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MetroPhysics Inc.

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Marshall Space Flight Center
Huntsville, Alabama

10 March 1965

FINAL REPORT

"DEVELOPMENT OF A SOLID STATE THERMOSTAT"

Contract No. NAS 8-11625

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1.0 INTRODUCTION

The description of a 1 Amp Solid State Thermostat designed and developed by METROPHYSICS, Inc. under Contract No. NAS 8-11625 is presented in this report, together with the test results obtained on it, and recommendations for future modifications.

All considerations which led to the adopted design are discussed.

This thermostat surpasses mechanical types with respect to accuracy and reliability. It also provides a temperature output signal which can be used to monitor the temperature under control continuously by automatic checkout equipment or telemetry systems. Its inherent ruggedness and the absence of any moving parts make this thermostat ideally suited for space and airborne applications.

MP/I efforts which resulted in the fabrication and delivery of 5 Solid State Thermostats can be called successful. These 5 units not only comply with the specifications, but exceed them in several respects.

2.0 FUNCTIONAL DESCRIPTION

The thermostat consists of five functional parts:

1. Temperature sensing element
2. Readout amplifier
3. Zero amplifier
4. Solid state switch
5. Power supply

Figure 1 shows how these five functional parts are interconnected. The temperature sensing element, a thermistor, forms the input resistor of an operational amplifier (readout amplifier). A constant voltage is applied to the thermistor and amplified by the readout amplifier. The gain of the readout amplifier depends on the ratio $\frac{R_F}{R_{(T)}}$. The resistance of the thermistor $R_{(T)}$ is a function of temperature. The output voltage of the readout amplifier is dependent on the ratio $\frac{R_F}{R_{(T)}}$ and, therefore, on temperature. This output voltage is used as a temperature signal. It also is applied to a preselected resistor network and compared to a reference voltage. Any deviation from this reference voltage is detected and amplified by the zero amplifier. The output of the zero amplifier is applied to the solid state switch, which connects the load to the 28 V line.

The power supply provides two regulated voltages, 18 V and -6 V. The 18 V line supplies the amplifiers, while the -6 V line serves as reference for both, readout and zero amplifier.

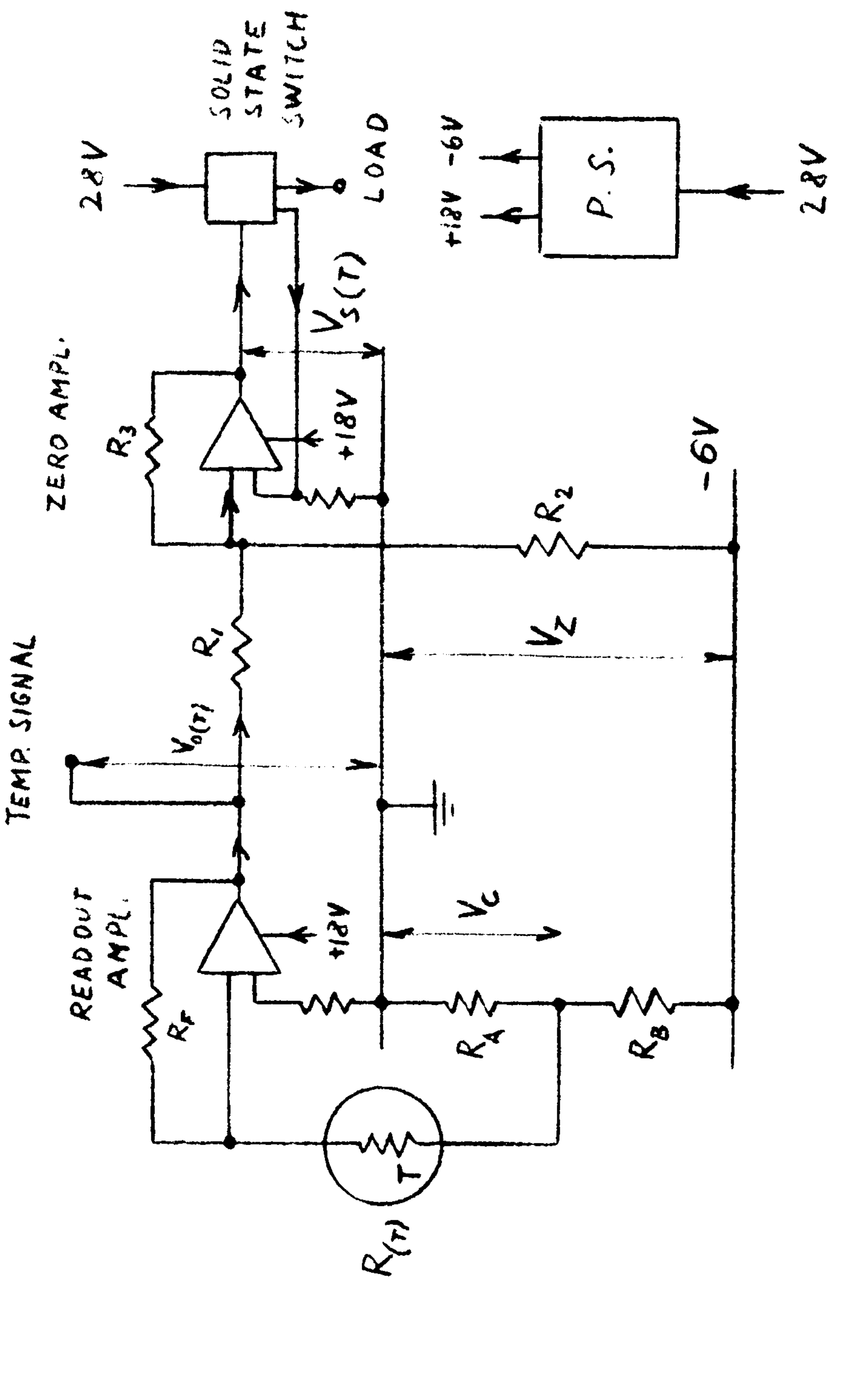


FIGURE 1 - Block Diagram, Solid State Thermostat

3.0 DESIGN CONSIDERATIONS

3.1 Electronic Design

The thermostat developed in accordance with NASA Specification R-P&VE-PMS-SPEC-2-63 has to fulfill the following requirements: It must be small in size, capable of handling 1A of current, be stable, and provide a temperature readout signal.

These requirements are contradictory in several respects; therefore, the final design must be a compromise.

The performance parameters were considered of prime importance. This emphasis led to a larger size than originally specified. All the other requirements could be met or exceeded.

The starting point for the design was the control point stability and accuracy. Control temperature range and readout signal range are not identical, and advantage was taken of this fact. While the control temperature range is the interval from 25°C to 50°C, the readout signal range extends from 0°C to 50°C. Accuracy requirements also differ. The control point stability is ±.2°C, but only ±.5°C accuracy is required for the readout signal.

Both control point stability and readout accuracy depend on the stability of the sensing device and the electronic circuit. It would be desirable to dispense with the electronic circuit, thereby reducing sources of possible errors. However, the requirement for a 5 V readout signal to be delivered into a 10 Kohm load would make it necessary to employ a temperature sensor of low impedance and a high excitation voltage. Power dissipation in the sensing element would introduce an uncontrollable error by self-heating. From this it follows that the most desirable sensing element would be one which gives the highest sensitivity for the least power. A device which excels all other comparable sensors with respect to sensitivity is the thermistor.

In the past, thermistors were considered insufficiently stable in time to find applications where accuracy is paramount. However, this limitation no longer exists. Thermistors with long time stability are now manufactured to close tolerances, and are readily available. The design of the thermostat is based on such a thermistor.

As previously stated, self-heating is a severe source of error. It can be resolved by employing a high impedance thermistor and by carefully choosing the voltage across it. Impedance does not influence the sensitivity as long as loading is negligible, but voltage does.

The thermistor selected is a Fenwal Iso-curve thermistor of the highest impedance available. A buffer amplifier is necessary to avoid loading the thermistor and associated network.

It might appear that the advantage of high sensitivity obtained with a high impedance thermistor is offset by the requirement for a buffer amplifier. However, no matter what approach is contemplated, an amplifier is always required. A low impedance sensor would not allow applying voltages to them which are high enough to produce the desired output signal level without amplification. The advantage gained by using a high impedance thermistor is the low gain required for the amplifier. A low gain is desirable, for not only the useful input signal is amplified, but also the drift of the input stage of the amplifier. With high gain, the error produced by drift might become intolerably large unless a sophiscated amplifier is employed. Size limitations exclude such an approach.

The next step after the selection of the thermistor is to decide on the network configuration in which it is to be used to produce the most useful signal for readout and switching.

