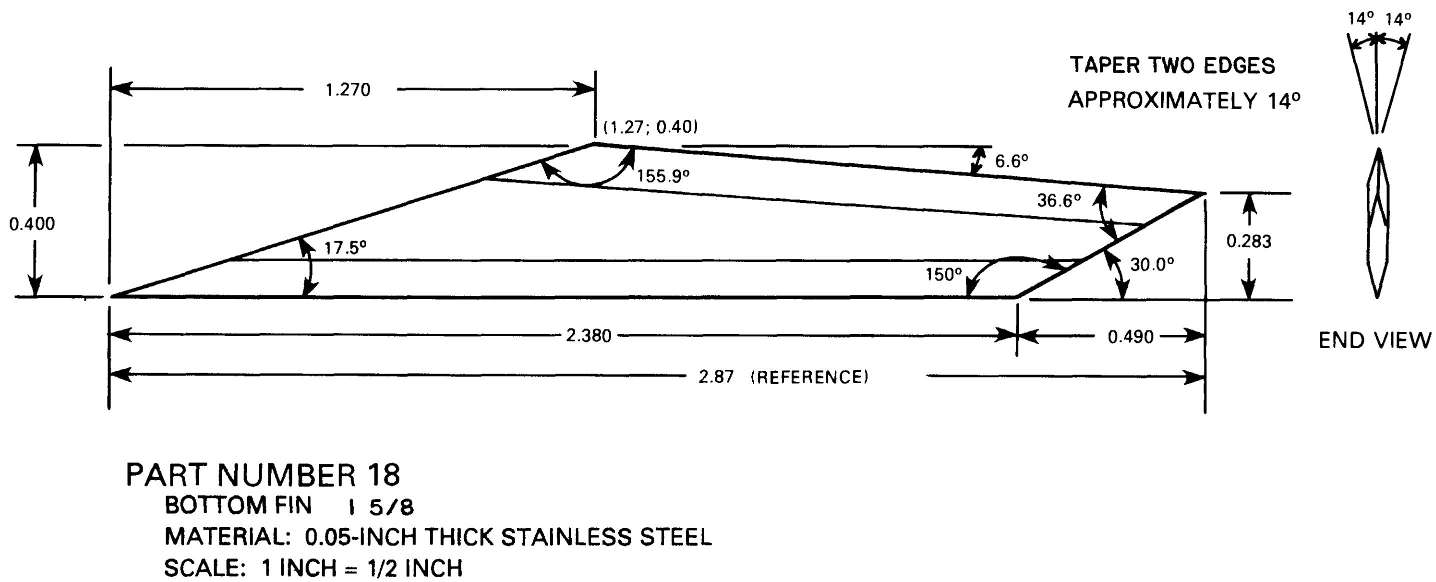
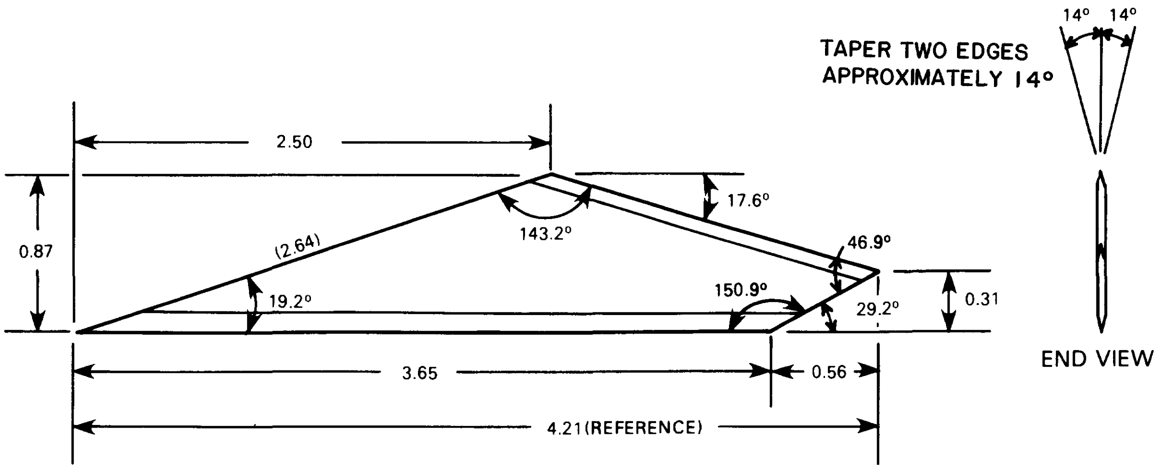


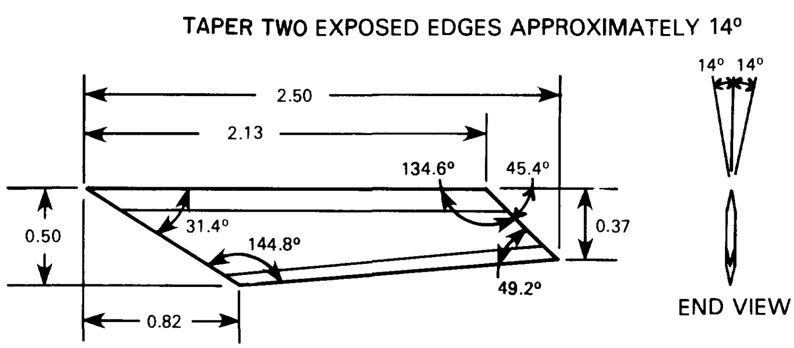
Figure 19. PN-18, bottom fin, 1 5/8.

*U.S. GOVERNMENT PRINTING OFFICE: 1990-0-773-204/20025



PART NUMBER 9A

TOP FIN 2 1/2
MATERIAL: 0.05-INCH THICK STAINLESS STEEL
SCALE: 1 INCH = 1 INCH



PART NUMBER 18A

BOTTOM FIN 2 1/2
MATERIAL: 0.05-INCH THICK STAINLESS STEEL
SCALE: 1 INCH = 1 INCH

Figure 20. PN-9A, top fin, 2 1/2; PN-18A, bottom fin, 2 1/2.

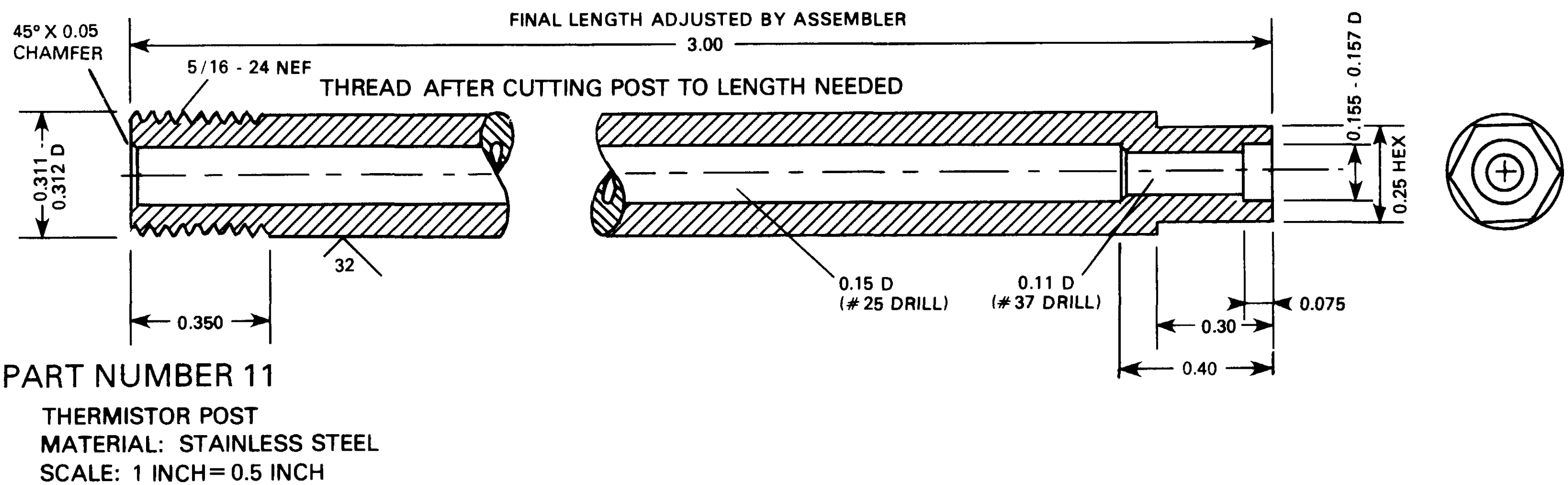
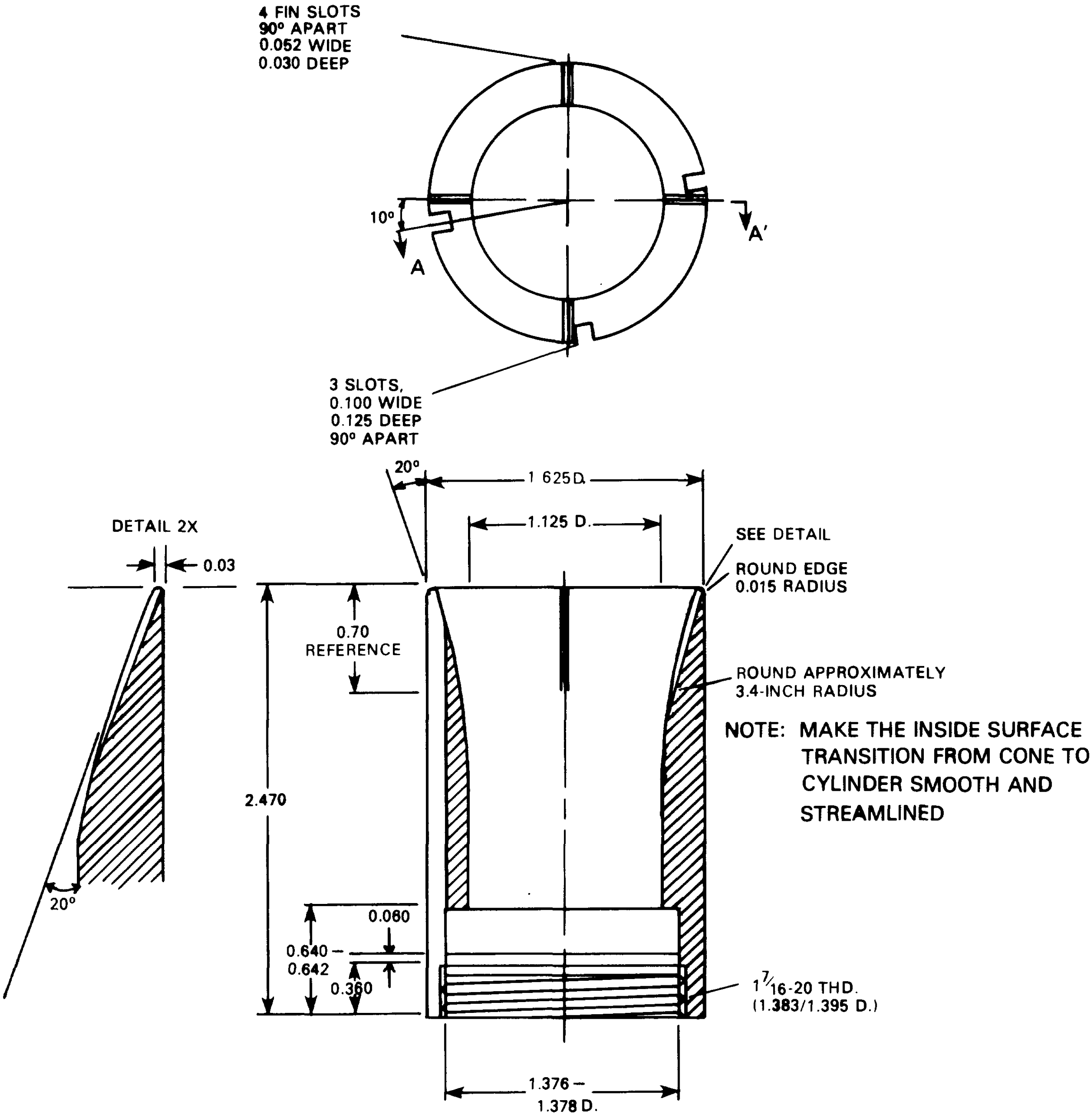


Figure 21. PN-11, thermistor post.



PART NUMBER 12 SECTION A-A'

TOP FLOW TUBE 1 5/8

MATERIAL: NON-CORRODING STAINLESS STEEL

SCALE: 1 INCH = 1 INCH

Figure 22. PN-12, top flow tube, 1 5/8.