A thermistor is an inherently non-linear device, but it can be used in conjunction with a resistive network to produce a linear transfer function within a limited temperature range. In this case, however, advantage was taken of its non-linearity. The thermistor is placed in the feedback path of an operational amplifier to which a constant voltage is applied (see Figure 1). A temperature change of the thermistor causes a change of the gain of amplifier and, thereby, of its output voltage. The output voltage of the amplifier is described by the following equation:

$$V_{o(T)} = \frac{-R_F}{R_{(T)}} V_c$$

The sensitivity, then, follows:

$$\frac{dV_{o(T)}}{dT} = \frac{R_F}{R_{(T)}^2} \cdot \frac{dR_{(T)}}{dT} \cdot V_c = \frac{R_F}{R_{(T)}} \cdot \alpha \cdot V_c$$

where α is the temperature coefficient of the thermistor and almost constant within the temperature range of interest.

It can be seen from the equation that the sensitivity increases with decreasing $R_{(T)}$. $R_{(T)}$ has a negative temperature coefficient and, therefore, decreases with increasing temperature. This effect is desired for temperature control which has to be obtained from 25°C to 50°C with an accuracy of ±.2°C, while temperature readout extends over a wider temperature range and requires a less stringent accuracy.

The scheme described above offers another advantage when considering temperature control action. In this case, a voltage change corresponding to .1°C has to be detected. This temperature change is translated into voltage change. However, with a 5 V full scale signal as available at the output of the readout amplifier, such a change would be too small to operate the power control element. Therefore, another amplifier must be added. Any deviation of the readout voltage from a reference voltage (-6V, Figure 1) is applied to this amplifier, called zero amplifier, and, after amplification, is used to operate the solid state switch. The temperature-voltage relationship of this arrangement (see Section 4.0 - Theory) is:

$$V_{s(T)} = -\left[\left(V_{o(T)} - V_z\right)\frac{R_2}{R_1+R_2} + V_z\right]\frac{R_3(R_1+R_2)}{R_1 R_2}$$

By differentiating:

$$\frac{d V_{s(T)}}{d T} = \frac{R_3}{R_1} \alpha V_{o(T)}$$

R_1 is chosen to make the input voltage to the zero amplifier zero at the control point temperature:

$$\frac{V_{o(T_s)}}{R_1} = \frac{|V_z|}{R_2} \quad \text{OR} \quad V_{o(T_s)} = \frac{R_1}{R_2} |V_z|$$

The sensitivity at the control point temperature then is:

$$\frac{d V_{s(T_s)}}{d T} = \frac{R_3}{R_2} |V_z| \alpha$$

This expression is almost independent of temperature (except for the slight change of α), a feature which assures uniform control over the entire control temperature range.

The discussion now arrives at the power control element or solid state switch. It is of primary interest to come up with a design which holds power dissipation in this part of the circuit to a minimum. The power transistor which has to be small because of size limitations should dissipate as little power as is feasible in order to avoid any thermal stress. The insertion of a small resistor between the 28 V line and the collector of the power transistor solved this problem.

The power supply is of conventional design. An inverter had to be included to obtain a negative reference voltage for both amplifiers.

As previously stated, difficulties in making the original size requirement became apparent after the electronic design was completed. The only packaging method which makes it possible to at least approach the desired size is cordwood packaging, using welded interconnections. This method, therefore, was adopted for the design.

3.2 Mechanical Design

The probe which houses and protects the temperature sensitive element caused considerable design difficulties. Flexibility of application leads to contradictory requirements. The probe should be rigid to withstand shock and vibration, but at the same time spring action in the tip is desirable to insure good heat contact with surfaces to be measured. In addition, sealing the unit hermetically was desired to make its use in liquids possible. Finally, the thermal mass should be small to allow the probe to follow rapid temperature change. Designs which meet these requirements are shown in the three drawings in the Appendix, and are discussed in Section 12.0 - "Recommendations".

These designs are quite sophisticated, and must be considered beyond the scope of this contract. Consequently, a simpler probe design was adopted. It provides rigidity and hermetical sealing, but lacks spring action of the tip. A copper tip assures good heat transfer to the thermistor.

4.0 THEORY

4.1 Temperature Readout Signal

Referring to Figure 2, the following equation can be written for the relationship between readout signal (voltage) and temperature:

$$V_{o(T)} = V_c G_{(T)} + (1 - G_{(T)}) V_{off} \tag{1}$$

Substituting

$$V_c = \frac{R_A}{R_A + R_B} V_Z \quad , \quad G_{(T)} = - \frac{R_F}{R_{(T)} + \frac{R_A R_B}{R_A + R_B}}$$

in above equation, we obtain:

$$V_{o(T)} = - \frac{R_A}{R_A + R_B} V_z \frac{R_F}{R_{(T)} + \frac{R_A R_B}{R_A + R_B}} + \left(1 + \frac{R_F}{R_{(T)} + \frac{R_A R_B}{R_A + R_B}} \right) V_{off} \tag{2}$$

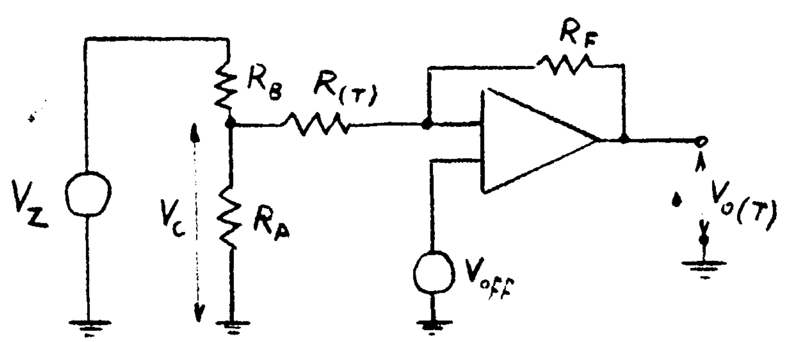


FIGURE 2

$V_{o(T)}$ is chosen for two temperatures:

$$V_{o(0°C)} = .500\ V$$

and

$$V_{o(50°C)} = 5.000\ V$$

$R_{(T)}$ is known at these temperatures:

$$R_{(0°C)} = 336,300\ \Omega$$

and

$$R_{(50°C)} = 35,280\ \Omega$$

V_Z = -6.360 V which is the average voltage of 6 Zener diodes with 6.2 V nominal breakdown voltage.

Using these values, we obtain two equations:

$$V_{o(0°C)} = -\frac{R_A}{R_A + R_B} V_Z \frac{R_F}{R_{(0°C)} + \frac{R_A R_B}{R_A + R_B}} + \left(1 + \frac{R_F}{R_{(0°C)} + \frac{R_A R_B}{R_A + R_B}}\right) V_{off} \quad (3)$$

$$V_{o(50°C)} = -\frac{R_A}{R_A + R_B} V_Z \frac{R_F}{R_{(50°C)} + \frac{R_A R_B}{R_A + R_B}} + \left(1 + \frac{R_F}{R_{(50°C)} + \frac{R_A R_B}{R_A + R_B}}\right) V_{off}$$

(4)

In these two equations, R_A, R_B, R_F and V_{off} are unknown. With certain conditions for two of these unknowns, the two others can be calculated.

One condition concerns the power dissipation in the thermistor. It should be kept low to keep the self-heating error small. Allowing .125 mW, we obtain:

$$V_c = \sqrt{.125\,mW \times 35.28\,k\Omega} = 2.1V$$

$$R_{(50°)} = 35,280 \text{ ohms}$$

Neglecting V_{off} and assuming R_A and R_B to be small compared to R_T,

$$V_{o(50°C)} = 5V = 2.1V \frac{R_F}{35.28\,k\Omega} \tag{5}$$

or R_F = 84 K ohms

R_F was chosen 90.9 K ohms. This larger value makes sure .125 mW are not exceeded in R_T.

From $V_c = \dfrac{R_A}{R_A + R_B} V_Z$ we could calculate the ratio $\dfrac{R_A}{R_B}$ and use it in equations (3) and (4). But because of the neglections made in equation (5), this would lead to discrepancies. It is simpler to assume R_9 and then calculate R_A and V_{off} using (3) and (4).

R_B was selected 4.75 K ohms.

Combining equations (3) and (4):

$$\frac{V_{o(50°C)} + \frac{R_A}{R_A+R_B} V_Z \frac{R_F}{R_{(50°C)} + \frac{R_A R_B}{R_A+R_B}}}{V_{o(0°C)} + \frac{R_A}{R_A+R_B} V_Z \frac{R_F}{R_{(0°C)} + \frac{R_A R_B}{R_A+R_B}}} = \frac{1 + \frac{R_F}{R_{(50°C)} + \frac{R_A R_B}{R_A+R_B}}}{1 + \frac{R_F}{R_{(0°C)} + \frac{R_A R_B}{R_A+R_B}}}$$

After rearranging the above equation and inserting the values for R_F and R_B, we arrive at the following equation for R_A:

$$17{,}279.706 \times R_A^2 + 41{,}719.0039 \times R_A - 192{,}068.294 = 0$$

It then follows that $R_A = -1.20716 \pm \sqrt{1.45724 + 11.11525}$

or $R_A = 2.3386$ K ohms.

Now V_C can be calculated:

$$V_c = \frac{R_A}{R_A + R_B} V_z = 2.098 V$$

This value is only correct with no load connected to the voltage divider $R_{A1}R_B$. With R_T connected, V_C is still further reduced, reaching its minimum when R_T reaches its minimum, thereby keeping the power in R_T well below .125 mW.

Now V_{off} can be calculated using either equation (3) or (4), resulting in

$V_{off} = -50.8$ mV

It should be remarked that this voltage must be introduced in order to obtain the desired end points of .5 V and 5 V. Any offset voltage inherent to the amplifier must be subtracted from V_{off} as outlined in paragraph 9.0 - "Calibration".

Equation (2) now can be used to calculate the temperature-voltage characteristic of the thermostat. Table I shows the results in 1°C steps.

4.2 Temperature Control Point

The second characteristic of the thermostat derived here is the sensitivity of the voltage V_S applied to the solid state switch.

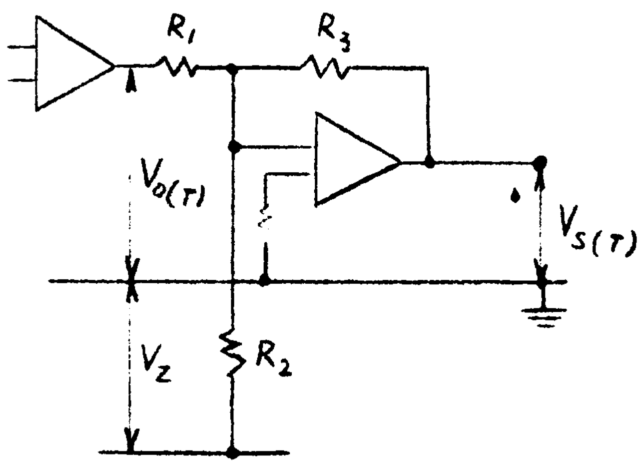


FIGURE 3

For this voltage, the following equation can be written:

$$V_{s(T)} = \left[\left(V_{o(T)} - V_z \right) \frac{R_2}{R_1 + R_2} + V_z \right] G'$$

$$G' = - \frac{R_3 (R_1 + R_2)}{R_1 R_2}$$

The sensitivity is:

$$\frac{dV_{s(T)}}{dT} = \frac{R_2}{R_1 + R_2} \cdot \frac{dV_{o(T)}}{dT} \cdot \frac{-R_3(R_1+R_2)}{R_1 R_2}$$

$$\frac{dV_{s(T)}}{dT} = \frac{-R_3}{R_1} \frac{dV_{o(T)}}{dT} \tag{6}$$

$\frac{dV_{o(T)}}{dT}$ is derived from equation (1).

$$\frac{dV_{o(T)}}{dT} = \left(V_c - V_{off}\right)\frac{dG(T)}{dT} \tag{7}$$

$$\frac{dG(T)}{dT} = \frac{R_F}{\left[R_{(T)} + \frac{R_A R_B}{R_A + R_B}\right]^2} \cdot \frac{dR_{(T)}}{dT} \approx \frac{R_F}{R_{(T)}} \cdot \frac{\frac{dR_{(T)}}{dT}}{R_{(T)}}$$

$$\frac{\frac{dR_{(T)}}{dT}}{R_{(T)}} = \alpha$$ the temperature coefficient of the thermistor

V_{off} is small compared to V_C and can be neglected

$$\frac{dV_{o(T)}}{dT} = \frac{dG(T)}{dT} V_c = \frac{R_F}{R_{(T)}} \alpha V_c = -\alpha V_{o(T)}$$

Substituting in (6):

$$\frac{d\,V_{s(T)}}{dT} = \frac{R_3}{R_1}\,\alpha\,V_{o(T)} \tag{8}$$

at the control point temperature T_S

$$\frac{V_{o(T_S)}}{R_1} = \frac{|V_Z|}{R_2}$$

or $$V_{o(T_S)} = \frac{R_1}{R_2}\,|V_Z|$$

Substituting in (8)

$$\frac{d\,V_{s(T_S)}}{dT} = \frac{R_3}{R_2}\,\alpha\,|V_Z|$$

With α changing very little with temperature and V_Z being constant $\frac{d\,V_{s(T_S)}}{dT}$ also is changing very little. Almost constant sensitivity is, therefore, assured over the entire control temperature range.

5.0 THE TEMPERATURE SENSITIVE ELEMENT

A good temperature sensitive element should feature high sensitivity and be stable in time. As previously stated, a thermistor fulfills these requirements.

The thermistor used in the thermostat is a Fenwal Co. iso-curve thermistor with 100 K ohms resistance at 25°C. Each iso-curve thermistor is matched to a standard temperature-resistance curve within ±.2°C in the temperature interval from 0°C to 50°C, and even tighter tolerances are available. .2°C was chosen because it is sufficient for the required overall accuracy of the readout voltage of ±.5°C. A tolerance of ±.2°C also allows interchanging thermistors without recalibrating the thermostat. Only one calibration curve or chart is necessary for all units.

6.0 ELECTRONIC CIRCUIT

6.1 The Amplifier

Readout amplifier and zero amplifier are almost identical. Both are of the operational type and differ only in gain and the collector resistors of the last stages (see schematic diagram). The readout amplifier serves essentially as a buffer. Its gain varies inversely with the resistance of the thermistor R_{37}. A differential input stage assures good temperature stability. This stage is a dual transistor (Fairchild 2N2979). The two transistors which are packaged in the same can are matched with respect to V_{EB1} and β. The following stage employs an emitter follower in order to hold the loading of the first stage to minimum. The gain of the first stage, therefore, is very high, which helps to reduce temperature drifts caused by Q_7 and Q_8.

The resistor network R_7, R_8, R_9 provides the constant input voltage (see Section 3.0 - "Functional Description"). R_7 and R_8 are in parallel, and have to be chosen during calibration.

The base of the second half of the input stage is returned through R_{15} to a resistor network R_{17}, R_{18}, R_{19}. This network provides the initial offset voltage V'_{off} (see Section 4.0 - "Theory"). The parallel combination R_{17}, R_{18} is selected during calibration. R_{15} reduces temperature drifts caused by changes of the base current of Q_5 and Q_6. Both bases are connected to resistor networks of considerable resistance. The base currents flowing through these networks cause voltages which vary with temperature. If these voltages are equal, no drift will result.

R_{15} is, therefore, chosen to make the impedance as seen from the base of Q_5 equal to the average impedance as seen from the base of Q_4. An exact matching is not possible because of the temperature dependence of R_{37}. Capacitors C_4 and C_6 prevent the circuit from oscillating, and cut down noise originating mainly in the inverter of the power supply.

The zero amplifier provides the gain necessary to actuate the solid state switch. It differs from the readout amplifier mainly in the way the base of the second half of the input stage (Q_{10}) is connected. By returning this base to R_{34}, a positive feedback path from the solid state switch is produced. Whenever the solid state switch starts to turn on, a voltage is developed across R_{34} and fedback to the base of Q_{10}. This signal aids the signal at the base of Q_9 and the collector voltage of Q_{12} increases. The solid state switch is turned on further, causing the voltage across R_{34} to increase, and so on. This accumulative action assures fast turn-on and turn-off when the control point temperature is reached.

Resistors R_{20} and R_{21} serve to compare the readout voltage to a fixed reference voltage derived from the power supply.

Capacitor C_5 slows down the switching action of the solid state switch. It increases the rise and fall time of the load current, thereby reducing electromagnetic interference.

The series combinations R_{13}, R_{14}, R_{22}, R_{23}, R_{24}, R_{27} and R_{28} become necessary to keep the size of the electronic module as small as possible. Single resistors of the same values as the series combinations are available only in lengths incompatible with size requirements.