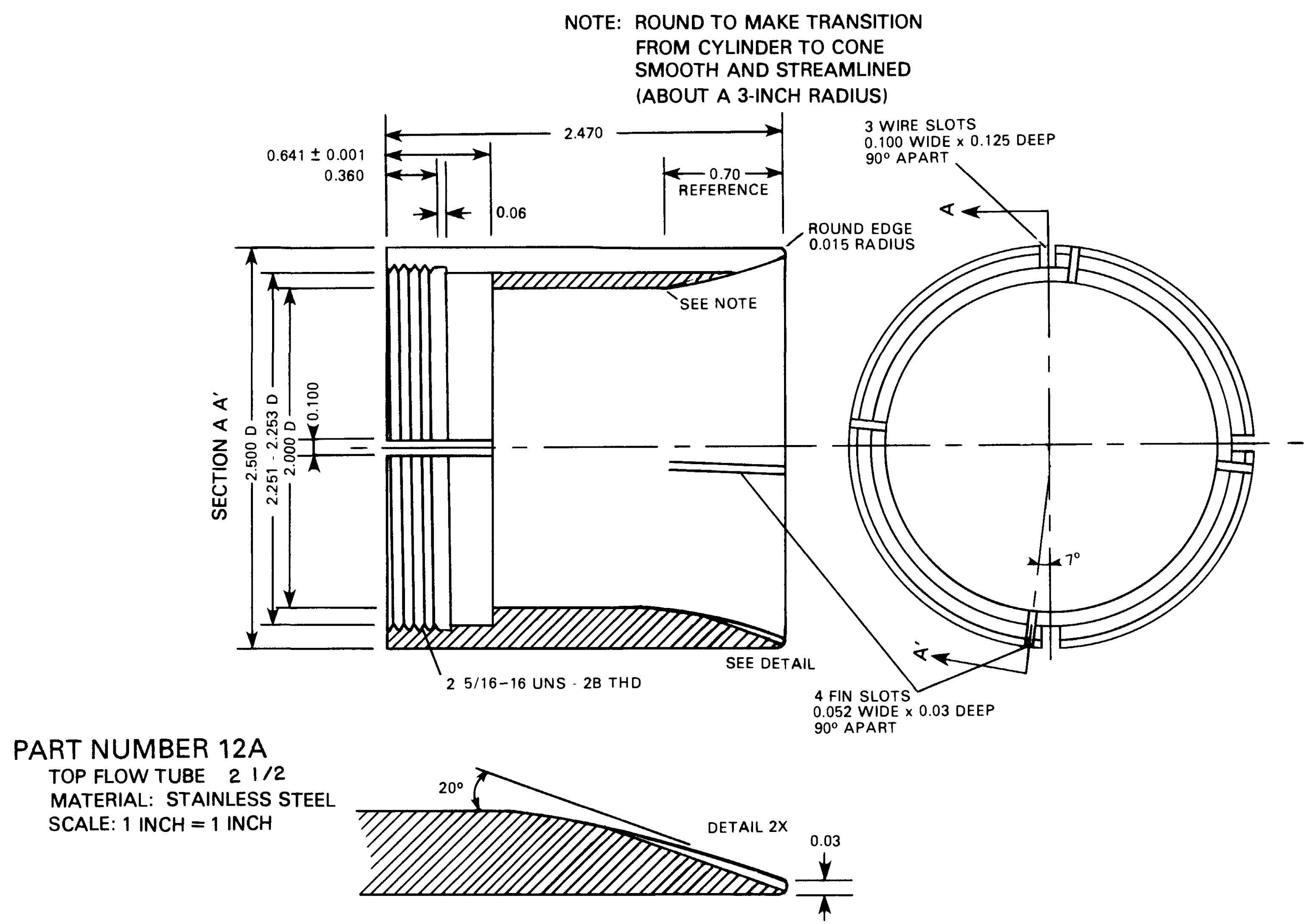
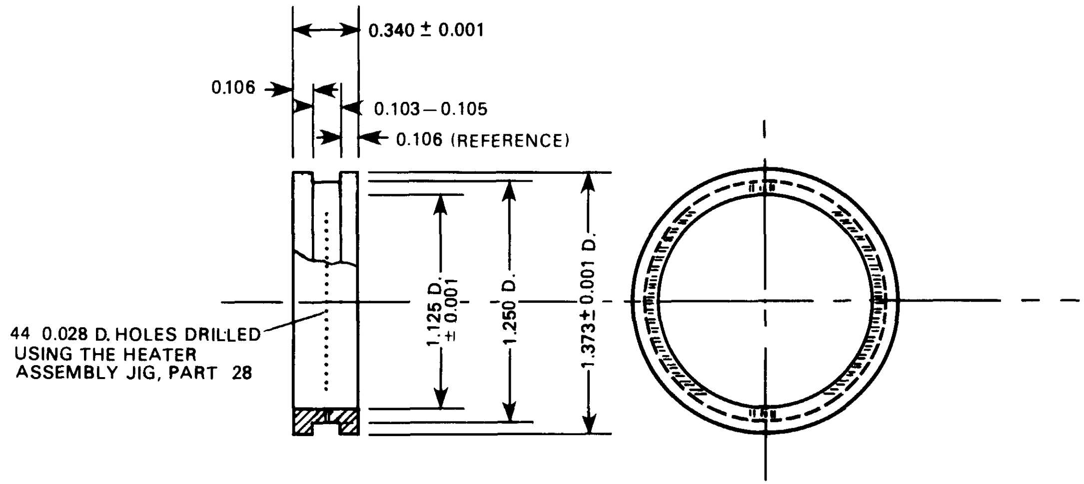


Figure 23. PN-12A, top flow tube, 2 1/2.



PART NUMBER 13
1 5/8-INCH HEATER FRAME
MATERIAL: NYLON (OR DELRYN)
SCALE: 1 INCH = 1 INCH

Figure 24. PN-13, heater frame, 1 5/8.

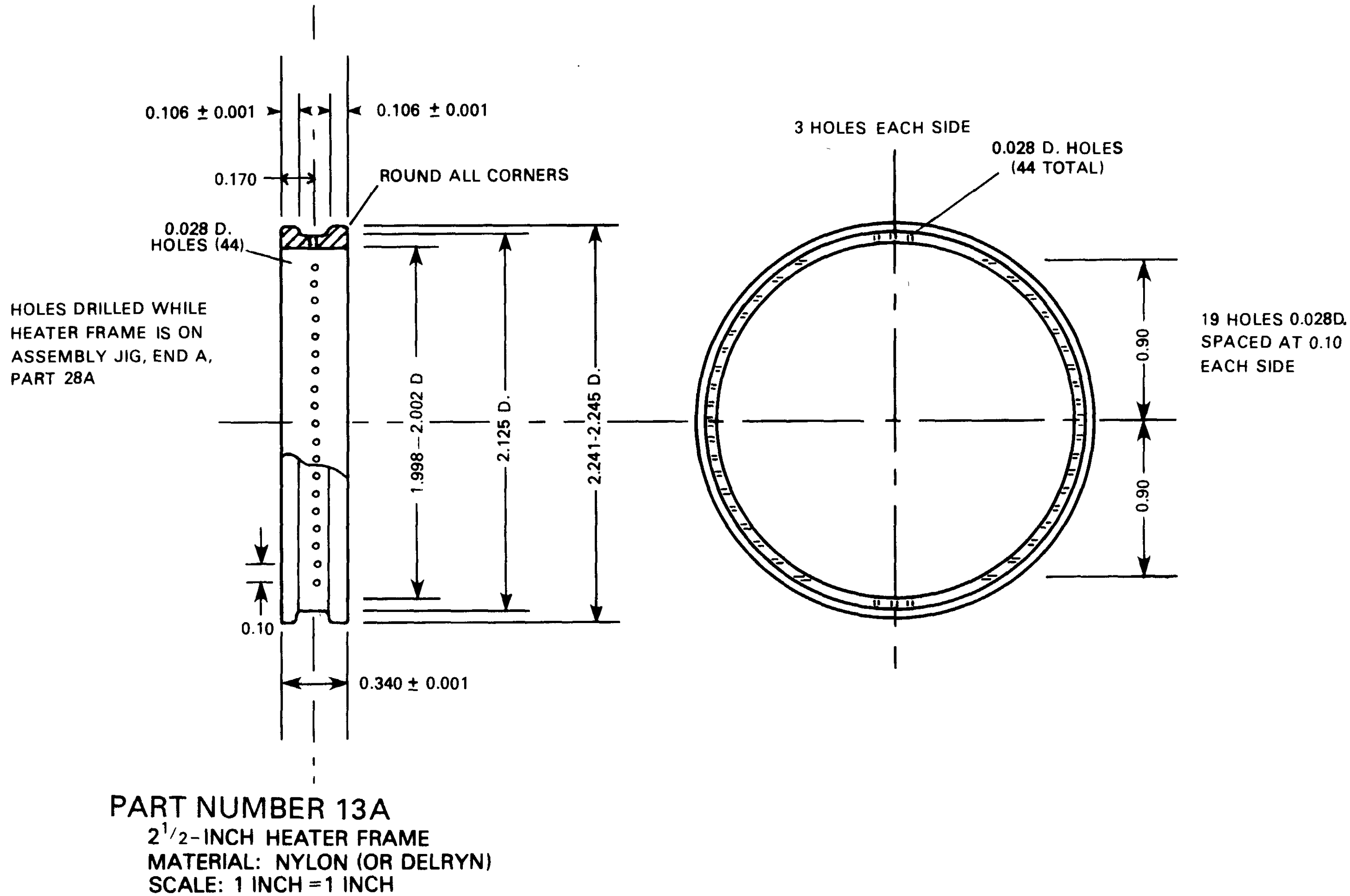


Figure 25. PN-13A, heater frame, 2 1/5.

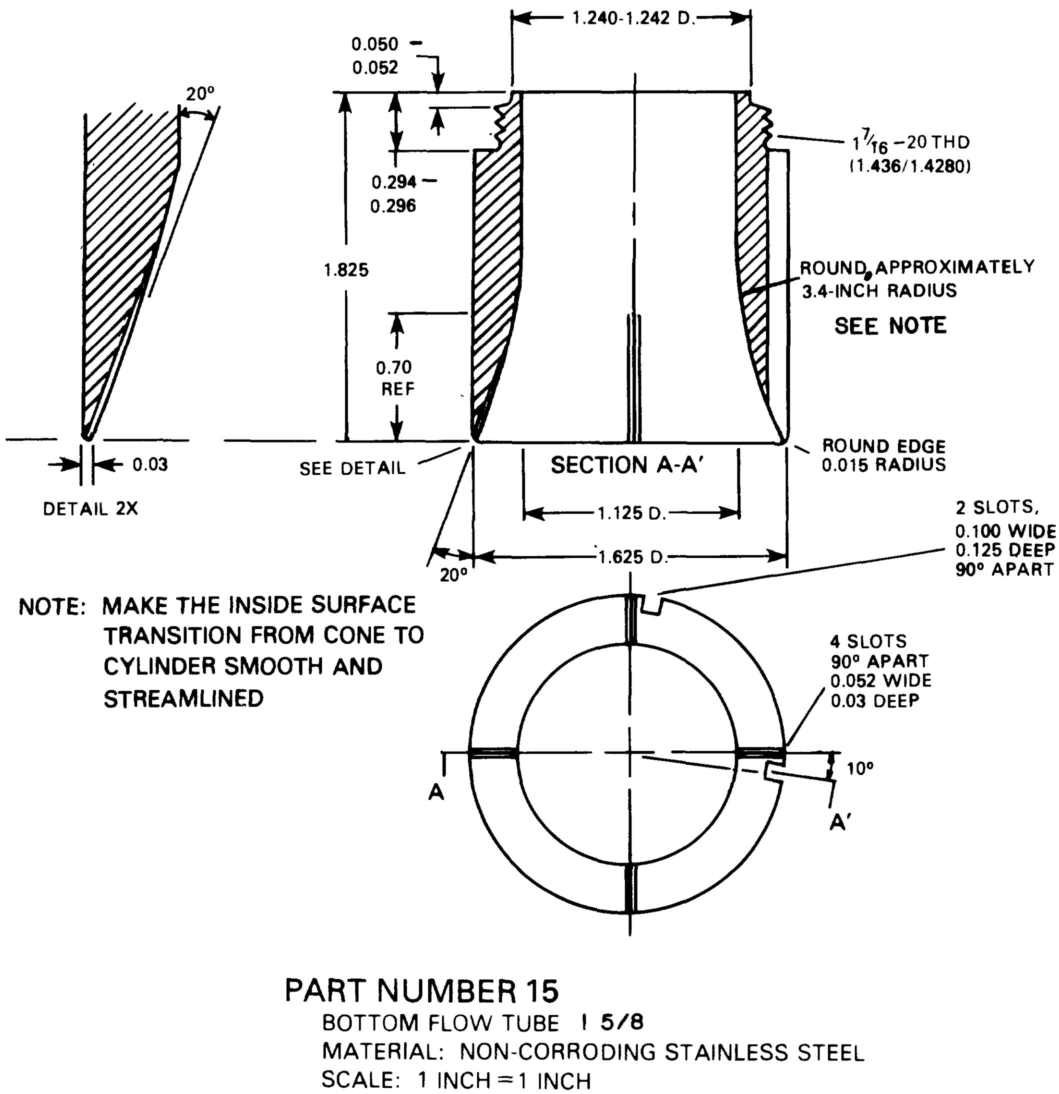


Figure 26. PN-15, bottom flow tube, 1 5/8.

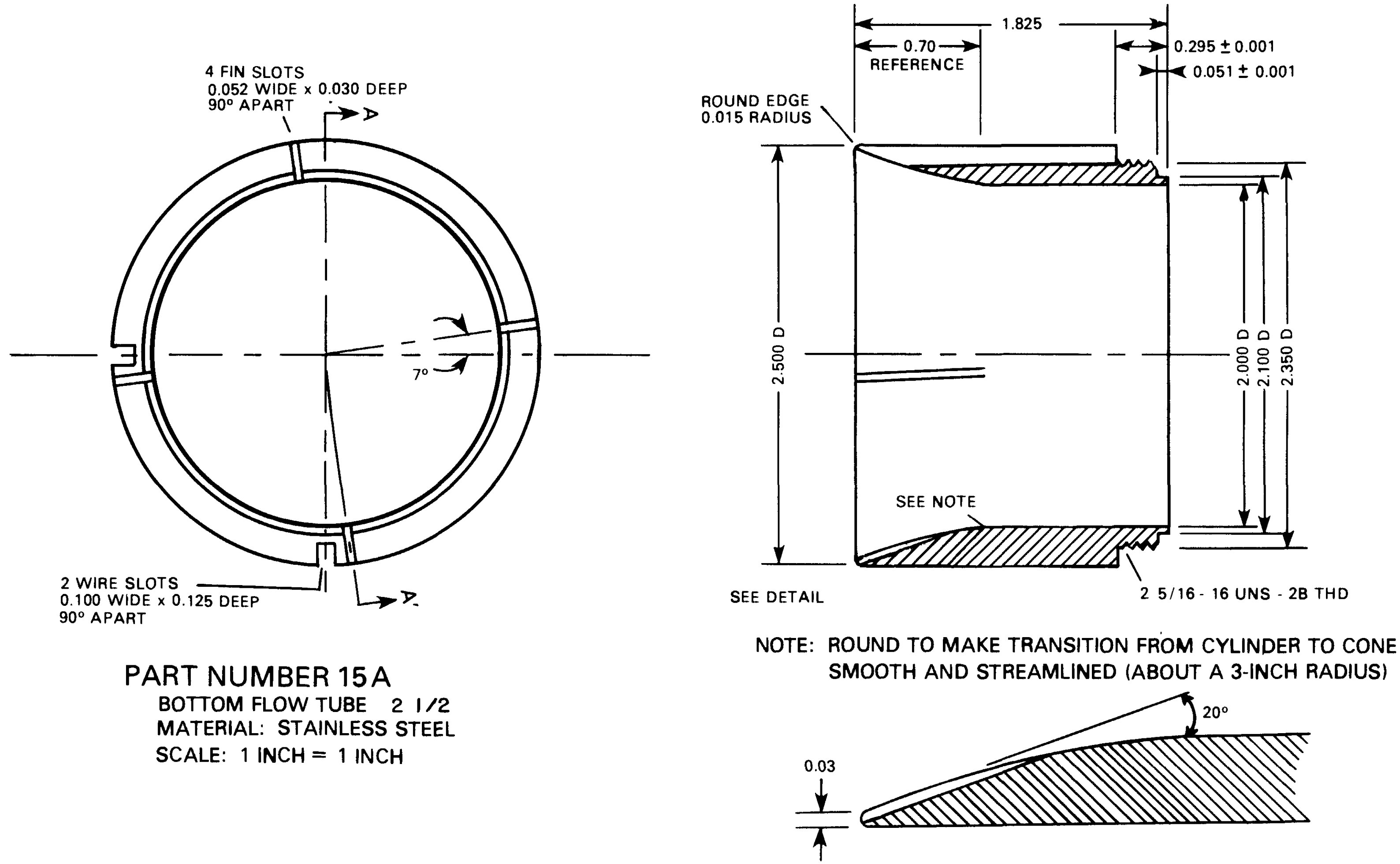


Figure 27. PN-15A, bottom flow tube, 2 1/2.

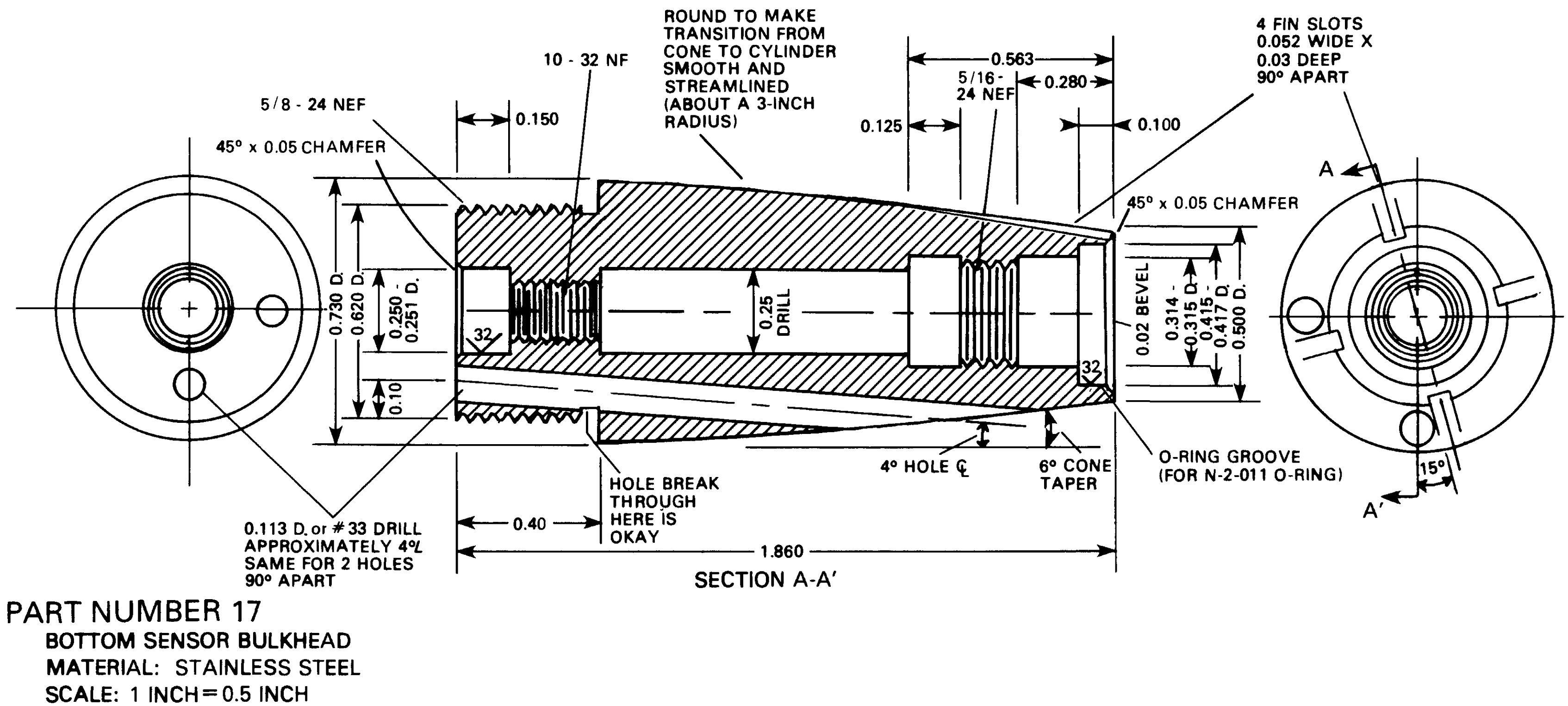


Figure 28. PN-17, bottom sensor bulkhead.

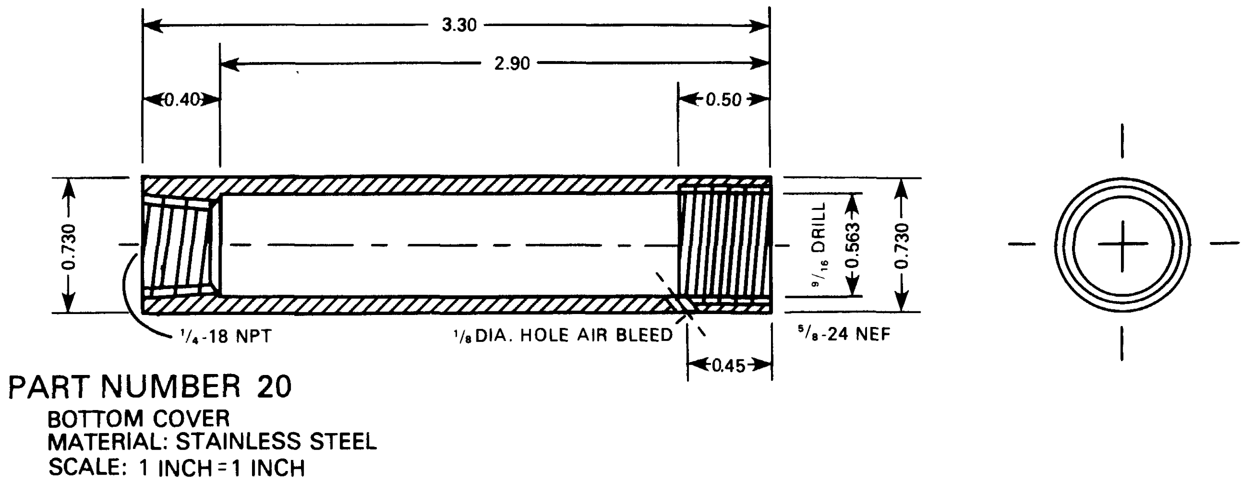


Figure 29. PN-20, bottom cover.

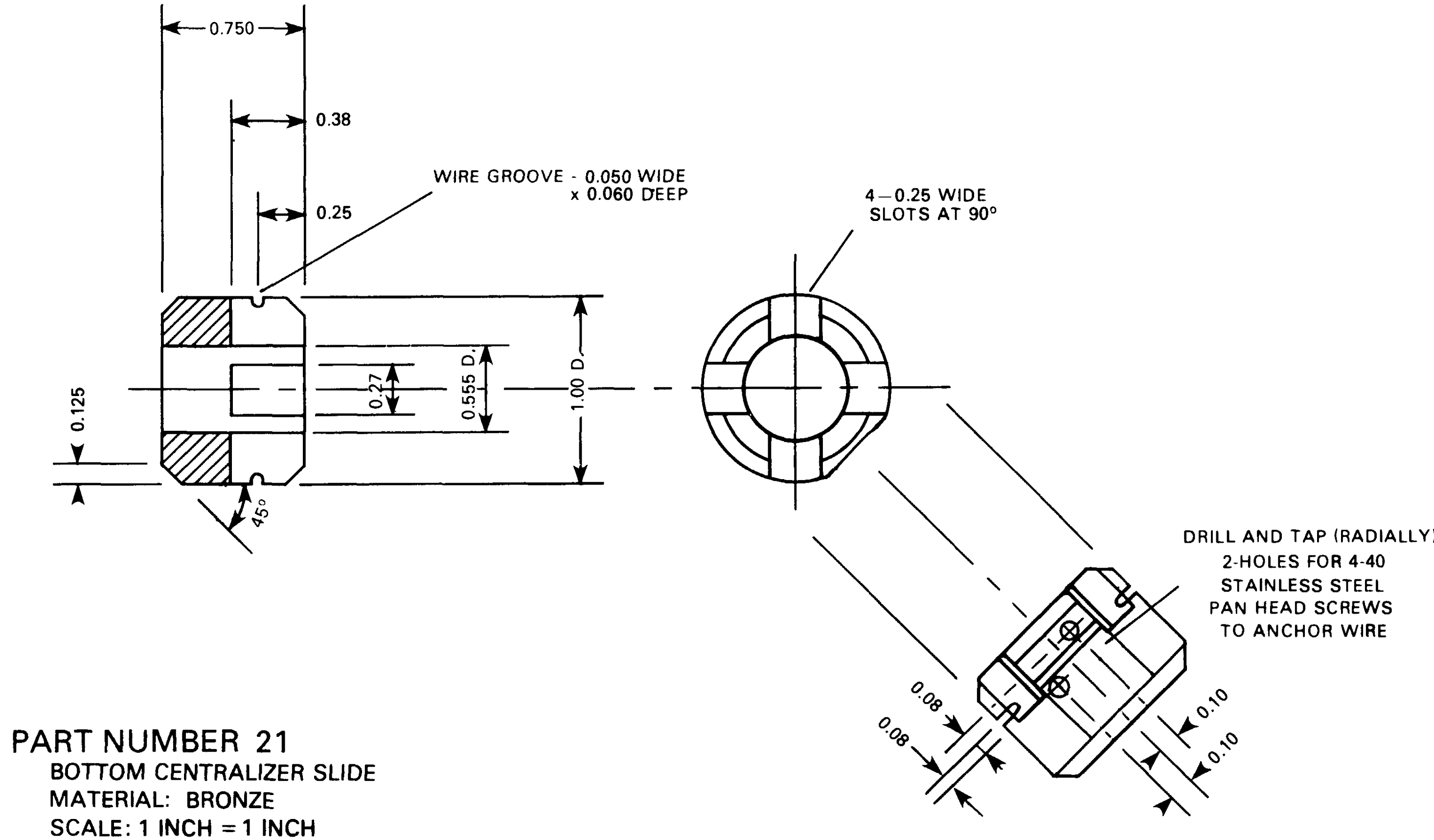


Figure 30. PN-21, bottom centralizer slide.