6.2 The Solid State Switch

The main objective in the design of a solid state switch is to keep power dissipation low. Low power dissipation permits the use of a small power transistor which is highly desirable when space is at a premium. The power dissipation of the power transistor could be reduced by inserting R_{36}. The voltage drop across Q_{15} would be equal to its base-emitter voltage plus the collector voltage of Q_{14}. This voltage is in the order of 1.2 V leading to more than 1.2 W of dissipated power. With R_{36} only 600 mW are dissipated in Q_{15}. By chosing a 2N2034 transistor for Q_{15}, it became possible to dispense with any special heatsink.

The two driver transistors Q_{13} and Q_{14} match the power transistor to the output of the zero amplifier.

Resistors R_{33} and R_{34} produce a positive feedback signal as described in Section 6.1.

6.3 The Power Supply

The regulated power supply is of conventional design. An inverter is used to produce a negative voltage for the amplifiers. The supply voltage of the amplifier transistor Q_2 is derived from the primary winding of the inverter transformer. This voltage is independent of line voltage variations which is the main reason for the circuit's excellent regulation against changes of the 28 V line.

The secondary voltage of the inverter is rectified, filtered and stabilized by a 1N823 Zener reference diode. The thus obtained voltage of approximately -6.2 V serves as reference for the regulated power supply and the amplifiers.

7.0 HOUSING AND PROBE

Drawing No. 100061 shows the assembled thermostat. Temperature probe and housing form one unit, and are made of stainless steel. The probe body protrudes 3 inches from the housing. The thermistor is located in its tip, which is made of copper. A mounting thread is provided on the neck of the probe close to the housing. This arrangement permits inserting the probe to its full length into a threaded well. A depth adjustment can be obtained by using a jam nut.

The connector is soldered to the cover which is held in place by 4 screws. An O-ring seals the inside of the housing. This cover design is not final, but was adopted to allow repeated removal of the cover to give access to the electronic module during testing and evaluation. The final design would be one where the cover is soldered into place after the unit has been calibrated. A saving in length and hermetical sealing are thereby achieved.

8.0 SPECIFICATIONS

Temperature Control

Control action: "ON" on falling temperature

Control point range: +25°C to +50°C

Control point accuracy: ±.2°C

Control point temperature: Adjustable by a fixed resistor

Load handling capability: 28 ohms from 28 V DC (1 Amp)

Temperature Output Signal

Temperature range: 0°C to 50°C corresponding to .500 V to 5.000 V

Transfer function: Non-linear, see calibration chart

Accuracy: ±.5°C

Stability: ±.3°C, 0°C to +25°C
±.2°C, +25°C to +50°C

Output impedance: 25 ohms

Power Requirements

Supply voltage: 23 V DC to 32 V DC

Supply current: 35 mADC above control point temperature

45 mADC below control point temperature

(without load current)

Environmental Temperature 0°C to +70°C operating

-25°C to +100°C non-operating

Connector Bendix PT1H-12-8P

9.0 CALIBRATION

9.1 Temperature Readout Signal

The temperature readout signal is adjusted by selecting two pairs of resistors, viz., R_1, R_8, and R_{17}, R_{18} (see schematic diagram). During calibration these resistors and the thermistor are simulated by decade resistor boxes. This procedure fixes the end points of the temperature range, 0°C and 50°C corresponding to .5 V and 5 V.

First, the resistor box simulating R_7, R_8 is set to 2.35 K ohms; the box simulating R_{17}, R_{18} is set to 0, and the box simulating the thermistor is set first to 336,300 ohms (corresponding to 0°C) and then to 35,280 ohms (corresponding to 50°C). The output voltages $V_o^*(0°C)$ and $V_o^*(50°C)$ are recorded.

The asterisks indicate actual value as opposed to ideal ones. From the theory we have:

$$V^*_{o(50°C)} = V^*_z G^*_{(50°C)} + (1 - G^*_{(50°C)}) V^*_{o::}$$

and

$$V^*_{o(0°C)} = V^*_z G^*_{(0°C)} + (1 - G^*_{(0°C)}) V^*_{o::}$$

Combining both equations, we achieve:

$$V^*_{o::} = \frac{V^*_{o(50°C)} - V^*_{o(0°C)} \frac{G^*_{(50°C)}}{G^*_{(0°C)}}}{1 - \frac{G^*_{(50°C)}}{G^*_{(0°C)}}}$$

The actual gain is always proportional to the theoretical gain because it depends solely on the ratio $\frac{R10}{R37}$ and varies with the deviations of R10 from its nominal value. Therefore, it is possible to use the theoretical value for the gains in the above equation:

$$V^*_{off} = \frac{V^*_{o(50°C)} - V^*_{o(0°C)} \frac{G_{(50°C)}}{G_{(0°C)}}}{1 - \frac{G_{(50°C)}}{G_{(0°C)}}}$$

With $G_{(50°C)} = -2.467$ and $G_{(0°C)} = -.269$

we obtain $$V^*_{off} = \frac{V^*_{o(50°C)} - V^*_{o(0°C)} \times 9.169}{-8.169}$$

V^*_{off} calculated from this formula is the offset voltage of the first amplifier stage.

This voltage must be subtracted from the theoretical offset voltage V_{off} and the so obtained voltage V'_{off} is the voltage to which the amplifier is adjusted.

$$V'_{off} = V_{off} - V^*_{off}$$

V'_{off} is measured across the decade resistor box simulating R_{17}, R_{18}. The resistor box is adjusted until the meter reads V'_{off}. R_{17} and R_{18} now are chosen in such a manner that the resistance of their parallel combination equals the reading of the box.

METROPHYSICS INC.

IP 645 201-4
C# NAS 8-11625,
W.A.#645201

CALIBRATION CHART

T°C	R_T* K ohms Min.	Nominal	Max.	$V_{0(T)}$** Volts Min.	Nominal	Max.	Temp. Coef.-α %
0	332.8	336.3	339.8	.487	.500	.513	5.22
1	316.0	319.3	322.6	.516	.529	.543	5.19
2	300.1	303.2	306.3	.546	.560	.574	5.15
3	285.[illegible]	287.9	290.8	.577	.592	.607	5.12
4	270.5	273.3	276.1	.610	.626	.642	5.09
5	257.2	259.8	262.4	.644	.661	.678	5.06
6	244.6	247.1	249.6	.680	.698	.715	5.02
7	232.6	235	237.3	.718	.736	.754	4.99
8	221.3	223.5	225.7	.757	.776	.795	4.96
9	210.5	212.6	214.7	.797	.818	.838	4.93
10	200.2	202.2	204.2	.841	.863	.884	4.90
11	190.1	192.6	194.5	.886	.908	.930	4.87
12	181.8	183.6	185.4	.931	.954	.977	4.84
13	173.2	174.9	176.6	.980	1.004	1.028	4.81
14	165.1	166.7	168.3	1.030	1.055	1.080	4.78
15	157.3	158.8	160.3	1.083	1.110	1.136	4.75
16	150.0	151.4	152.8	1.138	1.166	1.193	4.72
17	143.1	144.5	145.8	1.195	1.223	1.252	4.70
18	136.7	138	139.3	1.253	1.283	1.313	4.67
19	130.4	131.6	132.8	1.315	1.347	1.378	4.64
20	124.4	125.6	126.7	1.380	1.413	1.446	4.61
21	11[illegible]	119.9	121.0	1.448	1.481	1.516	4.58
22	113.5	114.6	115.6	1.516	1.551	1.587	4.55
23	108.6	109.6	110.6	1.587	1.623	1.660	4.53
24	103.7	104.7	105.6	1.662	1.701	1.739	4.50
25	99.10	100.0	100.9	1.[illegible]	1.781	1.821	4.47
26	94.81	95.67	96.52	1.822	1.863	1.905	4.45
27	90.73	91.50	92.30	1.906	1.949	1.992	4.42
28	86.83	87.61	88.38	1.991	2.036	2.081	4.40
29	83.14	83.88	84.61	2.081	2.127	2.174	4.37
30	79.60	80.30	80.99	2.175	2.223	2.271	4.35

TABLE I

CALIBRATION CHART (Continued):

	R_T* K ohms			$V_{O(T)}$** Volts			
T°C	Min.	Nominal	Max.	Min.	Nominal	Max.	Temp. Coef. -α %
31	76.21	76.88	77.54	2.272	2.322	2.372	4.32
32	72.98	73.62	74.25	2.373	2.425	2.477	4.30
33	69.94	70.55	71.15	2.476	2.530	2.584	4.27
34	67.03	67.61	68.18	2.584	2.640	2.696	4.25
35	64.26	64.81	65.35	2.695	2.753	2.811	4.22
36	61.59	62.12	62.64	2.811	2.872	2.932	4.20
37	59.05	59.55	60.04	2.932	2.995	3.057	4.17
38	56.62	57.10	57.57	3.057	3.122	3.186	4.15
39	54.35	54.81	55.26	3.183	3.250	3.317	4.13
40	52.20	52.64	53.07	3.313	3.383	3.452	4.11
41	50.07	50.49	50.90	3.452	3.524	3.596	4.09
42	48.07	48.47	48.86	3.594	3.668	3.743	4.06
43	46.15	46.53	46.90	3.742	3.819	3.896	4.04
44	44.33	44.69	45.04	3.893	3.972	4.052	4.02
45	42.61	42.96	43.30	4.047	4.129	4.212	4.00
46	40.96	41.29	41.61	4.206	4.292	4.377	3.98
47	39.36	39.68	39.99	4.373	4.461	4.549	3.95
48	37.84	38.14	38.43	4.545	4.637	4.728	3.93
49	36.37	36.66	36.94	4.724	4.818	4.912	3.91
50	35.00	35.28	35.55	4.903	5.000	5.097	3.89

* R_T min. and max. correspond to + .2°C

** $V_{O(T)}$ min. and max. correspond to + .5°C

TABLE I (Continued)

The resistor box simulating the thermistor is now set to 35,280 ohms and the box simulating R_7, R_8 is adjusted until the readout voltage equals 5.000 V. R_7 and R_8 are chosen so that their parallel combination equals the reading of the resistor box. The temperature readout signal is now calibrated.