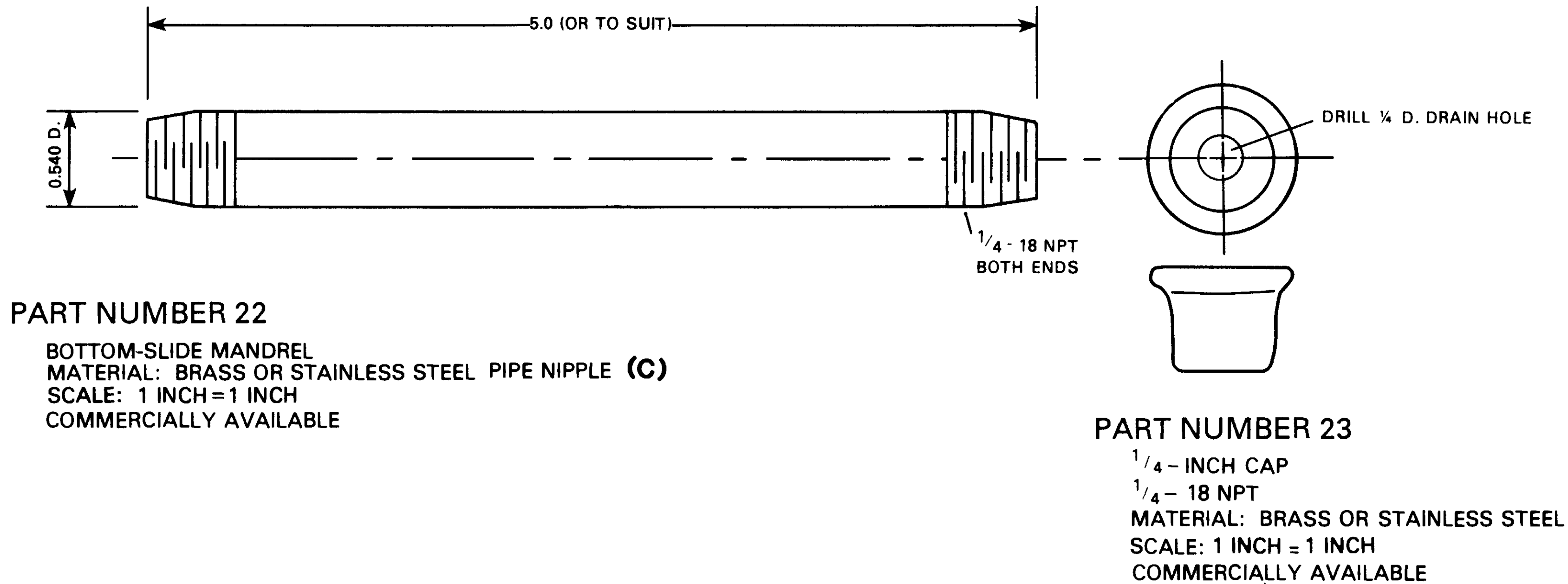
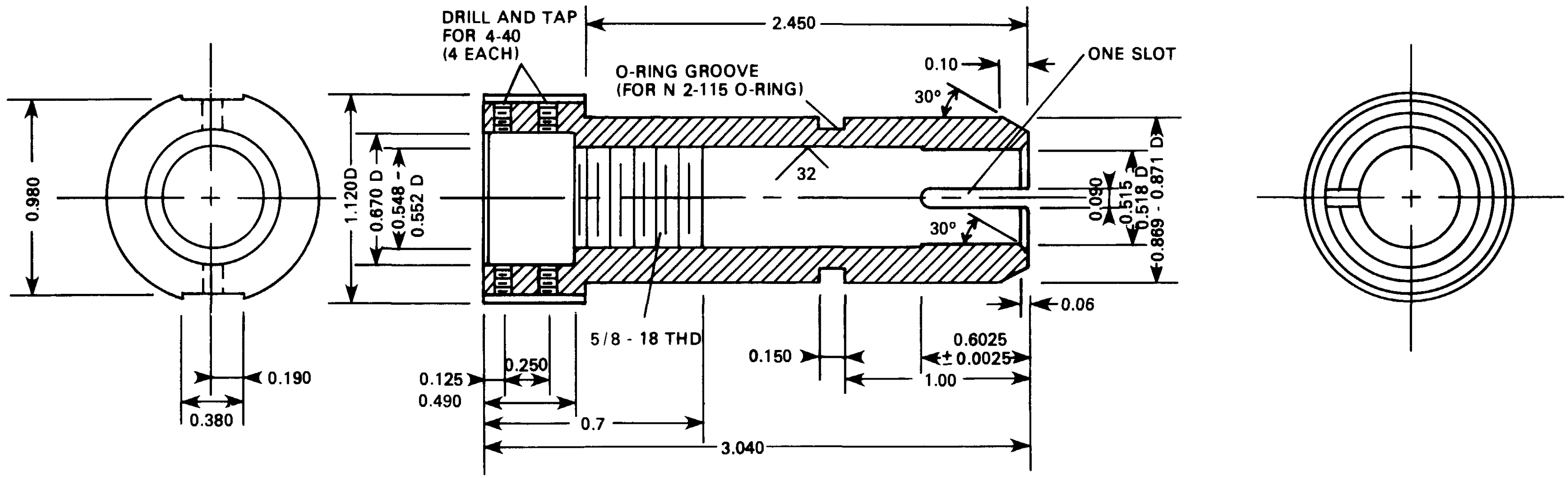


Figure 31. PN-22, bottom slide mandrel (1/4 in pipe nipple) (C);
PN-23, 1/4 in pipe cap (C).



PART NUMBER 26
PROBE CONNECTOR CARRIER
MATERIAL: BRASS
SCALE: 1 INCH = 1 INCH

Figure 32. PN-26, probe connector carrier.

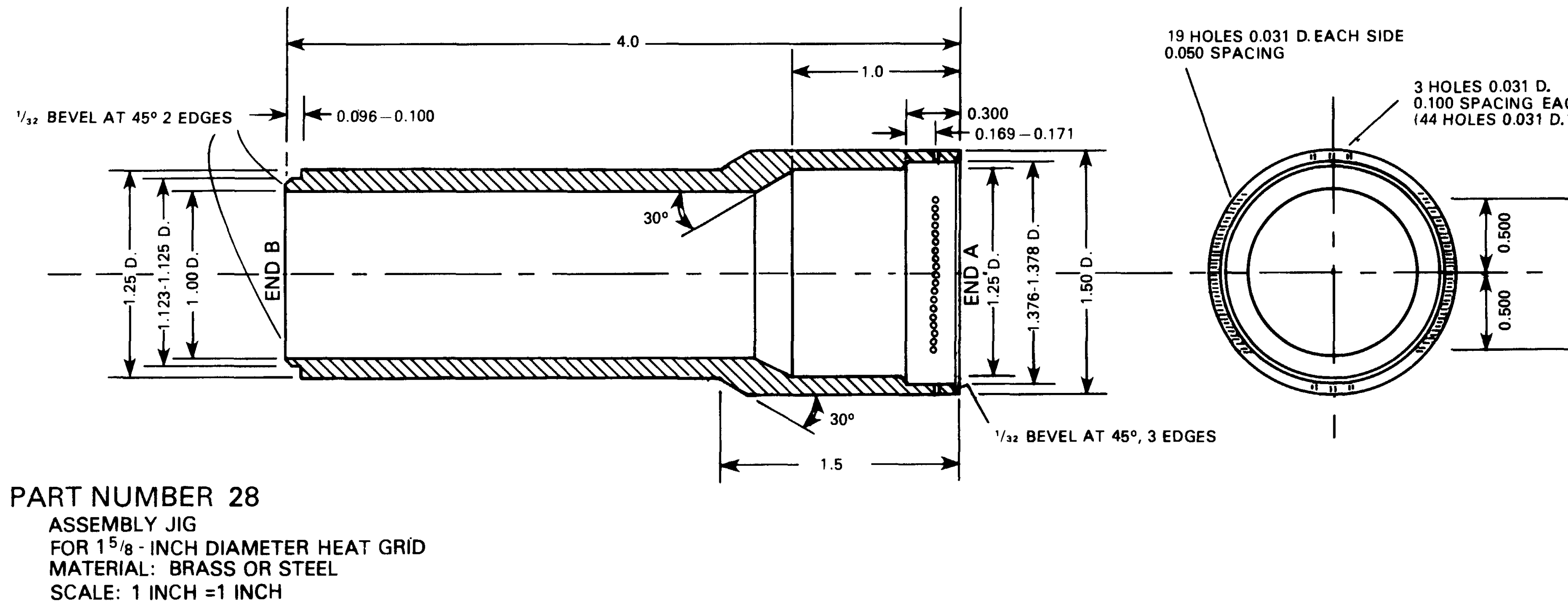
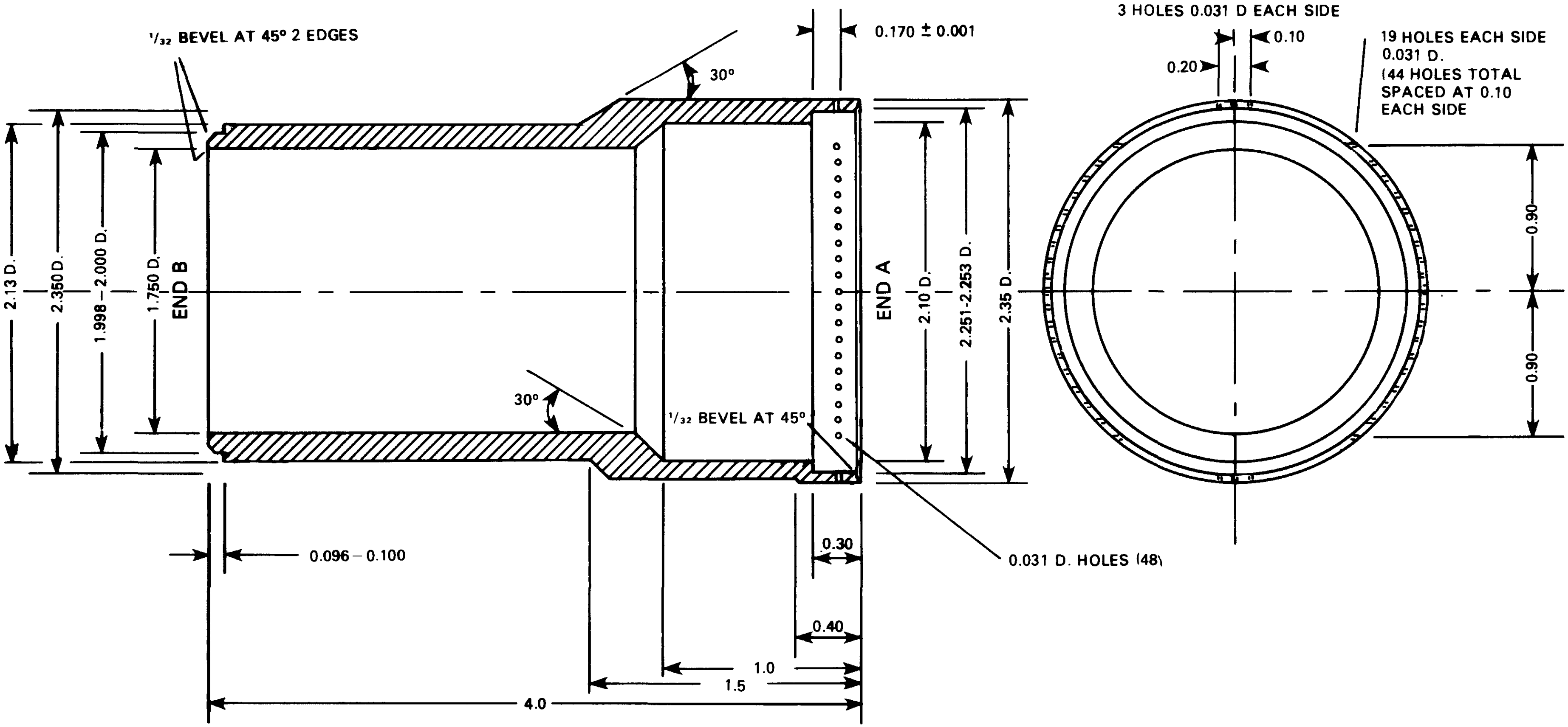
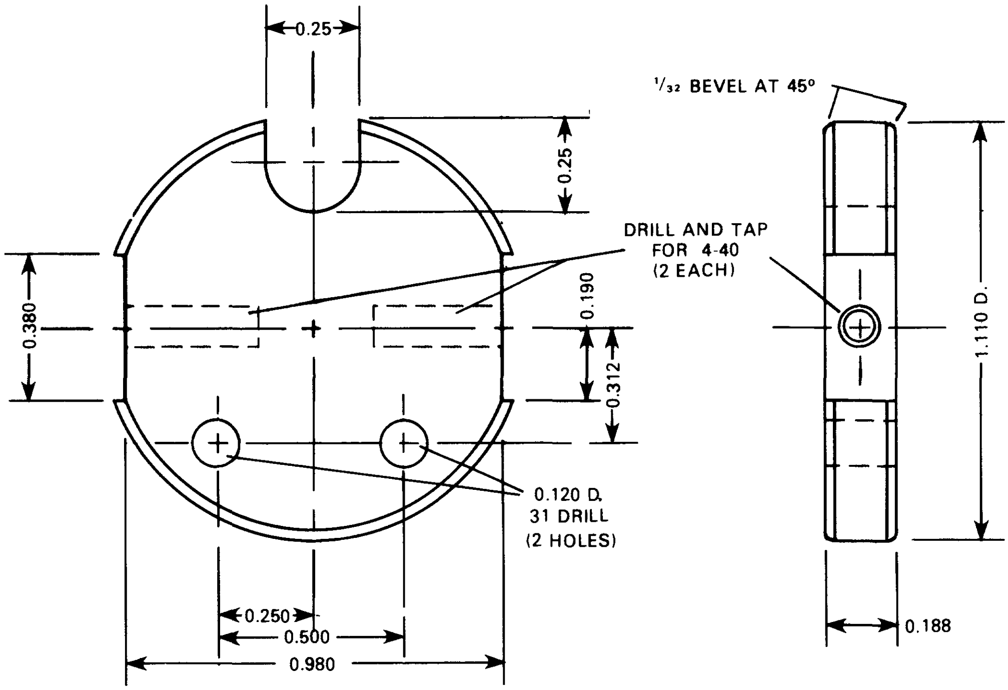