It should be remarked that both pairs, R_7, R_8 and R_{17}, R_{18} can be substituted by a single resistor. This was done in the 5 delivered units. When larger quantities are produced, it is advantageous to combine two resistors to obtain the desired values because fewer values have to be stocked and larger resistance tolerances are permissible.

When test results on the thermistors to be used with the thermostats are available at the time of calibration, it might be advantageous to adjust the readout voltage in such a manner that the deviations of the thermistors from nominal are compensated, thereby improving the overall accuracy.

Table I lists the relationship between temperature and readout voltage in 1°C steps. It also shows the corresponding thermistor resistance and its temperature coefficient.

The readout voltage $V_{o(T)}$ was calculated from

$$V_{o(T)} = (V_c + V_{off})\,G_{(T)} + V_{off} \quad \text{(see 4.0 - "Theory")}$$

where $V_{off} = -50.8$ mV, $V_C = -2.0982$ V and

$$G_{(T)} = \frac{R_{10}}{R_{37} + \dfrac{R_8 R_9}{R_8 + R_9}}$$

The thermistor resistance values were obtained from tables published by Fenwal Electronics Co., and the temperature coefficients were calculated from these tables.

9.2 Control Point Temperature

The temperature control point is set by selecting R_{20} (see schematic diagram). The value of this resistor can be roughly calculated according to

$$\frac{V_{o(T_s)}}{R_{20}} = \frac{|V_z|}{R_{21}}$$

$V_{o(Ts)}$ is the readout voltage at the desired control point temperature as obtained from Table 1. V_Z is equal to 6.2 V. A more accurate value for R_{20} is obtained by placing the tip of the temperature probe into a bath of known temperature, and by simulating R_{20} by a decade resistor box.

For the 5 delivered units the reverse procedure was followed. A fixed resistor (19.1 K ohms) was inserted and then the control temperature measured. This simplification was possible because no control point temperature was specified.

It should be noted that in spite of the tolerance of the resistors used for R_{20} (1%), all control points lie within a temperature interval of .4°C.

10.0 ERROR DISCUSSION

Three factors contribute to the error of the temperature readout signal: the tolerance of the thermistor, the temperature stability of the circuit, and the tolerances of the calibration resistors.

Of these three sources of error, only the tolerance of the thermistor and the temperature stability of the circuit are significant. The tolerances of the calibration resistors can be held as tight as desired, and their contribution to the error be made negligible.

The overall error E_s is the sum of the errors E_{Th} caused by the thermistor E_{EL}, caused by the circuit, and E_R, caused by the calibration resistors

$$E_s = E_{Th} + E_{EL} + E_R$$

E_{Th} and E_R are constant, while E_{EL} is a function of temperature.

The overall error E_s could be found by changing the ambient temperature to which the entire thermostat is exposed from 0°C to +70°C while holding the temperature of the tip of the probe constant. This procedure must be repeated for selected probe temperature in the range from 0°C to +50°C. Technical difficulties prohibit such an approach. Fortunately a simple method can be used where the overall error is computed from the results of two independent test series.

First, E_{EL} is measured by placing the thermostat into a temperature chamber and by simulating the thermistor for certain temperatures. For each thermistor temperature, a corresponding E_{EL} is found.

Second, the tip of the probe is placed into a constant temperature bath and measurements are taken at certain temperatures. Deviations of these measurements from the calibration chart (Table I) consitute the errors E_{Th} and E_R.

The overall error is then obtained by summing the individual errors. Care must be taken to add only errors which correspond to the same thermistor temperature.

To illustrate this method, reference is made to Figure 2 and Table II. From Table II we find that for a thermistor resistance of 35,280 ohms, which corresponds to 50°C, the readout voltage changes -9 mV when the ambient temperature is reduced from 25°C to 0°C, and +18 mV when the ambient temperature is increased from 25°C to 70°C. These voltage changes correspond to an error in temperature of -.05°C and +.09°C, respectively.

From Table II we take the error $E_{Th} + E_R$ for thermostat Serial #2 at 50°C which is +.36°C. The maximum error for 50°C probe temperature occurs then at an ambient temperature of 70°C. It is +.09°C +.36°C = .45°C.

The control point stability depends on the stability of both the readout voltage and the zero amplifier. Both are dependent on temperature.

First, the stability of the readout voltage at the control point is tested under changing ambient temperature. Then, the zero stability of the zero amplifier is tested. The sum of both drifts is then the drift of the control point temperature.

11.0 TEST RESULTS

11.1 Temperature Readout Signal Accuracy

Two series of tests were performed on each thermostat. First, after calibration, the behavior of the units under different ambient temperatures and supply voltages was tested while the thermistor was simulated by a decade resistor box. Second, the completed units were tested with the probe part immersed in a constand temperature bath. The readout voltage was measured and compared to the calibration chart.

Tables II through VI show the first part of the test results. The change of the readout voltage was well within ±.1°C in the entire temperature range and under all ambient temperatures. This performance is better than the specification requirements by a factor of two. No influence of supply voltage changes could be detected.

Table VII gives the values obtained with the probes immersed in a Rosemount Corp. temperature bath. The largest error was +.36°C. This error combined with the ambient temperature error is the overall error. It is smaller than .5°C on all five units.

11.2 Temperature Control Point Stability

Tables II through VI show the change of the temperature control (or switch) point of all 5 units. The readings were obtained by simulating the thermistor by a variable resistor and monitoring the temperature control (or load) output.

What these tests reveal is the temperature stability of the zero amplifier. The readings show that this error which is superimposed on the error of the readout voltage is insignificant, never exceeding the equivalent of .05°C.

The difference between turn-on and turn-off readings represent the ON-OFF differential. A slight dependence on supply voltage can be noticed, an effect with is due to R_{34}. This resistor decides the amount of positive feedback to the input of the zero amplifier. The current through and the voltage across it both increase with the supply voltage which is unregulated.

The ON-OFF differential is in the order of .03°C. It should be noted that this value was arbitrarily chosen and can be changed by changing the value of R_{34}.

Table VIII was obtained from measurements with the probe in a constant temperature bath. The difference between turn-on and turn-off temperature is the ON-OFF differential. These values, while being within specifications, differ from those obtained by simulating the thermistor. No explanation has been found for this behavior.

METROPHYSICS, Inc.

TEST SHEET

SOLID STATE THERMOSTAT DWG NO. 100 061, Serial No. 2

Temperature Stability of Readout Voltage

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

TEMPERATURE:	0°C			25°C			50°C			70°C			$\triangle V_R$	
P.S. Voltage / Decade Box	24V	28V	32V	24V	28V	32V	24V	28V	32V	24V	28V	32V	Tested	Permitted
336,000 ohms		.508			.508			.509			.510		2mV	13mV ∼ .5°C
100,000 ohms		1.805			1.808			1.811			1.814		9mV	16mV ∼ .2°C
35,280 ohms		5.067			5.076			5.086			5.094		21mV	40mV ∼ .2°C

Temperature Stability of Switch Point

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

	24V	28V	32V	24V	28V	32V	24V	28V	32V	24V	28V	32V	Tested	Permitted
TURN-ON	2.140	2.140	2.140	2.142	2.142	2.142	2.143	2.143	2.143	2.144	2.144	2.144	4mV	18mV ∼ .2°C
TURN-OFF	2.143	2.144	2.144	2.144	2.145	2.146	2.146	2.146	2.147	2.147	2.147	2.147	4mV	18mV ∼ .2°C

Difference Between Turn-On and Turn-Off Readings Should Be Smaller Than 9mV∼.1°C

TABLE II

METROPHYSICS, Inc.