Figure 33. PN-28, heater assembly jig, 1 5/8.



PART NUMBER 28A
ASSEMBLY JIG
FOR 2 1/2-INCH DIAMETER HEAT GRID
MATERIAL: BRASS
SCALE: 1 INCH = 1 INCH

Figure 34. PN-28A, heater assembly jig, 2 1/5.

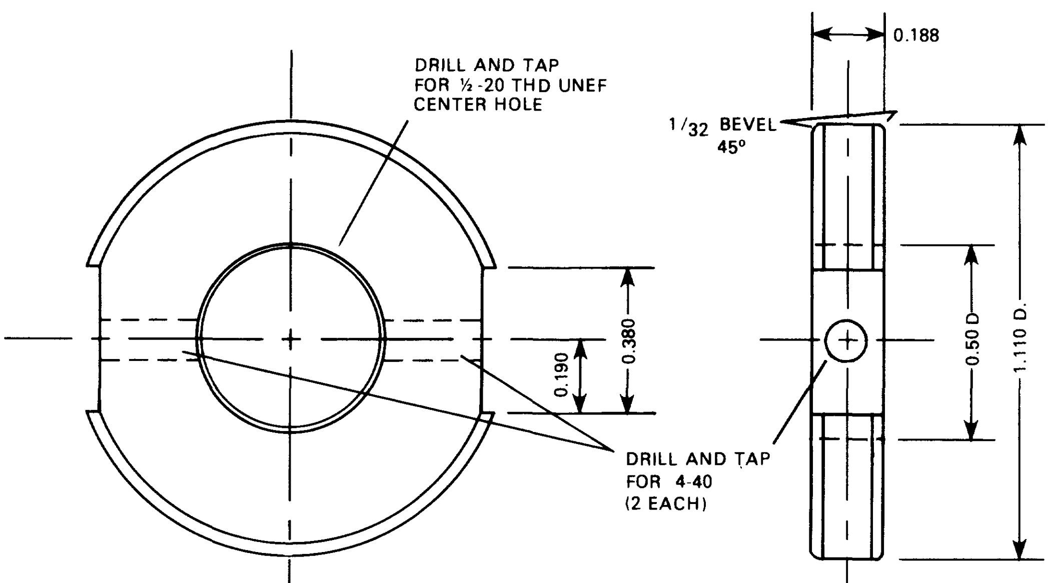


PART NUMBER 30

BULKHEAD

MATERIAL: BRASS

SCALE: 1 INCH=0.5 INCH



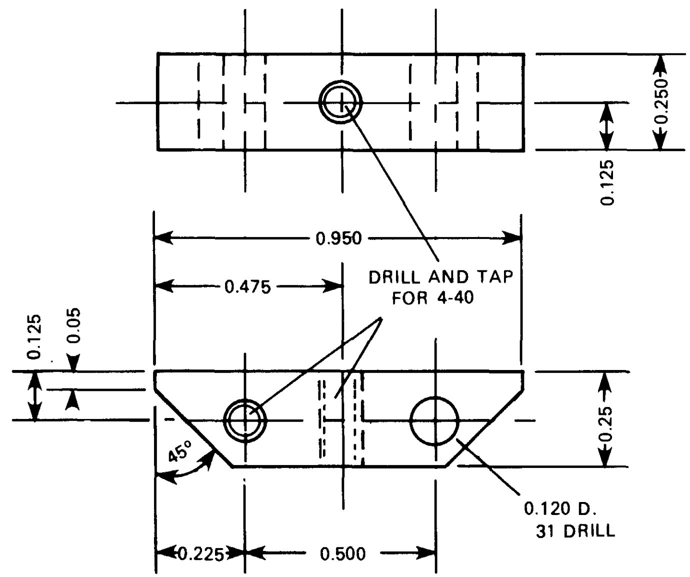
PART NUMBER 31

BULKHEAD

MATERIAL: BRASS

SCALE: 1 INCH=0.5 INCH

Figure 35. PN-30, bulkhead; PN-31, bulkhead.



PART NUMBER 32
PRINTED CIRCUIT BOARD MOUNTING BLOCK
MATERIAL: ¼-INCH SQUARE BRASS BAR STOCK
SCALE: 1 INCH= 0.5 INCH

Figure 36. PN-32, printed circuit board mounting block.

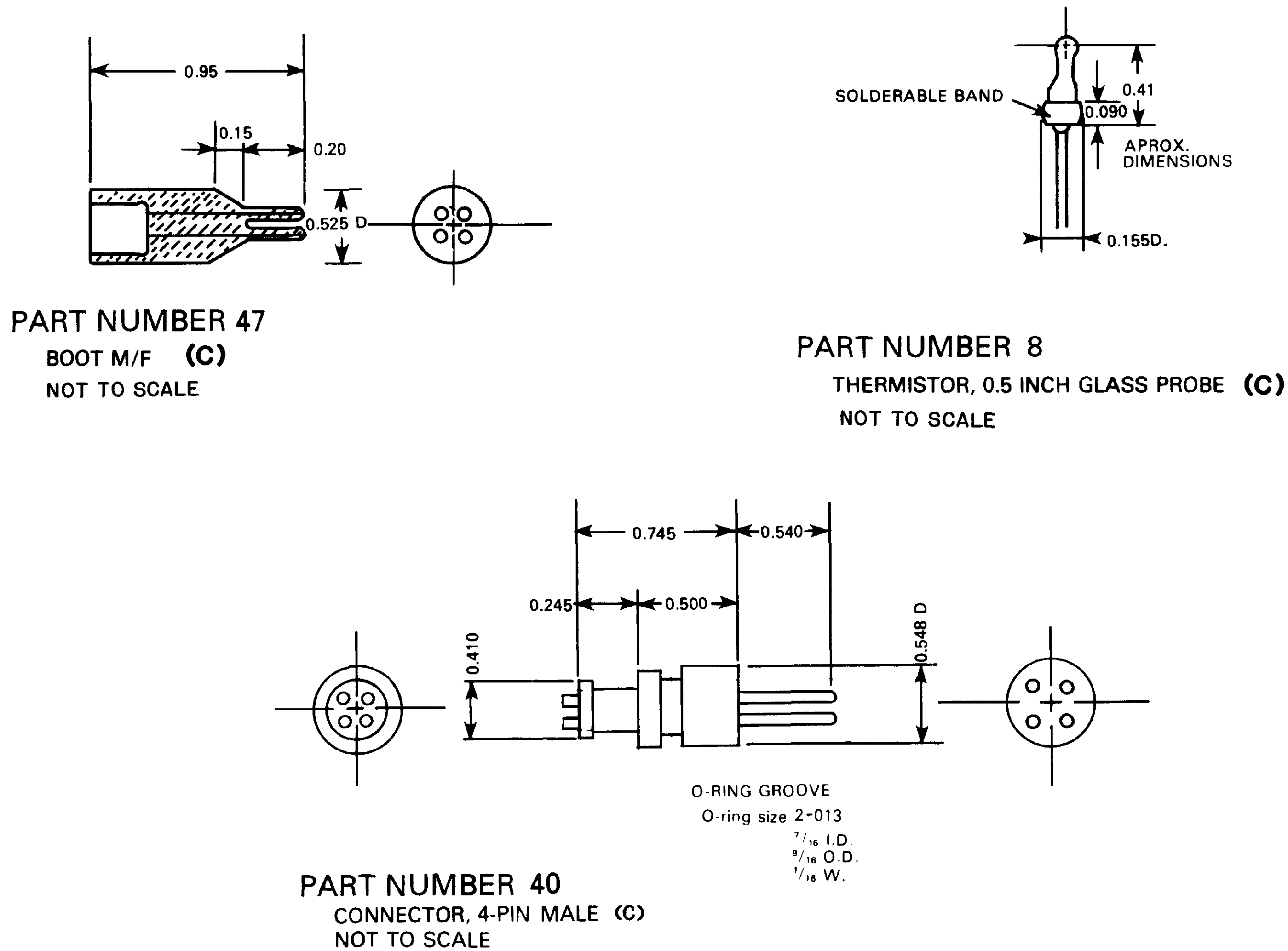
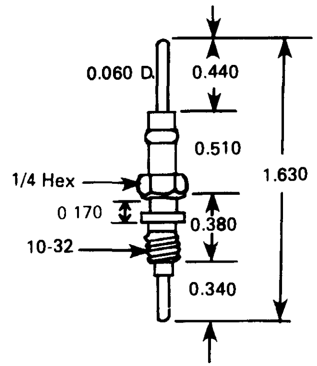
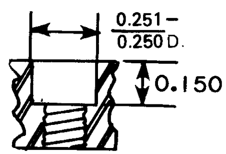


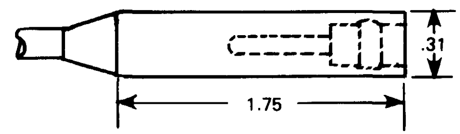
Figure 37. PN-8, thermister (C); PN-40, 4-pin male connector (C); PN-47,connector boot (C).



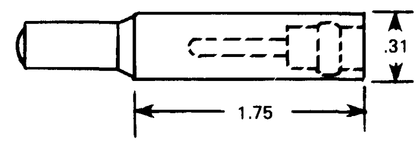
PART NUMBER 44 (C)
HIGH PRESSURE WATER PROOF
FEEDTHRU, MALE, PLASTIC, 20,000 psi
NOT TO SCALE



MOUNTING DETAIL

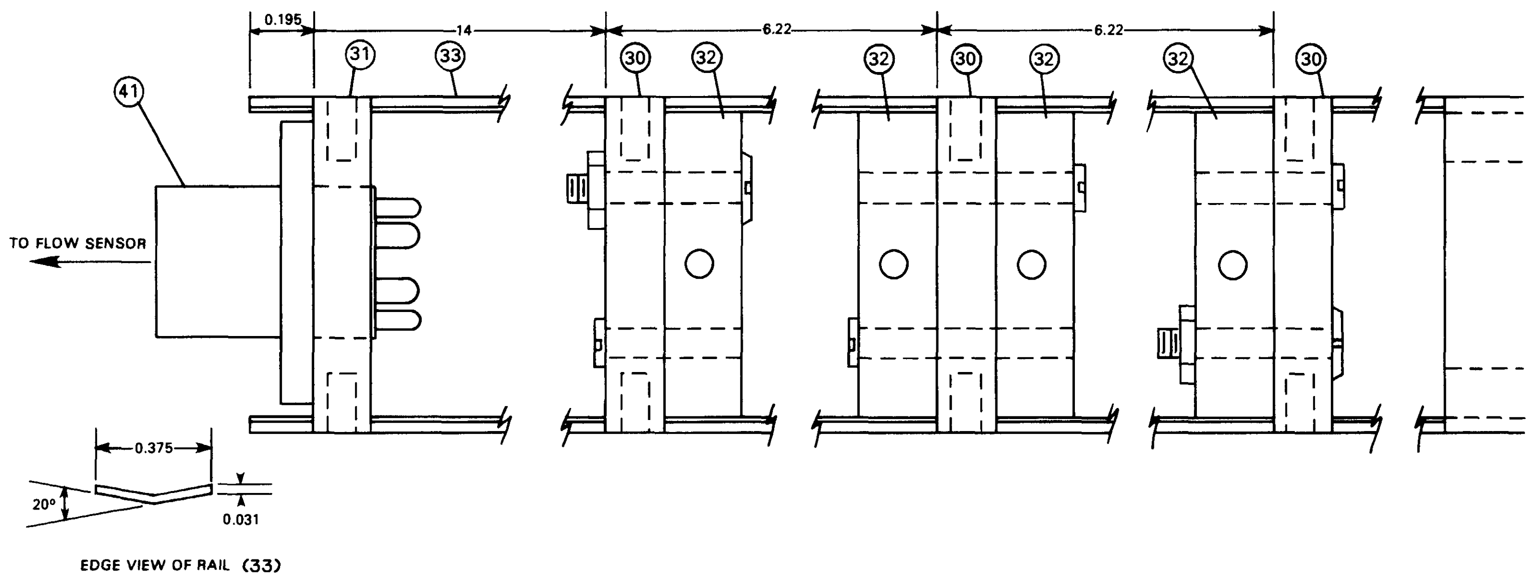


PART NUMBER 45 (C)
CABLE ASSEMBLY, MOULDED
FEMALE WITH 24 INCH CABLE,
0.105 INCH DIA
NOT TO SCALE



PART NUMBER 46 (C)
CONNECTOR, FEMALE, FOR
0.105-INCH DIAMETER CABLE
NOT TO SCALE

Figure 38. PN-44, high-pressure waterproof feedthrough (C) with mounting detail; PN-45, moulded waterproof connector and cable (C); PN-46, moulded waterproof female connector (C).



ELECTRONICS CARRIER ASSEMBLY
MATERIAL: STEEL (OR TEMPERED ALUMINUM OR BRASS)
NOT TO SCALE

Figure 39. Electronics carrier assembly, PN-30-33, and 41.

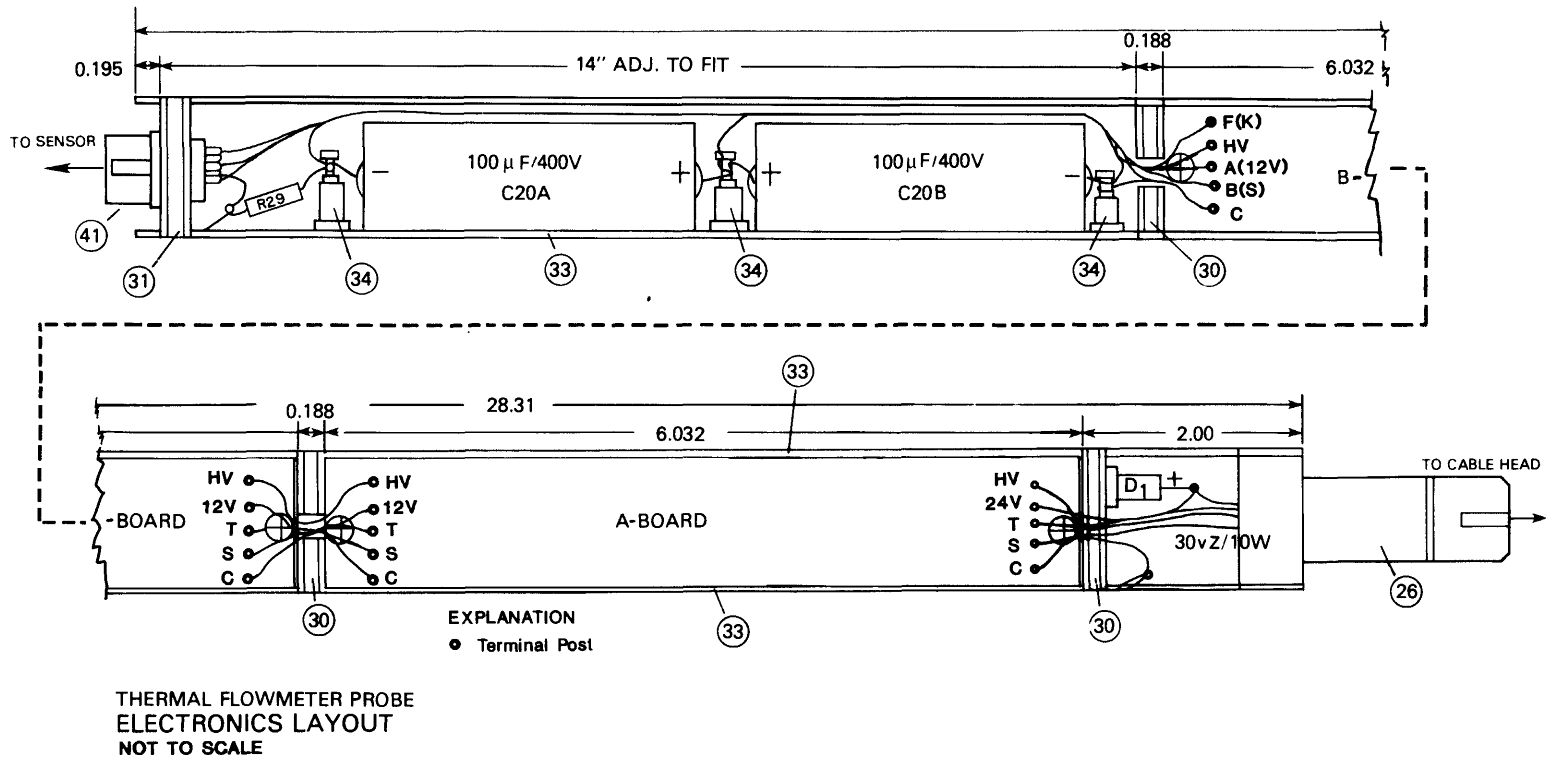


Figure 40. Probe electronics layout.

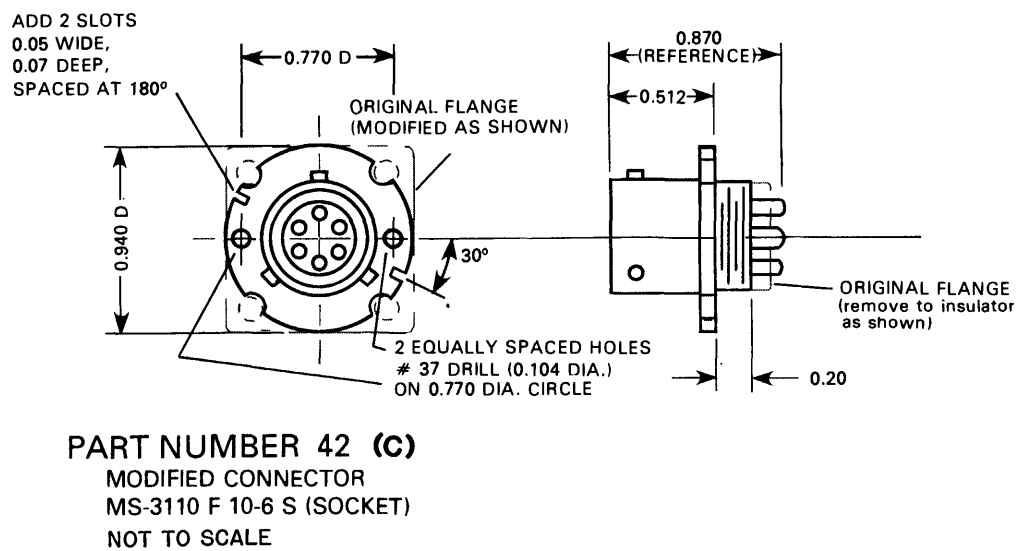


Figure 41. PN-42, modification to connector MS3110F10-6S.

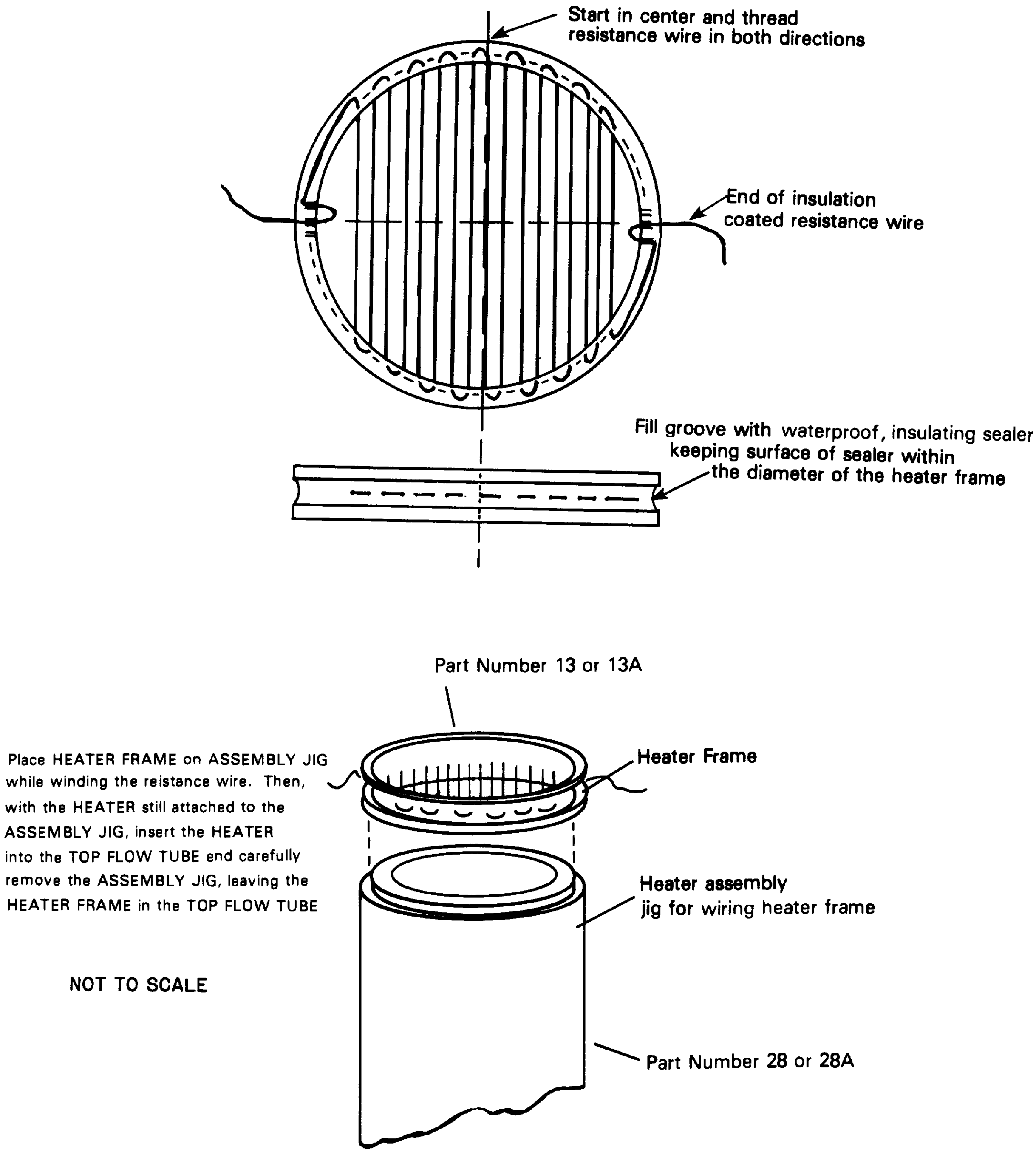


Figure 42. Assembly of heater (13 or 13A) using heater assembly jig (28 or 28A).