TEST SHEET

SOLID STATE THERMOSTAT DWG NO. 100 061, Serial No. 3

Temperature Stability of Readout Voltage

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

TEMPERATURE:	0°C			25°C			50°C			70°C			ΔV_R	
P.S. Voltage / Decade Box	24V	28V	32V	24V	28V	32V	24V	23V	32V	24V	28V	32V	Tested	Permitted
336,000 ohms		.500			.499			.499			.499		1mV	13mV ~ .5°C
100,000 ohms		1.779			1.779			1.778			1.776		3mV	16mV ~ .2°C
35,280 ohms		4.999			4.997			4.994			4.990		9mV	40mV ~ .2°C

Temperature Stability of Switch Point

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

TURN-ON	2.103	2.103	2.103	2.102	2.102	2.102	2.101	2.102	2.102	2.100	2.100	2.099	4mV	18mV ~ .2°C
TURN-OFF	2.104	2.104	2.105	2.104	2.104	2.105	2.103	2.103	2.104	2.102	2.102	2.102	3mV	18mV ~ .2°C

Difference Between Turn-On and Turn-Off Readings Should Be Smaller Than 9mV ~ .1°C

TABLE III

METROPHYSICS, Inc.

TEST SHEET

SOLID STATE THERMOSTAT DWG NO. 100 061, Serial No. 4

Temperature Stability of Readout Voltage

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

TEMPERATURE:	0°C			25°C			50°C			70°C			ΔV_R	
P.S. Voltage / De-cade Box	24V	28V	32V	24V	28V	32V	24V	28V	32V	24V	28V	32V	Tested	Permitted
336,000 ohms		.502			.503			.503			.503		1mV	13mV ~ .5°C
100,000 ohms		1.784			1.785			1.786			1.787		3mV	16mV ~ .2°C
35,280 ohms		5.008			5.015			5.019			5.022		14mV	40mV ~ .2°C

Temperature Stability of Switch Point

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

TURN-ON	2.106	2.106	2.106	2.106	2.106	2.106	2.105	2.105	2.105	2.104	2.104	2.104	2mV	18mV ~ .2°C
TURN-OFF	2.108	2.108	2.109	2.108	2.108	2.109	2.107	2.108	2.108	2.106	2.106	2.107	3mV	18mV ~ .2°C

Difference Between Turn-On and Turn-Off Readings Should Be Smaller Than 9mV ~ .1°C

TABLE IV

METROPHYSICS, Inc.

TEST SHEET

SOLID STATE THERMOSTAT DWG NO. 100 061, Serial No. 5

Temperature Stability of Readout Voltage

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

TEMPERATURE:	0°C			25°C			50°C			70°C			$\triangle V_R$	
P.S. Voltage / Decade Box	24V	28V	32V	24V	28V	32V	24V	28V	32V	24V	28V	32V	Tested	Permitted
336,000 ohms		.506			.506			.507			.507		1mV	13mV ~ .5°C
100,000 ohms		1.784			1.787			1.789			1.788		5mV	16mV ~ .2°C
35,230 ohms		5.003			5.008			5.012			5.013		10mV	40mV ~ .2°C

Temperature Stability of Switch Point

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

TURN-ON	2.130	2.130	2.130	2.131	2.131	2.131	2.131	2.131	2.131	2.130	2.130	2.130	1mV	18mV ~ .2°C
TURN-OFF	2.133	2.133	2.133	2.133	2.134	2.134	2.133	2.133	2.133	2.132	2.132	2.132	2mV	18mV ~ .2°C

Difference Between Turn-On and Turn-Off Readings Should Be Smaller Than 9mV ~ .1°C

TABLE V

METROPHYSICS, Inc.

TEST SHEET

SOLID STATE THERMOSTAT DWG NO. 100 061, Serial No. 6

Temperature Stability of Readout Voltage

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

TEMPERATURE:	0°C			25°C			50°C			70°C			ΔV_R	
P.S. Voltage / Decade Box	24V	28V	32V	24V	28V	32V	24V	28V	32V	24V	28V	32V	Tested	Permitted
336,000 ohms		.502			.500			.499			.499		3mV	13mV ∼ .5°C
100,000 ohms		1.780			1.778			1.779			1.779		2mV	16mV ∼ .2°C
35,280 ohms		4.991			4.996			5.000			5.004		13mV	40mV ∼ .2°C

Temperature Stability of Switch Point

READOUT VOLTAGE (DIGITAL VOLTMETER READINGS)

TURN-ON	2.121	2.121	2.121	2.122	2.122	2.122	2.122	2.122	2.122	2.122	2.122	2.122	1mV	18mV ∼ .2°C
TURN-OFF	2.123	2.124	2.124	2.124	2.124	2.125	2.124	2.124	2.125	2.124	2.124	2.125	2mV	18mV ∼ .2°C

Difference Between Turn-On and Turn-Off Readings Should Be Smaller Than 9mV∼.1°C

TABLE VI

TABLE VII.

T°C	SERIAL NO. 2 $V_o(T)$ in V	SERIAL NO. 2 Error in °C	SERIAL NO. 3 $V_o(T)$ in V	SERIAL NO. 3 Error in °C	SERIAL NO. 4 $V_o(T)$ in V	SERIAL NO. 4 Error in °C	SERIAL NO. 5 $V_o(T)$ in V	SERIAL NO. 5 Error in °C	SERIAL NO. 6 $V_o(T)$ in V	SERIAL NO. 6 Error in °C
0°C	.506	+.23	.496	-.15	.503	+.12	.502	+.077	.502	+.08
10°C	.867	+.1	.850	-.33	.857	-.14	.856	-.165	.860	-.07
20°C	1.421	+.12	1.394	-.29	1.402	-.17	1.398	-.23	1.406	-.11
30°C	2.232	+.033	2.190	-.34	2.210	-.135	2.202	-.22	2.212	-.11
40°C	3.402	+.145	3.334	-.35	3.347	-.26	3.358	-.18	3.365	-.13
50°C	5.070	+.36	4.976	-.123	4.985	-.08	5.006	+.03	5.008	+.04

TABLE VIII.

Control Point Accuracy

	SERIAL NO. 2 in °C	SERIAL NO. 3 in °C	SERIAL NO. 4 in °C	SERIAL NO. 5 in °C	SERIAL NO. 6 in °C
Temper-ature Turn-on	29	29	28.88	29.27	29.05
Temper-ature Turn-off	29.1	29.05	28.92	29.31	29.08

METROPHYSICS INC.

12.0 RECOMMENDATIONS

Most of the effort in the development of the solid state thermostat was directed towards a good solution for the electronic circuit. The final design is considered sound and is as simple as permitted by the performance parameters. However, there is one area where improvement is possible - in the inverter transformer. This transformer is an "off the shelf" item and, therefore, is not ideally tailored to its use in the thermostat. It is this transformer which is responsible for more than half of the current drawn by the electronic circuit, excluding the solid state switch. A special designed transformer could cut this current drain in half. The resulting reduction of heat dissipation inside the housing would help to improve reliability. When the production of larger numbers of thermostats is considered, the costs of a special transformer become negligible as compared to the advantage gained.

The mechanical design, especially that of the probe, is not ideal and leaves room for improvement. A design with the probe separated from the housing offers certain advantages in spite of the cable necessary to connect the probe to the electronics. Heat dissipated in the electronics, which in the present design can reach the tip of the probe where the thermistor is located, would be a problem no longer. The probe itself can be smaller and probes for special applications can be used interchangeably with one and the same electronic module.

The present design where probe and housing form one unit is not quite satisfactory in two respects. Thermal insulation of the tip from the housing is insufficient and the probe is rigid, making it difficult to use it in wells. Three drawings in the appendix show possible designs which can overcome such deficiencies.

MP/I Drawing No. 100217 shows a design where bellows provide both resiliency and hermetical sealing. Glass insulation keeps heat travelling down the probe body from reaching the tip of the probe.

Drawing No. 100218 shows a design employing a coil spring for resiliency and glass insulation. However, no hermetical sealing can be achieved with this approach.

Drawing No. 100220 shows another possibility to solve the resiliency and sealing problems by using a diaphragm.

The major difficulty with designs of this nature is the bonding of the probe tip to some heat insulating material, a problem which could not be solved within the limited scope of this contract.

One remark concerning the temperature-voltage characteristic of the thermostat should be made here:

For certain applications, a linear temperature-voltage characteristic might be desirable. A simple modification of the resistor network at the input of the readout amplifier will produce such a characteristic. Only minor changes of the electronic module would be required.