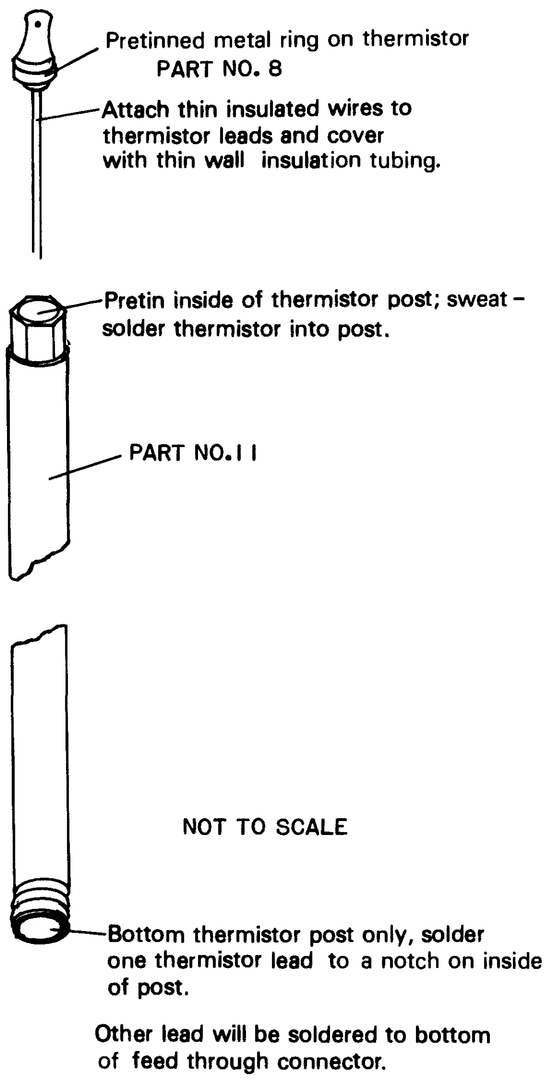


Figure 43. Assembly of thermistor (8) and post (11).

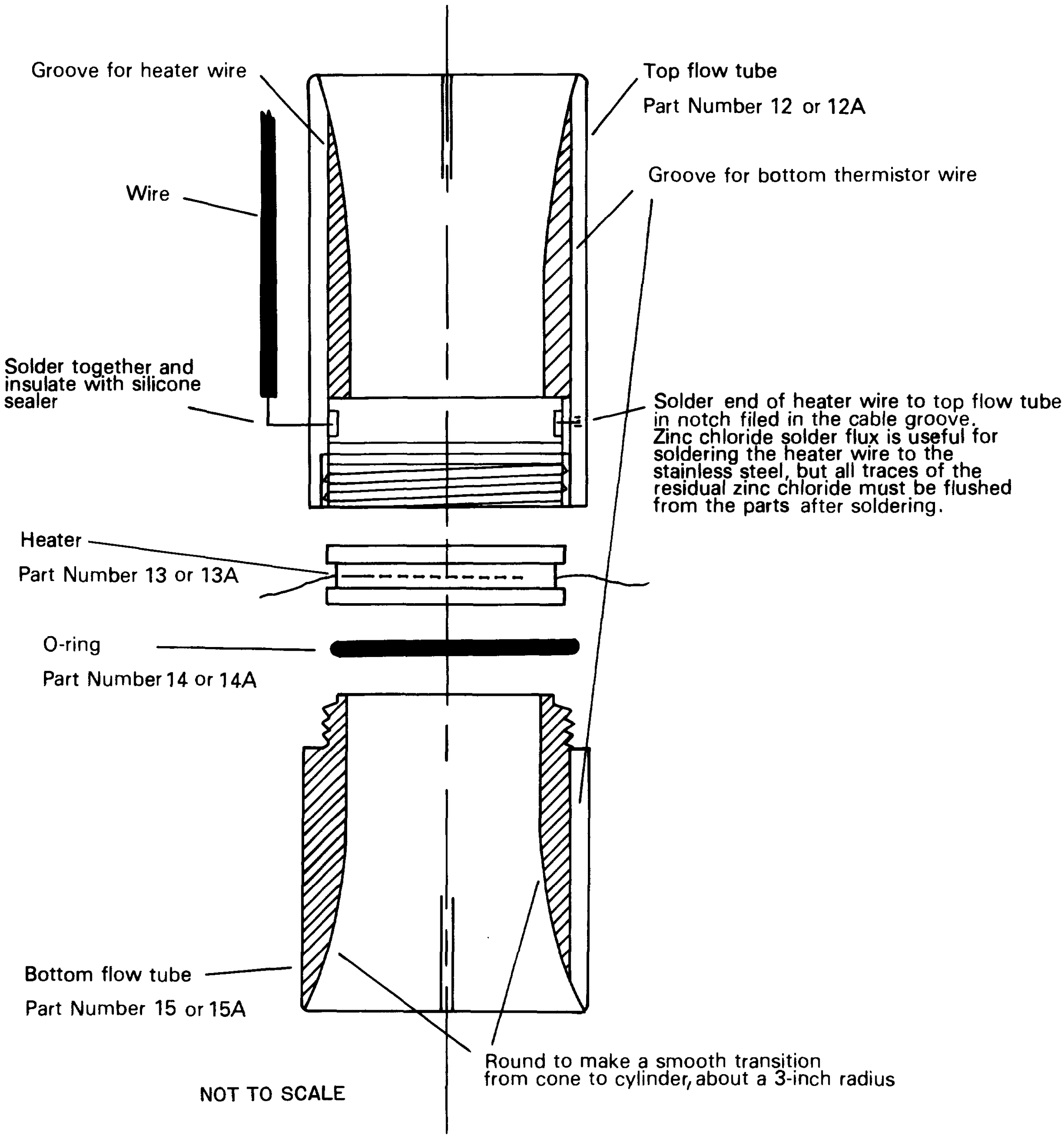
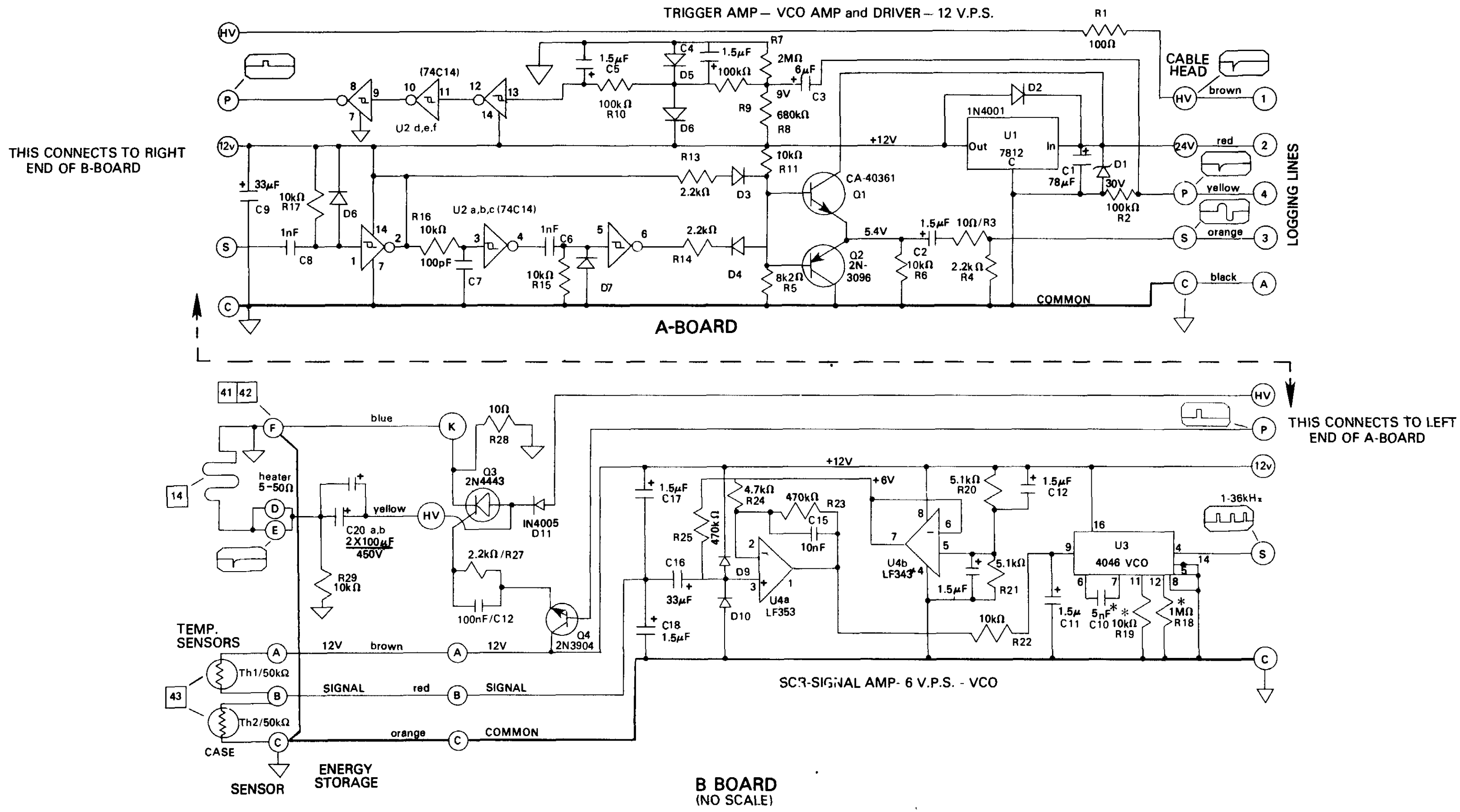


Figure 44. Assembly of flow sensor tube parts.



ALL DIODES ARE 1N914 UNLESS OTHERWISE DESIGNATED

[43] ARE PART NUMBERS

* TEMPERATURE STABLE COMPONENTS

Figure 45. Schematic of probe electronics, A- and B-boards.

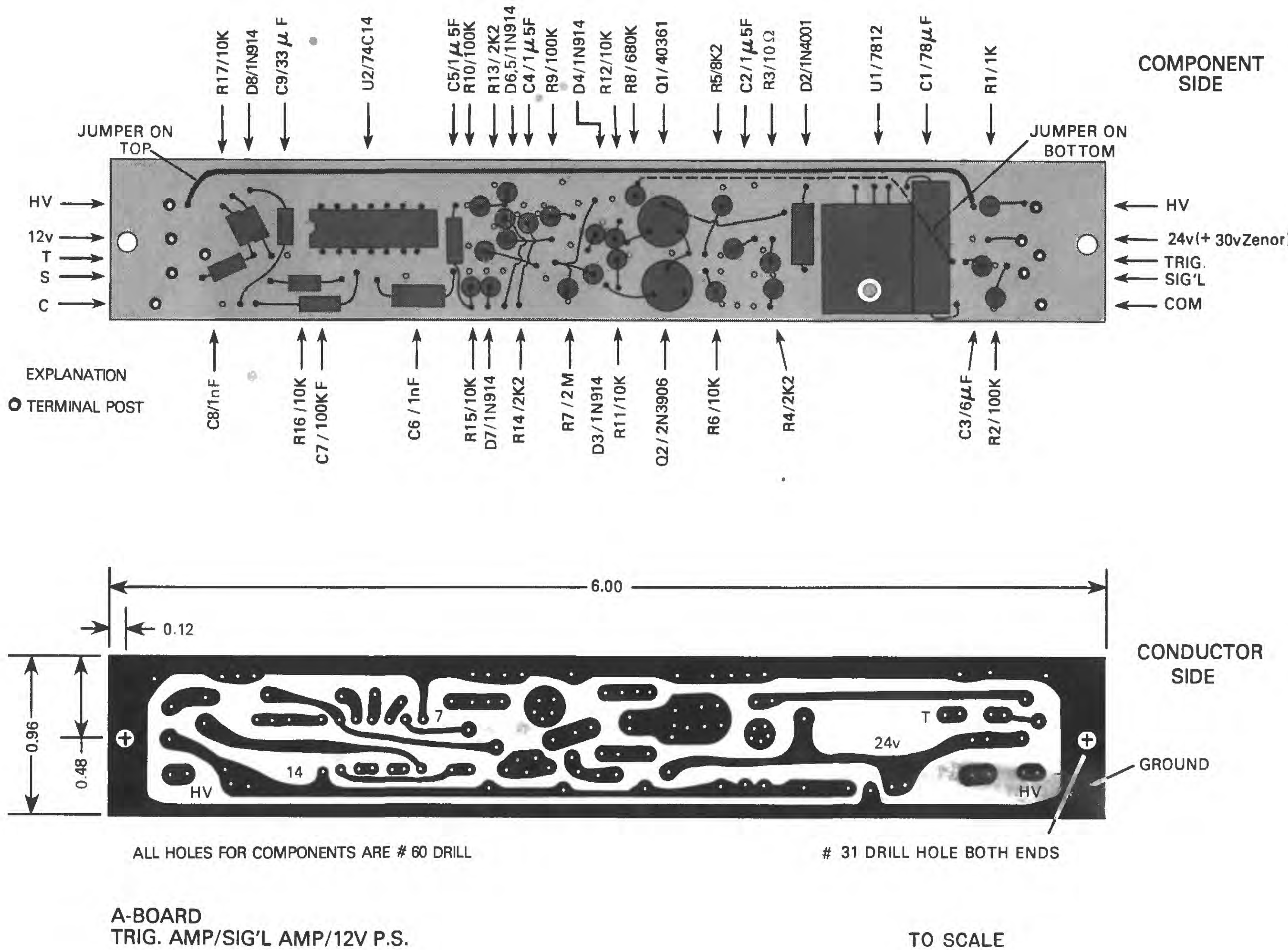


Figure 46. A circuit board, probe electronics.

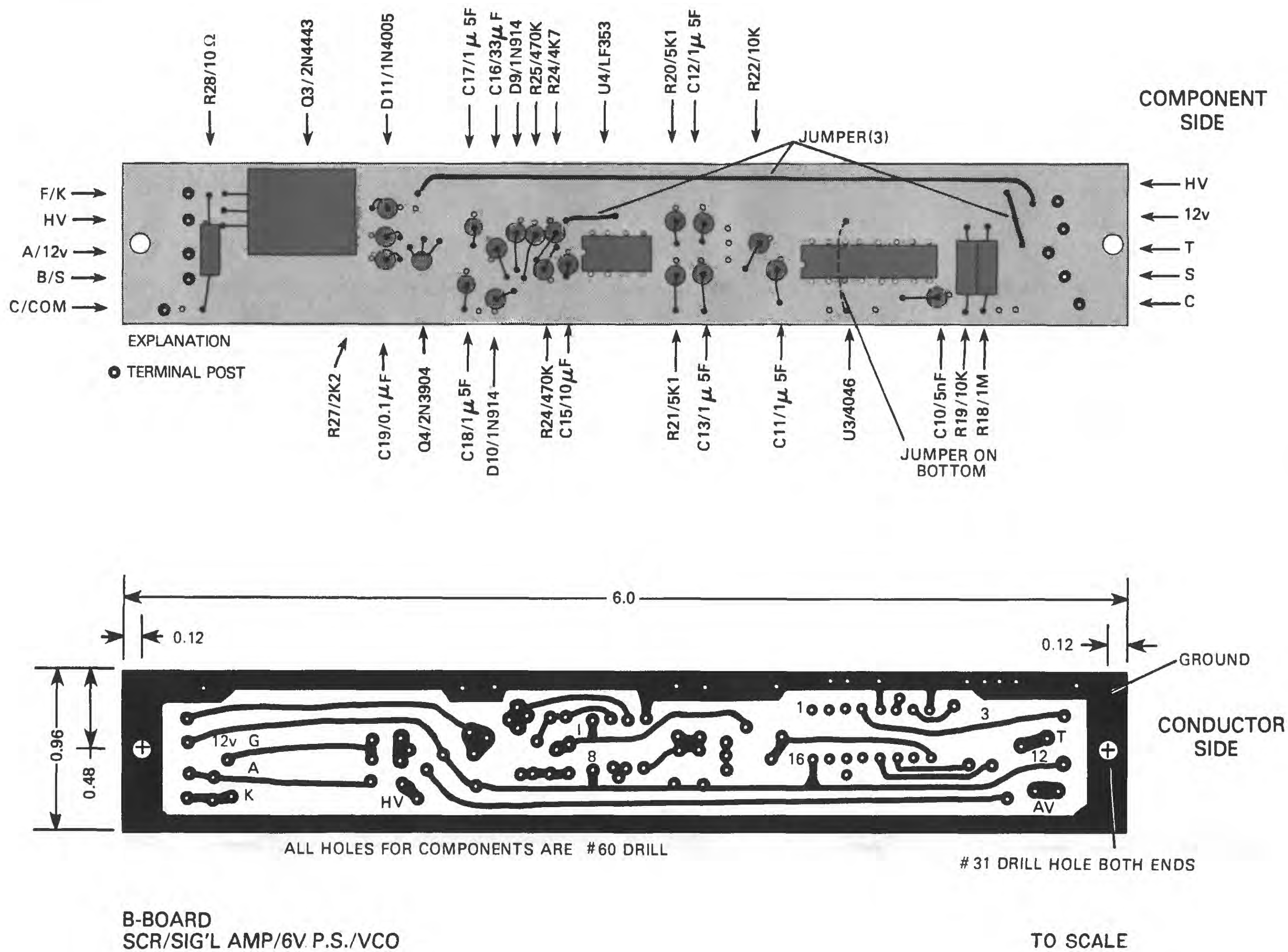


Figure 47. B circuit board, probe electronics.

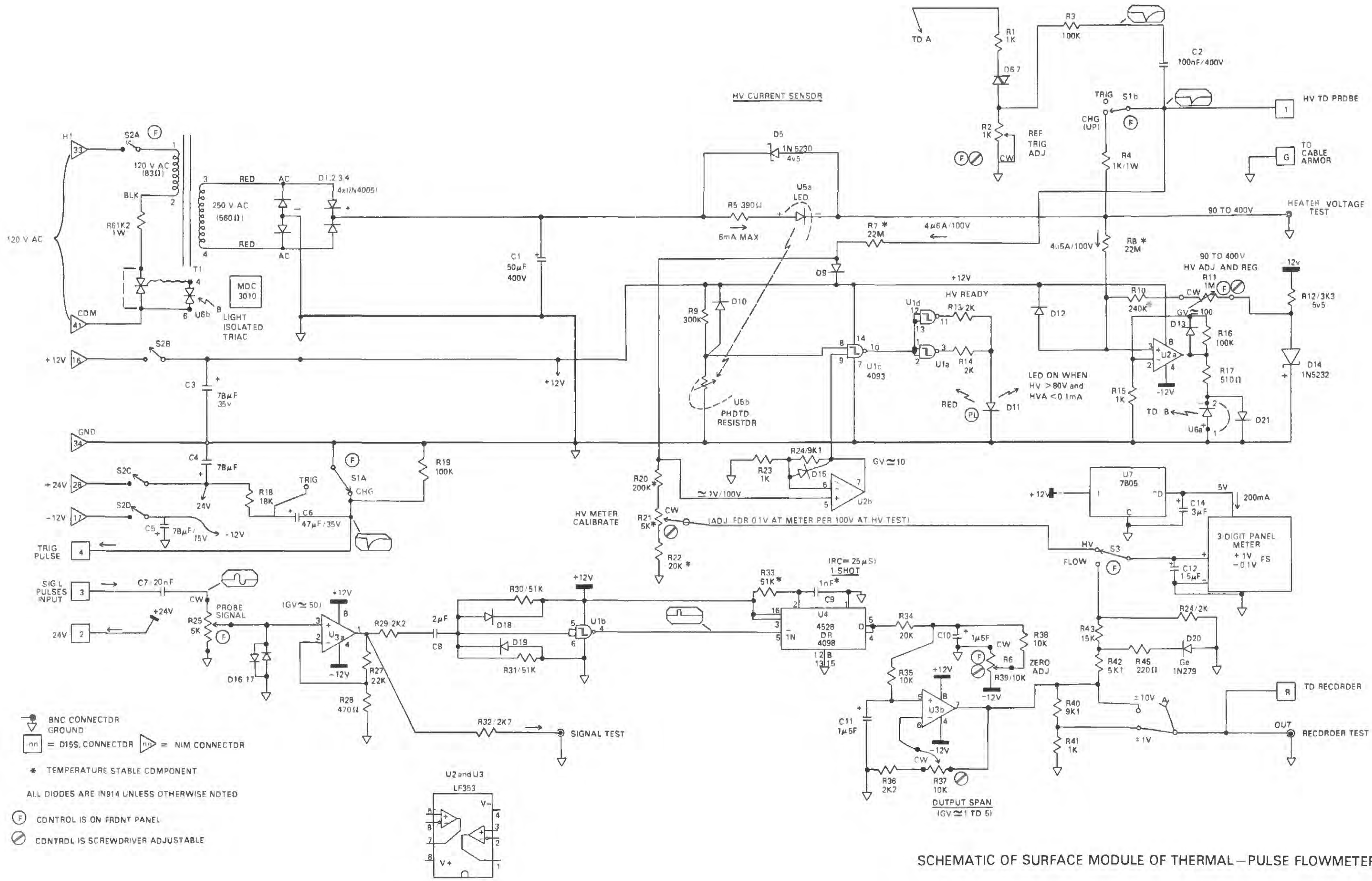


Figure 48. Schematic of surface module electronics.

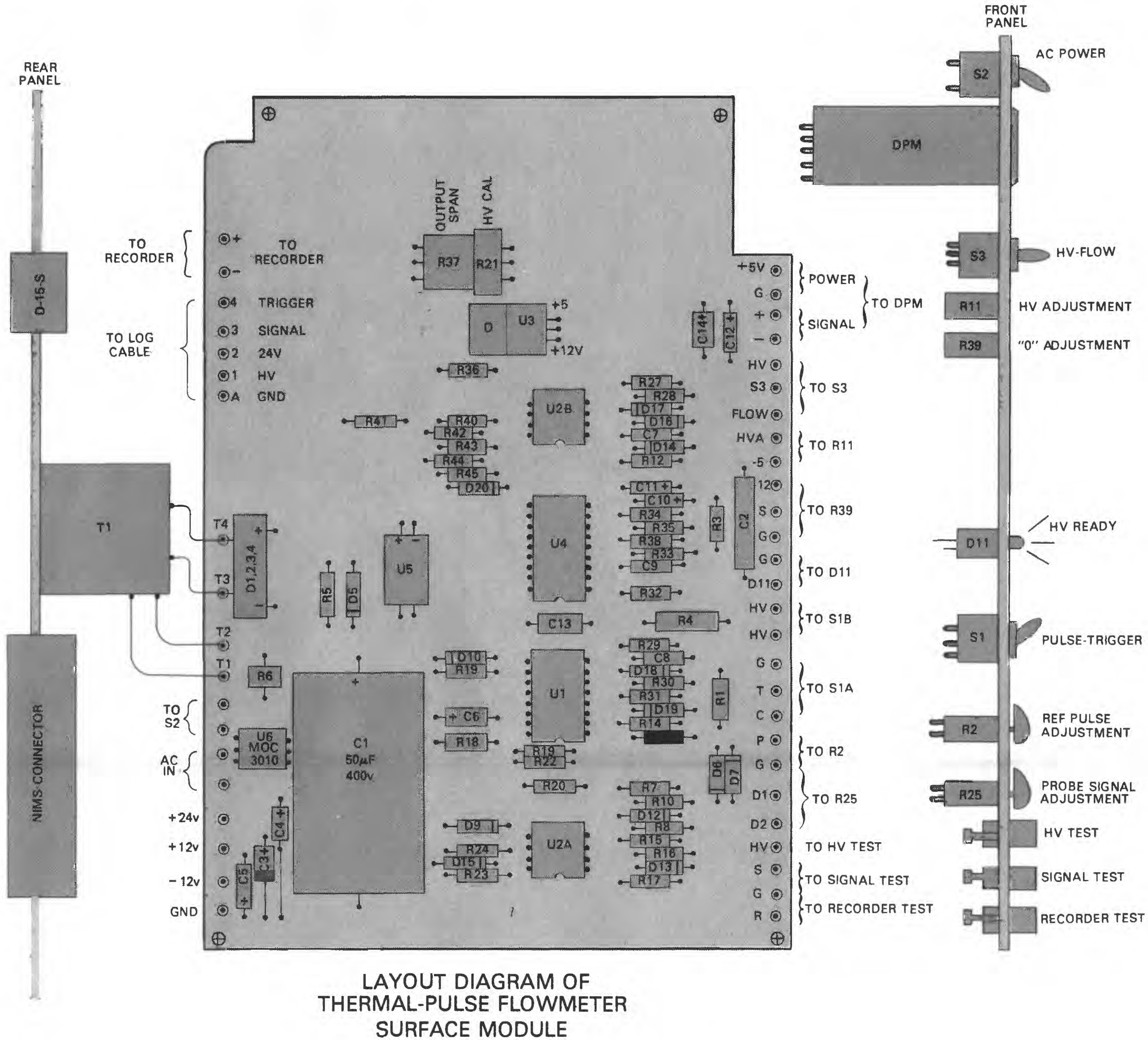


Figure 49. Electronic component layout for surface module.

*U.S. GOVERNMENT PRINTING OFFICE: 1990-0-773-204/20025