13.0 CONCLUSION

The 1 amp solid state thermostat developed by MP/I for NASA meets all performance specifications and, as the test results show, even exceeds some of them. The electronic circuit leaves little room for improvement, and other temperature-voltage characteristics than the one in present use could be obtained with only minor modifications.

The area in which considerable improvement can be achieved is the mechanical design of the probe. Future effort should be directed to this goal.

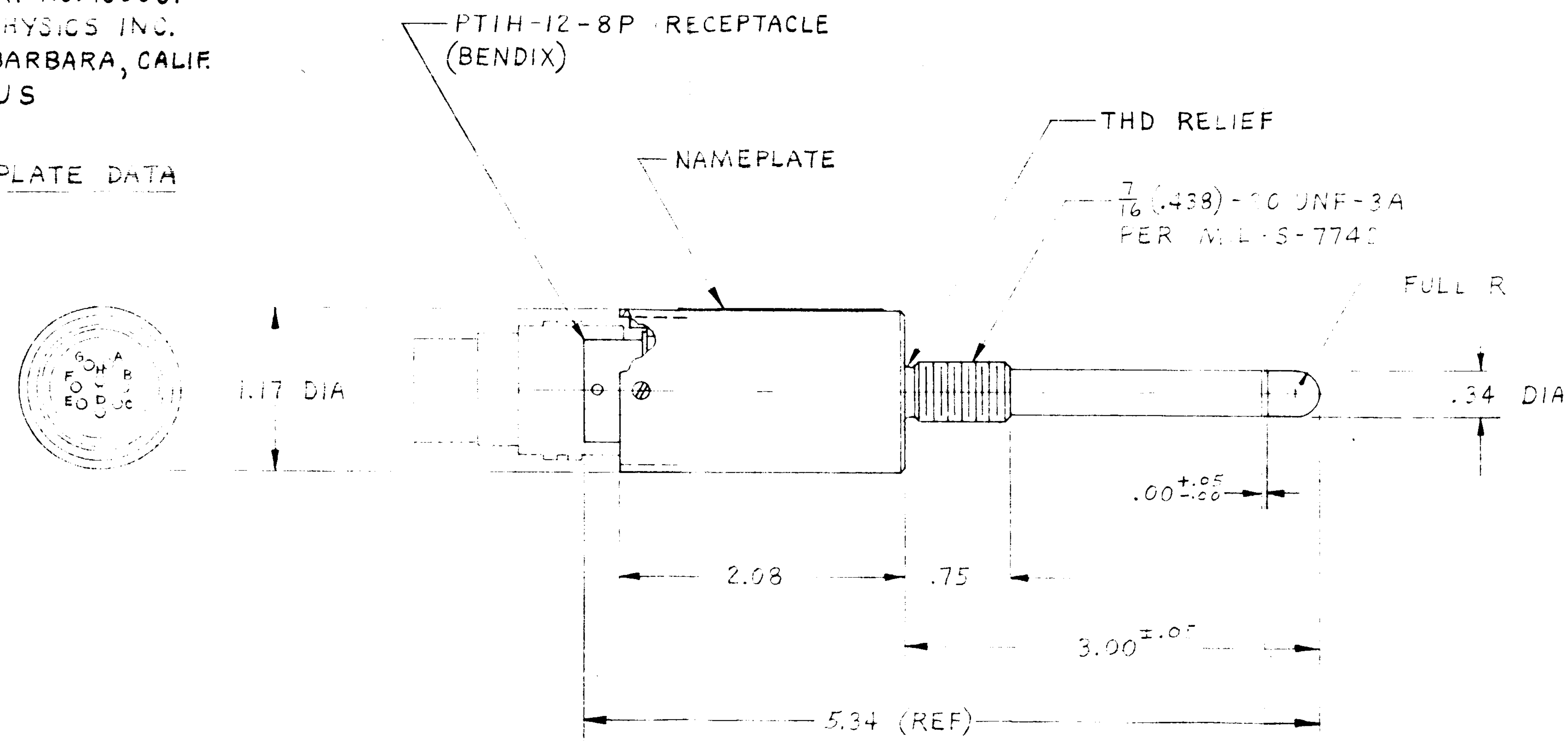
SYM	DESCRIPTION	BY	APPROVAL

CHANGE LTR

100061

1 AMP THERMOSTAT
CONTRACT NO. 8-11615
STOCK NO.
24 TO 32 VOLTS D.C.
SERIAL NO.
MFR PART NO. 100061
METROPHYSICS INC.
SANTA BARBARA, CALIF.
US

NAMEPLATE DATA



ITEM NO.	DESCRIPTION	NO REQD	PART NO	MATL	REMARKS

UNLESS OTHERWISE SPECIFIED
1. DIMENSIONS ARE IN INCHES
2. BREAK SHARP EDGES .005-.015
3. ALL MACHINED RADII .005-.015
5. ALL DIMENSIONS TO BE MET AFTER PLATING
TOLERANCES .XX ±.03 .XXX ± — ANGLES ± —

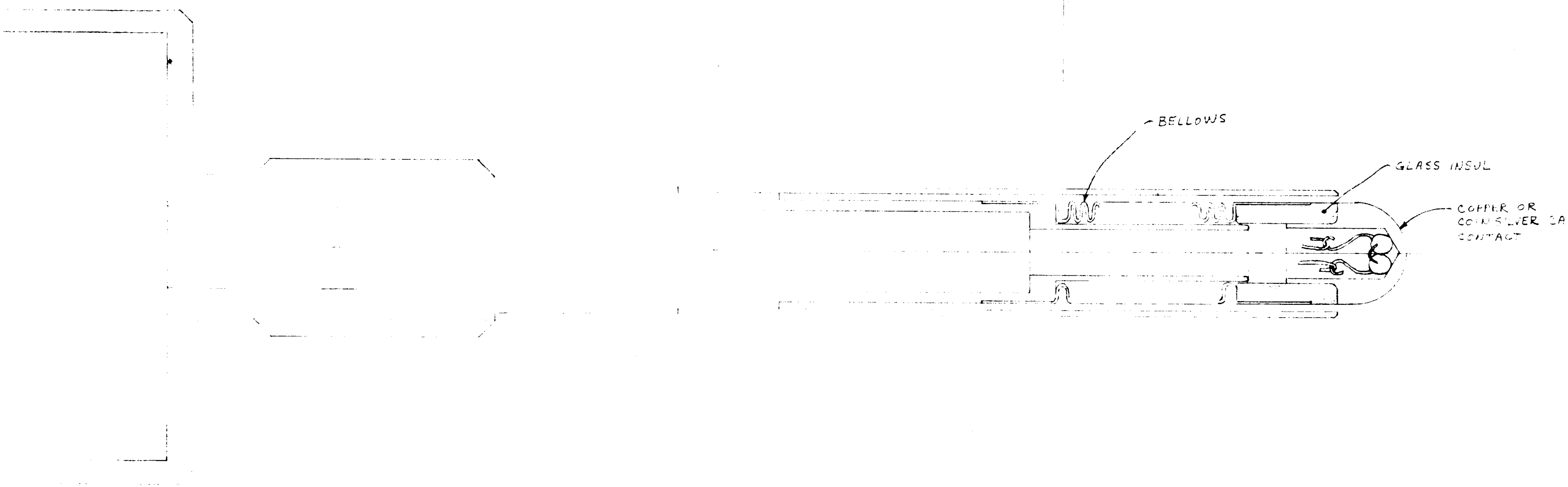
TITLE
THERMOSTAT, 1 AMP SOLID STATE

DRAWN BY Billy 10-16-64	MATERIAL ST STL HOUSING	CODE	METROPHYSICS INC. SANTA BARBARA, CALIF.
CHECKED BY	HEAT TREAT	WT	
APPROVED BY	FINISH PASSIVATE	SCALE 1/1	DWG SIZE B — DWG NO 100061

USED ON	TOTAL REQD

CHANGE LTR	
100217	

SYM	DESCRIPTION	BY	APPROVAL



ITEM NO.	DESCRIPTION	NO REQD	PART NO.	MATL	REMARKS

UNLESS OTHERWISE SPECIFIED

1. DIMENSIONS ARE IN INCHES
2. BREAK SHARP EDGES .005/.015
3. ALL MACHINE RADII .005/.015
4. ALL MACHINE SURFACES 125 MICRO INCH
5. ALL DIMENSIONS TO BE MET AFTER PLATING

TOLERANCE .XX ± .XXX ± ANGLES ±

TITLE: PRELIM. LAYOUT, BELLOWS PROBE

DRAWN BY: Killeen	MATERIAL
CHECKED BY	HEAT TREAT
APPROVED BY	FINISH
CODE	
WT	
SCALE: 4/1	

METROPHYSICS INC.
SANTA BARBARA CALIF

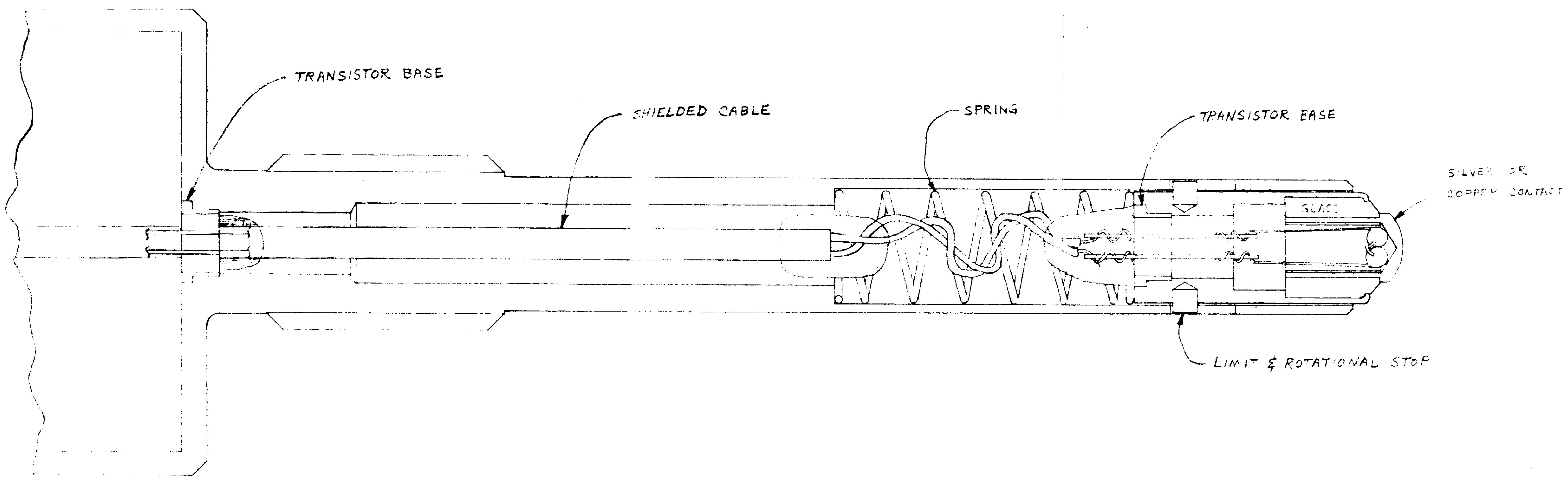
DWG SIZE: B — DWG NO: 100217

USED ON	TOTAL REQD

100218

CHANGE LTR

SYM	DESCRIPTION	BY	APPROVAL



ITEM NO.	DESCRIPTION	NO. REQD	PART NO.	MATL	REMARKS

UNLESS OTHERWISE SPECIFIED

1. DIMENSIONS ARE IN INCHES
2. BREAK SHARP EDGES .005/.015
3. ALL MACHINE RADII .005/.015
4. ALL MACHINE SURFACES 125 MICRO INCH
5. ALL DIMENSIONS TO BE MET AFTER PLATING

TOLERANCES XX ± XXX ± ANGLES ±

TITLE
PRELIM. LAYOUT, FLEXIBLE SPRING PROBE

DRAWN BY Lilley	MATERIAL
CHECKED BY	HEAT TREAT
APPROVED BY	FINISH

USED ON	TOTAL REQD

CODE

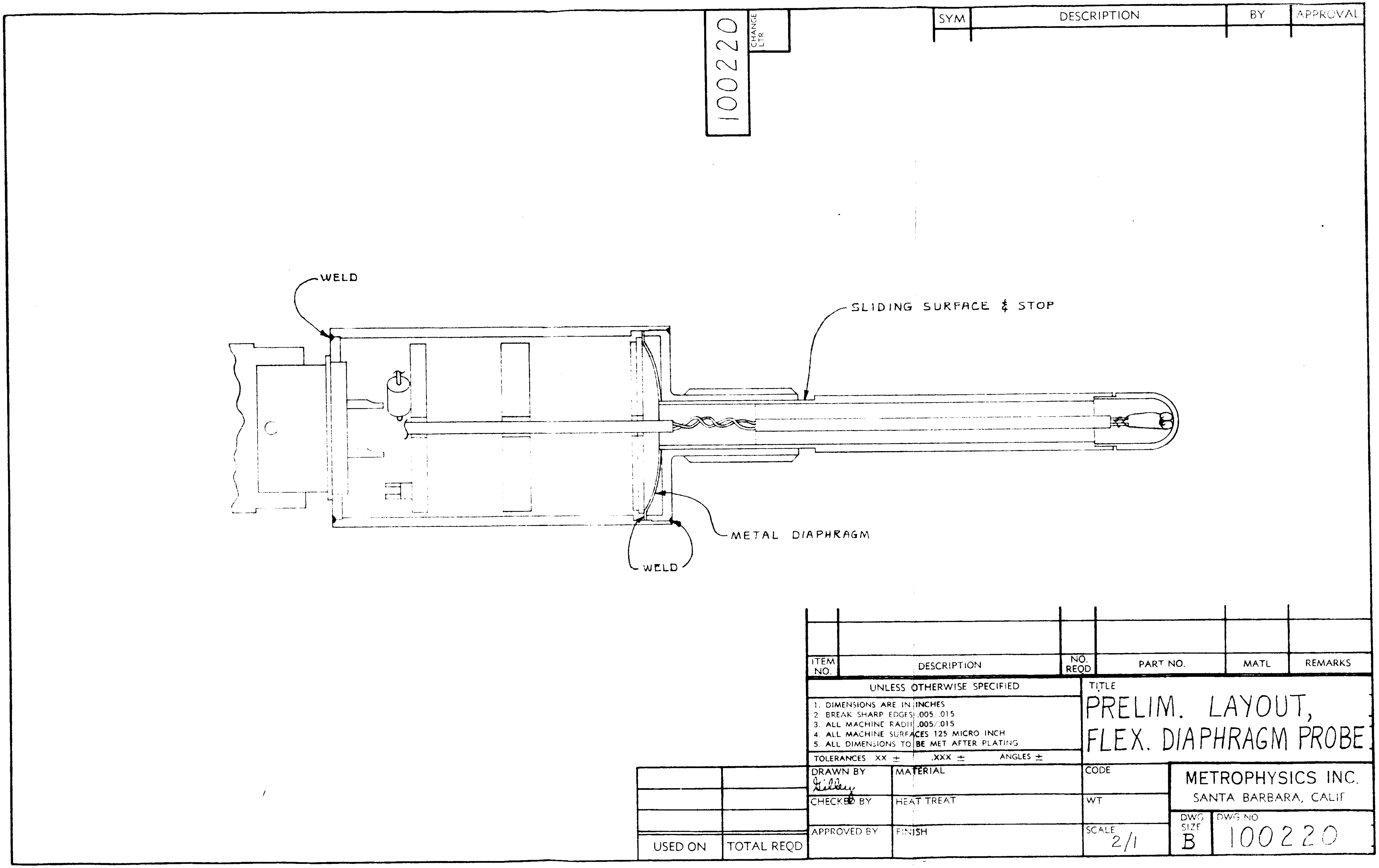
WT

SCALE 4/1

METROPHYSICS INC
SANTA BARBARA, CALIF

DWG SIZE B

DWG NO. 100218



100220
CHANGE LTR
SYM
DESCRIPTION
BY
APPROVAL
WELD
SLIDING SURFACE & STOP
METAL DIAPHRAGM
WELD
ITEM NO.
DESCRIPTION
NO. REQD
PART NO.
MATL
REMARKS
UNLESS OTHERWISE SPECIFIED
1. DIMENSIONS ARE IN INCHES
2. BREAK SHARP EDGES .005/.015
3. ALL MACHINE RADII .005/.015
4. ALL MACHINE SURFACES 125 MICRO INCH
5. ALL DIMENSIONS TO BE MET AFTER PLATING
TOLERANCES XX ± .XXX ± ANGLES ±
DRAWN BY Gilbey
CHECKED BY
APPROVED BY
MATERIAL
HEAT TREAT
FINISH
TITLE
PRELIM. LAYOUT, FLEX. DIAPHRAGM PROBE
CODE
WT
SCALE 2/1
METROPHYSICS INC.
SANTA BARBARA, CALIF
DWG SIZE B
DWG NO 100220
USED ON
TOTAL REQD